Issus of Long-Term Protection: Landfilling of Hazardous Wastes and Municipal Solid Wastes

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Introduction

Industrial and other wastes in the US are categorized as "hazardous" or "non-hazardous" according to protocols outlined in the Resource Conservation and Recovery Act (RCRA). While that categorization is not a literal one that describes the public health or environmental quality risks associated with the material, it does define the options and requirements for handling and disposal of the waste. For many hazardous waste generators the preferred, least expensive, approach is to treat/"detoxify" the wastes in accord with RCRA guidelines and then dispose of the treated residues in a hazardous waste "US EPA Subtitle C" "dry-tomb"-type landfill. Despite waste treatment prior to disposal, the treated waste residues cannot be considered "non-toxic;" they still retain a significant potential to cause water pollution when the landfill liner system fails to contain the leachate generated in the landfill. Despite the engineering and management requirements for Subtitle C and D landfills, such facilities are limited in their ability to protect public health and environmental quality for as long as the buried wastes remain a threat. A dry-tomb landfill simply provides storage of the wastes and at best serves to delay the infiltration of water into the waste and generation of leachate, and the leakage of leachate into area groundwater.

It is becoming well recognized that landfill containment and monitoring systems allowed under Subtitle C and D will ultimately fail to prevent escape of hazardous waste residue-containing leachate through the liner system; the monitoring systems will fail to detect the initial groundwater pollution that will occur as the liner fails. The result is that substantial environmental pollution will occur before action is taken to retard it, contain the damage, and try to prevent further pollution. The conventional postclosure monitoring and maintenance period for landfills extends for 30 years after closure; during that time the landfill owner is responsible for monitoring, maintenance, and remediation of problems that may occur. However, time does not render the buried wastes harmless or unable to generate leachate, and a landfill system may be expected to provide sufficient containment to prevent escape of leachate and pollution of groundwater for 30 years after closure. The threat of the wastes will, in fact, only be reduced as hazardous and otherwise deleterious components of the wastes are leached from them, which would not occur in an ideal "dry-tomb" landfill. There is increasing concern about the post-postclosure care needed for a landfill as the realization dawns that the mandated minimum 30-year postclosure period is only a small part of the time that the waste residues in the landfill will be a threat to public health/welfare and environmental quality.

The long-term liability for the buried wastes and the adverse impacts they will inevitably cause decades, centuries, or longer beyond postclosure remains an issue. RCRA requires that after the postclosure period those who places hazardous waste and waste residues in a hazardous waste landfill will be bear what will be the substantial financial Superfund-like liability for the eventual remediation of environmental pollution that will occur from waste residues that escape from hazardous waste landfills. The reality of such liability is coming to be more widely recognized and is causing some hazardous waste generators to evaluate the possibility of completely treating the hazardous waste so that the treated waste residues placed in a Subtitle D or an industrial waste landfill will not cause environmental pollution when the landfill containment system fails to prevent the escape of the fully treated waste residues. The ability to demonstrate the long-term (centuries) efficacy of a treatment process for rendering a particular waste truly non-hazardous, non-leachable, and non-reactive with whatever other wastes are co-disposed in a given landfill has yet to be defined. Furthermore, whether or not such additional treatment will actually absolve an individual waste discharger from all liability remains to be seen; that liability may still become a matter for the courts in the future.

This report discusses these issues, focusing on RCRA-required approaches for managing hazardous wastes and long-term liability for adverse impacts of the wastes for as long as the wastes remain a threat to public health/welfare and environmental quality.

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Elements of Landfilling Hazardous Wastes

Understanding long-term protection associated with management of hazardous wastes in Subtitle C landfills and of municipal solid wastes in Subtitle D landfills begins with understanding RCRA requirements for landfilling wastes in landfills and problems with and limitations of the RCRA approaches.

Regulatory Aspects

In 1988 the US EPA sponsored a seminar on the design of hazardous waste landfills according to requirements of RCRA, presented by experts in the field of landfill development. An overview of the presentations made was compiled in the US EPA publication US EPA (1989), which states:

> "*This seminar publication is based wholly on presentations made at the U.S. Environmental Protection Agency (EPA) Technology Transfer seminars on Requirements for Hazardous Waste Landfill Design, Construction, and Closure. These seminars were held from June 20 to September 16, 1988.*"
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> "*The U.S. Environmental Protection Agency's (EPA's) minimum technological requirements for hazardous waste landfill design were set forth by Congress in the 1984 Hazardous and Solid Waste Amendments (HSWA). HSWA covered requirements for landfill liners and leachate collection and removal systems, as well as leak detection systems for landfills, surface impoundments, and waste piles. In response to HSWA and other Congressional mandates, EPA has issued proposed regulations and guidance on the design of these systems, and on construction quality assurance, final cover, and response action plans for responding to landfill leaks.*
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> *This seminar publication outlines in detail the provisions of the minimum technology guidance and proposed regulations, and offers practical and detailed information on the construction of hazardous waste facilities that comply with these requirements. Chapter One presents a broad overview of the minimum technology guidance and regulations. Chapter Two describes the use of clay liners in hazardous waste landfills, including the selection and testing of materials for the clay component of double liner systems. Chapter Three discusses material and design considerations for flexible membrane liners, and the impact of the proposed regulations on these considerations. Chapter Four presents an overview of the three parts of a liquid management system, including the leachate collection and removal system; the secondary leak detection, collection, and removal system; and the surface water collection system. Chapter Five describes the elements of a closure system for a completed landfill, including flexible membrane caps, surface water collection and removal systems, gas control layers, biotic barriers, and vegetative top covers. Chapters Six and Seven discuss the construction, quality assurance, and control criteria for clay liners and flexible membrane liners, respectively. Chapter Eight discusses the chemical compatibility of geosynthetic and natural liner materials with waste leachates. Chapter Nine presents an overview of long-term considerations regarding hazardous waste landfills, surface impoundments, and waste piles, including flexible membrane and clay liner durability,*

potential problems in liquid management systems, and aesthetic concerns. Chapter Ten reviews proposed requirements for response action plans for leaks in hazardous waste landfills."

The US EPA (2003) released the third edition of its RCRA "Orientation Manual" that provides an overview discussion of various components of the regulations governing the management of solid wastes, including those classified as "hazardous waste" and municipal solid waste in US Subtitle C and D landfills.

RCRA requires that Subtitle C and D landfills be developed to, in theory, keep the buried wastes dry; if the wastes are kept dry it is argued, leachate cannot be formed, and thus groundwater and environmental quality are not threatened by the buried wastes. In theory, free liquids are prohibited, the final cover prevents entrance of moisture, and liquid that enters from precipitation during the active life is removed in the leachate collection and removal system. Lee and Jones-Lee (2015a) discussed the technical understanding of the issues of such "dry tomb" landfilling and why it is a seriously flawed technology.

To the end of achieving "dry-tomb" landfills, the US EPA required that hazardous waste landfills incorporate a double-composite liner with a leak detection layer between the two composite liners. One of the issues that remained of concern was the amount of leakage of leachate through the upper composite liner that would be considered to be "excessive" and trigger action be taken to prevent eventual leakage of that leachate through the lower composite liner. Peggs (2009) discussed the expected leakage of leachate through the upper composite liner and stated:

"*Sensible designers, regulators, and facility owners, have learned to accept some leakage and to incorporate an under-drain or leakage detection system (LDS) that will safely remove that leakage without further damage to the subgrade or the lining system. But what should that maximum allowable, or Action Leak Rate (ALR) be, above which the leak must be found and repaired? Zero is not, as they say, an option if for no other reason than water in a deep pond will diffuse through a geomembrane at a significant rate. USEPA terms this the "de minimis" leak flow rate which for a reference evaporation pond 70 acres in area and with an average depth of 30 ft is 28 gallons per acre per day (gpad), or a total of 840 gallons per day (gpd) for a 0.040 in. thick HDPE geomembrane. This is not insignificant! "*

"In 1992 after much research the USEPA promulgated a Final Rule for the ALRs through the primary liners of double lining systems in solid and liquid hazardous waste surface impoundments. They arrived at 100 gpad for solid waste with a maximum leachate head of 1 ft, and 1000 gpad for ponds. Since that time 20 gpad has typically been adopted by state regulators throughout the USA for municipal solid waste landfills. This seems to have worked quite well."

The US EPA (1992) reviewed this issue and issued the following regulations governing the acceptable upper composite liner:

"*SUMMARY: The Environmental Protection Agency (EPA) is today amending its current regulations under the Resource Conservation and Recovery Act (RCRA) concerning liner and leachate collection and removal systems for hazardous waste surface impoundments, landfills, and waste piles. EPA is also adding new regulations requiring owners and* *operators of hazardous waste surface impoundments, waste piles, and landfills to install and operate leak."*

"On November 8, 1984, Congress enacted the Hazardous and Solid Waste Amendments (HSWA) to the Resource Conservation and Recovery Act (RCRA), placing stringent new requirements on the land disposal of hazardous waste. Among other requirements, Congress amended section 3004 of RCRA and added section 3015 to impose specific design standards for land disposal units.

Section 3004(o)(1)(A) of RCRA, added by HSWA, requires each new landfill and surface impoundment, and each replacement and lateral expansion of a landfill and surface impoundment for which an application for a final permit determination is received after November 8, 1984, to install two or more liners (i.e., a double-liner system) and a leachate collection system above (for landfills) and between the liners. Section 3004(o)(5)(A) of RCRA requires EPA to promulgate regulations or issue technical guidance implementing the requirements of section 3004(o)(I A) by November 8, 1986. These HSWA requirements for double liner systems are intended to prevent the migration of hazardous constituents to ground water from land disposal units."

"III. Summary of Today's Rule
A. Summary of Rule
Today's rule modifies the existing double-liner and leachate collection and removal system requirements for new and replacement surface impoundments and landfills and for lateral expansions of these units, including those Units at interim status facilities. New surface impoundment and landfill units for which construction commences after January 29, 1992, and replacement units reused after and lateral expansions of existing units for which construction commences after July 29, 1992 must have a double liner consisting of a top liner designed to prevent the migration of hazardous constituents into the liner during the active life and post-closure period (e.g., a geomembrane) and a composite bottom liner consisting of a geomembrane underlain by at least 3 feet of compacted soil material having a hydraulic conductivity of no more than $1X10^{-7}$ *cm/sec."*

The US Department of Energy (DOE, 1992) issued an "Environmental Guidance Regulatory Bulletin" discussing the US EPA allowed liner leakage rates, which stated,

"*On January 29, 1992, EPA published (57 FR 3462) regulations establishing new and amended standards for hazardous waste land disposal units under the Resource Conservation and Recovery Act (RCRA). The rule, which finalizes regulations proposed on March 28, 1986 (51 FR 10706) and May 29, 1987 (52 FR 20218), takes an important step in implementing EPA's groundwater policy by setting standards intended to minimize the potential for migration of hazardous constituents from hazardous waste land disposal units to underlying groundwater. The amended standards, promulgated in response to Sect. 3004(o)(5)(A) of RCRA, concern liner and leachate collection and removal system requirements for new and replacement surface impoundments, landfills, and waste piles and for lateral expansions of these units ("affected units"). Owners and operators of existing units will also have to meet new standards centering on the required installation of an approved leak detection system as mandated by Sect. 3004(o)(4) of RCRA."*

"The revised standards require that affected units have a double liner and a leachate collection system to prevent hazardous constituents from migrating from the unit into groundwater or surface water. The top liner must be designed "to prevent the migration of hazardous constituents into such liner" during the unit's active life and postclosure period. The bottom liner is a composite. The upper component of the bottom liner must be designed and constructed of materials (e.g., a geomembrane) "to prevent the migration of hazardous constituents into this component during the active life and post-closure period." The lower component of the bottom liner must consist of at least 3 feet (91 cm) of compacted soil material having a hydraulic conductivity no greater than 1 x 10^{-7} cm/sec."

"The rule also requires owners and operators of regulated units to install and operate leak detection systems " capable of detecting, collecting, and removing leaks of hazardous constituents at the earliest practicable time through all areas of the top liner likely to be exposed to waste or leachate during the active life and post closure care period." EPA interprets "earliest practicable time" as the period between when a liquid passes through a breach in the top liner to the time a technology-based leak detection system can detect the liquid, assuming saturated, steady-state flow. Such a leak detection system is designated by EPA as the leachate collection and removal system drainage layer located immediately above the bottom composite liner. It will have to meet several design criteria as set forth in the rule."

Summary of Problems with Landfill Containment for Protection

Presented below is summary information on characteristics of components of Subtitle C and D landfill systems for containments and groundwater protection, and their expected performance over the period during which the wastes in the landfill will be threat to public health and groundwater quality. These components are discussed at greater length and detail by Lee and Jones-Lee (2015a). That comprehensive discussion, which includes more than 80 references to additional professional literature by experts in the field, is revised at about annual intervals to add new and updated information that becomes available.

Liners and Leachate Collection Systems

The US EPA requires that a Subtitle C landfill incorporate a dual-composite liner system beneath the wastes, with a leak detection layer – a leachate collection and removal system (LCRS) – between the two liners. Some states and other political jurisdictions also require double-composite liners for municipal solid waste (MSW) landfills, rather than US EPA minimum-design single-composite liners. The upper composite liner in a double-composite-lined landfill is intended to funnel leachate that develops during the active life of the landfill (and subsequently due to cover degradation or failure) to a sump where it can be removed by pumping. The lower composite liner is intended to provide protection against leakage of leachate that collects in the LCRS.

Each of the two composite liners consists of a 60-mil-thick high density polyethylene (HDPE) plastic sheet overlying and in intimate contact with a several-foot layer of compacted clay with a design permeability to water of $1x10^{-7}$ cm/sec. The combination of the two types of layers, when kept in intimate contact over the expanse of the liner, provides a more effective barrier to the passage of liquid than two such layers laid independently. Some landfill designers use a thin geosynthetic clay liner (GCL) as a substitute for a considerably thicker clay layer. While regulatory agencies allow such a substitution, there is considerable concern about the ability of a GCL to perform as intended over time to slow the rate of leachate penetration. Among other factors, they are subject to diffusion-controlled penetration and physical damage, which diminish their integrity over time in ways that deeper layers of compacted clay are not.

In the 1970-1980s Dr. Lee had US EPA and private research support to evaluate the expected performance of HDPE liners in landfills. While he concluded that while HDPE may be the best liner material for the cost, and some claim that they can be expected to perform satisfactorily for hundreds of years, there is considerable controversy about the long-term performance that can be realistically expected from HDPE sheets in retarding and retaining leachate in landfill environments. As discussed by Lee and Jones-Lee (2015a) HDPE sheets have some holes in them at the time of construction, and the placement of the wastes can cause additional holes and tears in the material that allow the passage of moisture during the active life. The HDPE layer is subject to degradation, including free radical degradation of the polymer chains in the HDPE membrane, which diminishes the integrity of the liner over time; some chemical solvents can pass directly through intact HDPE. Overall, HDPE-based composite liners can be effective as a base for collecting leachate and, in concert with a clay layer, for delaying groundwater pollution for several decades if they have been properly constructed and the wastes have been carefully placed in the landfill. However, neither they nor the ancillary systems in a Subtitle C landfill, can be presumed to be able to function as intended in perpetuity as would be needed to protect public health and environmental quality for as long as the buried wastes pose a threat.

Between the two composite liners is a porous layer in which leachate that has penetrated the upper composite liner is collected in a sump. Conceptually, this layer serves the purpose of identifying that moisture has entered the buried wastes and has generated leachate that has penetrated through the upper composite liner.

Aside from the pervasive problem of the unavoidable problem of deterioration of the engineered structures and their function over time, important to the long-term functionality of the landfill is the rate of leakage of the upper composite liner as measured by the rate and amount of leachate that accumulates in the leak detection layer between the two composite liners. A key determinant of what is considered to be "failure" of the landfill liner system that provokes regulation-stipulated corrective action to control this leakage is the rate and amount of leachate accumulation in the leak detection layer.

In the US EPA (1989) seminar on Subtitle C landfill design, Daniel discussed the factors influencing the rates of leakage of landfill liners, which include the number of holes in the HDPE layer, the characteristics of the underlying clay barrier, and the head (depth) of leachate that accumulates on the liner. These relationships are governed by Darcy's Law. That rate is also a function of the rate at which liquid enters the buried wastes from all sources, the rate of movement of the liquid/leachate through the buried wastes, the efficiency of the LCRS in collecting the leachate, and the integrity of the lower composite liner that serves as a base for the LCRS. The leachate head that develops on the upper liner affects the rate at which leachate will penetrate the liner. A critical factor affecting the head that develops on the upper plastic sheeting liner is the plugging of the leachate collection and removal system (LCRS) that is supposed to transport the leachate to the collection sump. Only a thin layer of leachate is allowed to be present on the top of the liner. The regulations prevent a leachate depth in the LCRS of greater than one foot. The plugging of the LCRS occurs when particulate fines from the waste buildup to form a dam on the flow path to the sump. For some types of wastes biological growths develop in LCRS that enable the buildup of a dam that impedes the transport of leachate to the sump. While some landfills are developed with systems to attempt to flush out any accumulation of "dams" in the LCRS the effectiveness of these approaches is in question over the period of time that the wastes in the landfill will be a threat.

The failure of the upper liner is monitored by leachate presence in the leak detection layer between the two composite liners. The rate and amount of leachate production that signals "failure" is established rather arbitrarily by regulations rather than based on significance for the protection of public health/welfare and environmental quality. Nevertheless, failure to expediently and reliably control the rate of leakage of the upper composite liner will eventually lead to leachate penetration of the lower composite liner and groundwater pollution.

In accord with US EPA Subtitle D municipal solid waste (MSW) landfills normally incorporate a single-composite rather than double-composite liner, although about 10 US states or parts thereof require double-composite liners for MSW landfills. As discussed in detail by Lee and Jones-Lee (2015a), a single-composite liner is ineffective for preventing groundwater pollution by landfill leachate or protecting groundwater from pollution by landfill leachate. The continued acceptance of that flawed technology is related to the politics of waste management; those in control of federal and state funding and regulatory requirements do not want to be responsible for increasing the cost of solid wastes management to the public, even if it is required to provide more reliable, long-term protection of public health and groundwater quality.

Leachate that escapes the confines of a landfill will migrate to groundwater. While groundwater monitoring is considered by regulation to be the final element of protection from landfill leachate pollution, as discussed in this report and in greater detail by Lee and Jones-Lee (2015a), conventionally used groundwater monitoring approaches incorporating wells around the perimeter of the landfill are largely ineffective in detecting landfill liner failure before there is offsite groundwater pollution.

Groundwater Pollution Monitoring

In practice, the Subtitle D and Subtitle C "dry tomb" landfilling approach is a flawed technology in large part, as discussed above, because the landfill liner systems will eventually fail to prevent the development of leachate, leachate penetration of the liners, and leachate pollution of groundwater in perpetuity, and the buried wastes do not become innocuous with the passage of time. Further, the approach does not incorporate a reliable fail-safe early-warning/monitoring system that ensures the detection of diminished integrity of the landfill before widespread groundwater pollution has occurred. As originally conceptualized, the incipient, or first, pollution of the groundwater under the landfill would be detected by the groundwater monitoring wells, and would thereby enable corrective action to be taken in the landfill structure, and the polluted groundwater beneath the landfill remediated before off-site groundwater became polluted. While that conceptual approach still by design allowed the pollution of groundwater, which cannot be entirely restored by treatment, it was intended to prevent off-site pollution of groundwater. However, the groundwater monitoring systems that are in fact allowed, and indeed prescribed, for landfills are largely cosmetic and have a very low probability of detecting initial groundwater pollution before widespread offsite pollution has occurred.

As discussed by Lee and Jones-Lee (2015a) groundwater monitoring programs for landfills typically employ vertical monitoring wells spaced hundreds of feet apart along the down-groundwater-gradient perimeter of the landfill. Because of the way in which the conventionally used monitoring wells are constructed and sampled, they only collect groundwater within about a one foot radius of the well at the specific depth or depths at which they are screened. Such a system presumes that incipient leakage from lined landfills appears as massive clouds of pollution with a wide and deep front down-groundwater gradient. However, incipient leakage from lined landfills will occur from tears or small areas of deterioration and will pass as narrow, finger-like plumes of leachate in the aquifer system. The likelihood of such a finger-plume of leachate being intercepted by a monitoring well is remote; the narrow plumes of leachate that are formed from the initial failure of the liner will more likely pass the groundwater monitoring well array without being detected by the monitoring wells. The first evidence of a landfill's failure to contain the leachate will likely be when pollution is found in an offsite private or production well.

The siting of landfills above fractured rock/clay or low-permeability aquifers is of special concern since the flow paths of leachate-polluted groundwater would be poorly anticipated and defined. In such circumstances, leachate-polluted groundwater could well take a path or paths through fractures and cracks, and be transported to groundwaters not connected to those sampled by monitoring wells located at the point of compliance.

As discussed by Lee and Jones-Lee (2015) while this fundamental deficiency in groundwater monitoring for initial landfill liner leakage has been known by professionals and regulatory agencies for several decades, neither the US EPA nor many states have taken action to correct this problem. It is for this reason that we recommend that all dry-tomb type landfills incorporate double-composite liners with a leak detection layer between the two composite liners. They also need to provide that when excessive leachate in found in the leak detection layer, action must be immediately taken to prevent additional water from entering the landfill through the landfill cover and other areas. In the longer term, the upper composite liner would need to be repaired, which would necessitate waste exhumation.

Some landfill consultants and governmental agency staff attempt to discredit and dismiss the finding that all of today's landfill liners will eventually leak; they claim that there have been no failures of landfill liner systems since no groundwater pollution has been detected by the monitoring systems of so-called modern single-composite-lined landfills. However as discussed by Lee and Jones-Lee (2015a), the lack of evidence of leachate pollution in monitoring wells is not a testament to the ability of lined landfills to protect groundwater quality for as long as the wastes remain a threat. First, this type of liner has only been required in MSW landfills since 1992. Alone, the conventional clay layer portion of a composite liner, 2 ft of clay compacted to a permeability of 1 $\times 10^{-7}$ cm/sec, would not be expected to be penetrated by leachate under as much as 1 ft of head, for about 25 years. The addition of the HDPE layer to create a composite liner would be expected to further delay liner breach. This means that leachate would be expected to have already penetrated even the early composite-lined landfills. Second, as noted above and discussed by Lee and Jones-Lee (2015a), groundwater monitoring systems allowed today for lined landfills would not be expected to detect the early failure of the landfill liner system; the eventual failure of the landfill liner system would most likely be detected in offsite production wells after widespread groundwater pollution has occurred.

Since the landfill liner system is buried under the deposited wastes, its flaws and areas of deterioration that allow passage of leachate through it cannot be located and corrected by liner repair. Once a landfill liner system is breached the only approach available to stop further groundwater pollution is to try to locate and eliminate the breaches in the landfill cover that have allowed entrance of moisture into the wastes.

Landfill Covers

The typical "dry-tomb" landfill cover allowed today consists of a vegetated topsoil layer underlain by a somewhat porous drainage layer on top of a low permeability layer (usually a plastic sheeting layer of low-density polyethylene or compacted clay) that is sloped to allow water that enters the top of the landfill cover to drain off the landfill without entering the wastes. The base of the low-permeability layer is formed by a soil layer over the top of the wastes. Since the functionality of a "dry-tomb" landfill is dependent on keeping the waste dry, the integrity of the cover to keep moisture out of the waste must be maintained for as long as the wastes can generate leachate. While the US EPA regulations allow for the penetration of some water through the cover and thus entrance of liquid into the buried wastes, in principle and with proper design, construction, and meticulous attention to inspection and repair, such a cover system should be capable of at least initially preventing the entrance of water into the wastes.

There are examples of closed landfills with this type of cover that stop producing leachate as the wastes in the landfill dry out; but over time, as the properties of the low-permeability layer in the cover deteriorate and moisture is allowed into the landfilled wastes, leachate is again generated that has the potential to cause groundwater pollution. As discussed by Lee and Jones-Lee (2015a), studies of landfill covers composed of clay/soil rapidly develop cracks that can allow water to readily penetrate the clay cover.

The maintaining the integrity of the cover is dependent on the rigorous inspection and repair of areas of compromise or deterioration in the cover, in perpetuity. However, the key element of the moisture barrier in the cover, the plastic sheeting, is buried beneath the porous layer and vegetated topsoil layer and hence cannot be subject to rigorous visual inspection for flaws, areas of deterioration, etc. that would reduce the cover's efficacy. The typical landfill permit allows the landfill developer to "maintain" the landfill cover by visual inspection of the cover and filling in cracks, areas of depression associated with waste compression/compaction, animal activity, etc. The permits do not require that the landfill developer make postclosure funds available to monitor and maintain the low-permeability layer in the cover.

Several years ago, two companies developed "leak-detectable" landfill covers that permitted detection of deterioration of the low-permeability layer in the cover that would allow water to penetrate the cover. While keeping the wastes dry is key to the "dry-tomb" approach and placement of reliable leak-detectable covers would significantly improve the ability of "dry-tomb" landfills to protect groundwater quality, federal and state regulatory agencies did not incorporate that technology into landfilling requirements because of the increased cost. The companies that developed the leak-detectable covers have stopped making these type of covers available. There are alternative landfill cover designs that can, if properly constructed, can at least initially keep the wastes in the landfill dry. However all have the same long-term problem of deteriorating and allowing water to enter the wastes through the cover.

Faced with the need to monitor and maintain landfill covers and monitoring systems "for as long as the wastes in the landfill will be a threat," some landfill developers claim that detection of no leachate in the LCRS is evidence that the landfill is no longer a threat. However as discussed by Lee and Jones-Lee (2015a), the absence of leachate in a LCRS is not a reliable indicator that landfill monitoring and maintenance can be terminated. The cessation of production of leachate that initially develops in the LCRS results from the initial functionality of the cover to prevent/minimize entrance of moisture, and the drying of the buried wastes. It is a temporary cessation; leachate generation will resume as the containment systems and cover deteriorate and maintenance becomes insufficiently effective. The wastes in a landfill will no longer be a threat when, and only when, they cannot leach hazardous or otherwise deleterious chemicals. To make that determination, it would be necessary to appropriately sample the wastes in the landfill by coring the wastes and subjecting those waste samples to water leaching. Adequate and reliably representative sampling of the contents of a landfill will be a challenge, but will be necessary before proper monitoring and maintenance can be terminated.

Funding of Postclosure Monitoring & Maintenance

As reviewed in this report, the requirements and provisions for funding of postclosure monitoring and maintenance for as long as the wastes in the landfill are a threat when contacted by water are by far the most significant deficiencies in the US EPA Subtitle C and D landfill regulations. It has been known from the start that "dry-tomb" landfills provide little more than stop-gap provisions, and that eventually the real threats of the buried wastes would have to be addressed. While the regulations state that the US EPA Regional Administrator can extend the required period of postclosure care, the US EPA has only recently started to review this issue as the end of the 30-yr required period approaches for the early Subtitle C landfills. There is no assurance that this issue will be effectively addressed because it would require substantial increases in the cost of waste management for waste generators, landfill owners, and the public; governmental agencies are loathe to make such politically unpopular decisions especially since landfills tend to be sited in sparsely populated areas where landowners have less political voice. As discussed elsewhere in this report, the proposed Canadian hazardous waste landfill regulations recommend that the period of postclosure funding continue for as long as the waste are a threat. There is no information on how effectively those requirements are being implemented by the Canadian Provinces.

Some US states have taken action to address this problem by eliminating the prescription of a 30-yr minimum postclosure care funding period in favor of more protection-based language. For example, the California Integrated Waste Management Board (now called CalRecycle) that regulates waste disposal explicitly required that postclosure funding be required for as long as the waste are a threat, which is likely to be hundreds of years or more. It remains to seen how well this approach is implemented given the poor implementation of other such open-ended requirements in the state. The California State Water Resources Control Board (SWRCB), which governs water quality in the state, has required in its Chapter 15 regulations that postclosure care be conducted so as to prevent groundwater use-impairment. Despite that SWRCB groundwater protection requirement, the SWRCB has approved landfills that do not incorporate postclosure funding provisions that ensure that level of protection.

Private landfill companies such as Waste Management, Inc. have vigorously opposed the extension of the 30-yr postclosure period since it could cause significant additional and indefinitely long postclosure funding liabilities. Lee and Jones-Lee (2015a) discuss the technical reliability of arguments that Waste Management and others have put forth in opposition to extending the postclosure care period.

We have been involved in the evaluation of about 80 MSW, hazardous waste, and Superfund site landfills. For those landfills for information was available on the extent of a groundwater pollution plume, we found that (with the exception of one that was sited over a fractured rock aquifer) the pollution plume was found to extend as far as about one mile from the landfill. In sand and silt aquifers, pollutants and salts in the leachate were diluted by diffusion and by input of precipitation on the areas above the plume to reduce the concentrations of measured pollutants to levels below those that would be expected to have adverse impacts. However, it has been found that once an aquifer is polluted by landfill leachate it is not possible to restore it to usable conditions. This raises the issue of whether a "zone of pollution" down-groundwater-gradient from landfills should be acknowledged and provided for as part of the landfill. Under the Ontario Canadian province administration regulations of this type were adopted, but subsequent administrations reversed them. The current US Subtitle C and D regulations would not allow the adoption of this approach; however, the US EPA landfill regulations do, *de facto*, establish zones of pollution since it is not possible to remediate a landfill-leachate-polluted aquifer to safe, usable conditions. The advantage of acknowledging that this is what occurs would enable the Agency to specify that that zone be within the confines of landfill-owner-owned property so as to better protect offsite groundwater. Adoption of site-specific, on-site zones of allowed pollution could acknowledge and reduce the real long-term costs of landfilling and remediation of polluted groundwaters.

Pretreatment of Hazardous Wastes

An approach that has been suggested to reduce or eliminate the liability of hazardous waste generators for adverse impacts of their wastes in landfills is to pretreat the hazardous wastes prior to burial of the treated residues. Aside from costs for various pretreatment alternatives, the efficacy of this approach for reducing or eliminating long-term liability depends on the leachability/reactivity/impact character of the treated residues; the type of landfill into which the treated residues are placed; the ability to demonstrate that the treated residues do not impact the leachability of other wastes in the landfill, and the leachability and potential impacts are not affected by the other wastes; the ability to obtain binding assurance of release of future liability.

Pretreating a hazardous waste so that it meets the criteria for classification as a "non-hazardous" waste is unlikely to relieve a waste generator of potential liability. While achieving that degree of pretreatment could result in residues that could be placed in "non-hazardous waste" landfills, as discussed in this report such treatment does not mean that the waste residue is “safe” or that it cannot leach chemicals that could be hazardous or otherwise deleterious in groundwater that it contaminates. Caution should be exercised in placing pretreated hazardous wastes residues in municipal solid waste (MSW) landfills since, as discussed by Lee and Jones-Lee (2015a), today’s MSW landfills will all eventually lead to groundwater pollution. Companies that pretreat hazardous wastes to enable the treated residues to be placed in a non-hazardous waste landfills could still find they are held liable for paying for or contributing to the cost of the remediation of MSW landfill leachate-polluted groundwaters as a contributor of so-called non-hazardous waste to the MSW landfill.

An issue that should be understood is that RCRA and especially Superfund regulations focus on controlling what are administratively defined as “hazardous” concentrations of administratively designated “hazardous” chemicals in wastes and pollution plumes; those regulations can ignore salts and other chemicals that, while not classified as “toxic” by regulatory protocols, are in fact deleterious to beneficial uses of groundwater. At some of the sites at which we have worked the US EPA regulations required removal of hazardous chemical such as volatile organics as a condition of remediation without requiring control of other chemicals in the waste plume that were present in concentrations sufficient to prevent the use of the water for domestic and animal water supplies. This approach is changing in some areas such as the Central Valley of California where the Central Valley Regional Water Quality Control Board (RWCQB) has mounted an effort to control excessive salts in the groundwater. Thus, what is designated as “pollution” in groundwater continues to evolve; pretreatment to prevent “pollution” of a waste by today’s criteria may well be inadequate as the concept of what constitutes pollution broadens.

It may be the best option to place the pretreated hazardous wastes in industrial landfill that does not contain other wastes that can produce leachate that impairs groundwater use. The issue of obtaining assurance of release from liability for pollution in perpetuity remains, however.

The greatest likelihood of elimination of future liability for pollution would be achieved if a waste were pretreated in a way such that the treated residues buried in a landfill could be demonstrated to be incapable of leaching hazardous or otherwise deleterious chemicals or of interacting with other buried materials; any leachate that may be generated from the landfill would be devoid of chemicals from their wastes.

At this time, cost advantage of pretreating hazardous waste beyond that which is required must be compared with the unknown costs and unknown liabilities they the company may face decades in the future, because the real issues of liability and cost for post-postclosure maintenance and remediation are ill-defined and still evolving. From our experience in working with companies on environmental quality issues, until those uncertainties are resolved decisions to practice pretreatment not required of all similar companies in the hope of eliminating long-term liability for pollution will be driven by demonstration of near-term profitability.

Waste Exhumation

The exhumation and removal of buried waste has been suggested as an approach for addressing the pollution of groundwater by a landfill; we have followed this issue at a number sites including the BFI CECOS Superfund site. The exhumation and treatment of the buried wastes to render them unable to leach leachate is the ultimate and total solution to further groundwater pollution, however the costs and potential hazards associated with handling exhumed wastes have rendered this approach unfeasible. While it is technically possible to conduct landfill waste exhumation under a dome to collect and treat all air emitted at such a site, the costs are very high and there will be considerable public opposition to adopting this approach.

Waste exhumation (landfill mining) has been practiced at old MSW landfills in Florida and New York, primarily for the purpose of recovering landfill space in areas deficient in landfill space. These landfills did not contain significant amounts of what were classified as "hazardous" wastes. In such operations a front-end loader picks up the wastes and deposits them on a mining screen to sort rocks/solid into various particle sizes. The fine organic fraction is used as compost. Based on our experience waste exhumation is not likely to be used to control a polluting hazardous waste landfill. Several discussions of these issues can be found in an Internet search of landfill mining.

Summary

Overall, the fundamental problem with a "dry tomb" landfill for hazardous waste or MSW disposal is that the wastes remain hazardous as they sit in the tomb; they do not detoxify or become innocuous over time. The engineered systems for containment and moisture elimination deteriorate over time; even under the most vigilant eternal inspection of the cover, many of the systems relied upon for protection of public health/welfare and environmental quality are not amenable to inspection or repair without waste exhumation and rehandling. Leakage of conventional "dry-tomb" landfills will not likely be detected before widespread, offsite groundwater pollution has occurred. Once groundwater has been polluted with landfill leachate, it cannot be fully recovered to serve as a reliable source for people and animals. It is for these reasons that there will be need for monitoring, maintenance, and remediation of pollution, and entities with money to fund those activities for an indefinitely long period after closure.

Postclosure Management Issues

A hazardous waste or MSW landfill is considered "active" during the period in which it accepts wastes; a "closed" landfill is no longer accepting wastes and has had a final cover placed over the landfilled material. As described above, after closure the landfill is an elaborate tomb for the wastes; the postclosure period is defined by regulatory agencies and typically extends for 30 years following "closure" during which time the landfill owner is responsible for all required monitoring, maintenance, and remediation required for the landfill. Concerns about the reliability of landfill liability insurance instruments for providing adequate funds to address foreseeable problems during the postclosure period have been raised by many including Lee and Jones-Lee (2015a). When such insurance proves inadequate, it is likely that liability for the landfill and remediation of pollution that occurs will fall to those depositing wastes in the landfill.

After the postclosure care period, the responsibility for the landfill and pollution that it causes falls to those who contributed wastes in a Superfund-type plan. Neither the hazardous waste landfill structure nor the "closure" of a hazardous waste landfill renders the buried wastes innocuous, and its engineered systems will eventually and inevitably fail to keep moisture out, to prevent the generation of leachate, and the escape of that leachate from the landfill. At best, a hazardous waste landfill delays the inevitable pollution of area groundwater. Key to delaying that pollution, and hence critical to the long-term liability for the pollution, is the approaches followed for postclosure monitoring, maintenance, and remediation of closed hazardous waste landfills.

One of the most significant errors made in the development and subsequent review of the RCRA hazardous waste landfilling regulations is that congress and the US EPA accepted the fallacy that a 30-year postclosure care period is sufficient and appropriate for protecting public health/welfare and environmental quality from adverse impact by a landfill. It has been recognized for more than three decades that a 30-year postclosure care period was woefully inadequate; 30 years is an infinitesimal portion of the time during which wastes buried in a dry tomb landfill will remain able to generate leachate and thus pose a threat to public health/welfare and environmental quality. These issues have been discussed in the technical literature and have been reviewed by Lee and Jones-Lee (1994, 2015a,b) and Jones-Lee and Lee (2014).

The cover letter transmitting the US General Accounting Office (GAO, 1990) report to Congress stated:

> "*The Superfund Amendments and Reauthorization Act of 1986 directed that we study options for a program to manage liabilities associated with hazardous waste disposal facilities after closure which complements the policies set forth in the Hazardous and Solid Waste Amendments of 1984 and assures the protection of human health and the environment. This report presents the results of our review by discussing*
> • *the likelihood that permitted hazardous waste disposal facilities will leak after closure,*
> • *the magnitude of liabilities that may be incurred,*
> • *the adequacy of current postclosure funding assurance requirements, and*
> • *the feasibility of other mechanisms that could provide greater postclosure funding assurances."*

The Executive Summary of that report stated:

> "*Although past land disposal of hazardous waste has resulted in major environmental contamination and serious health effects, land disposal of these wastes continues. About 13 million metric tons of hazardous waste is land disposed each year. Better disposal practices-including treatment of wastes to reduce toxicity-and containment methods are now required at operating hazardous waste disposal facilities; nevertheless, the possibility exists that hazardous substances will eventually leak from these facilities and costly cleanup actions would be required to protect the public health and environment.*"

> "*Concerned about the funding of long-term liabilities-.costs, damages, or other expenses-that may be associated with permitted hazardous waste facilities once they have closed, the Congress required GAO to conduct a study of options for managing postclosure liabilities."*

> *"The Resource Conservation and Recovery Act (RCRA) regulates the management and disposal of hazardous waste. As implemented by the Environmental Protection Agency (EPA), the act requires owners/operators of disposal facilities to obtain an operating permit in order to continue waste disposal operations. To obtain a permit, facilities must meet*

certain standards intended to prevent and/or detect leakage to the environment. About 200 land disposal facilities have, or are expected to obtain, operating permits.

After a disposal facility ceases operation, EPA requires that closure activities be performed, including the installation of covers over the disposed waste. EPA further requires the owner/operator to perform maintenance and monitoring activities at the facility for a 30-year postclosure period. Owners/operators must provide financial assurance that funds will be available to conduct mandatory postclosure activities.

Certain liabilities, such as costs for cleanup and third-party damages, may result during postclosure if facilities leak and contaminate the groundwater. A postclosure liability trust fund to manage these costs was established under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA). However, concerned that, as structured, the postclosure fund may not provide sufficient resources, the Congress suspended the transfer of any liability to the fund."

"The long-term effectiveness of current land disposal practices in controlling the migration of hazardous waste is not known, but EPA and others believe it is likely that some of the permitted hazardous waste disposal facilities will release hazardous substances into the environment at some period after they close. However, the timing and magnitude of any resulting postclosure liabilities-such as the costs of corrective action and off-site damages-are uncertain.

Although EPA is aware of the potential for releases, it has not developed a strategy for addressing long-term postclosure concerns. EPA has given this issue a low priority in the RCRA program because of limited resources and the lack of historical data on the magnitude and extent of the potential problem."

EPA does require funding assurances for mandatory postclosure care and known corrective action costs, but it does not require funding assurances for potential but unknown postclosure liabilities. Although there are several options for funding postclosure liabilities, few of these are currently viable in large part because the risk associated with closed hazardous waste facilities is difficult to quantify. As data on long-term risks become available, the Congress will be in a better position to decide on the need for additional postclosure funding mechanisms."

"EPA requires facilities obtaining operating permits to design and construct disposal units with waste migration prevention measures, such as liners and covers, intended to mitigate releases into the environment. Little experience-based data exist, however, on the long-term performance of these technology requirements in preventing waste migration. Although at least one company producing liner and cover material estimates that the material will last hundreds of years, EPA and others believe that permanent containment of wastes is not possible and that leakage will occur at some time after the 30-year postclosure period. (See ch. 2.)"

"EPA officials have identified activities, such as extended postclosure care and long-term research that may be required to identify and reduce the potential for leakage after facilities close. However, EPA has not developed a strategy to comprehensively obtain data on the effectiveness of current disposal requirements and examine long-term postclosure issues because (1) experience with current disposal requirements is limited and (2) available resources have been needed in other RCRA program efforts that address more immediate environmental concerns. Such a strategy needs to be developed and implemented in a timely manner in order to assure that actions needed to reduce postclosure concerns are promptly taken."

The GAO (1990) discussion of these issues addressed various aspects of the need for addressing the liability issues for hazardous waste landfills after a 30-year postclosure period and suggests alternatives for addressing this issue. While that GAO discussion of these issues was developed in 1990, it was not until 2015 that the US EPA began to address these issues when it released a request for comments (US EPA, 2015) on extending the 30-year postclosure period. That memorandum stated:

"*The purpose of this memorandum is to provide guidance to assist regulators in evaluating the length of the post-closure care period for hazardous waste disposal facilities subject to Subtitle C of the Resource Conservation and Recovery Act (RCRA), and in determining whether it should be adjusted. This guidance also provides information to assist facility owners and operators in preparing documentation to support a decision to adjust the post-closure care period.*"

In response to that request, we provided comments (Lee and Jones-Lee, 2015b) on technical justification for the US EPA guidelines to extend the required postclosure care period beyond 30 years and discussion of key issues that need to be considered for that post-postclosure period.

It is clear that until adequate measures are adopted to reliably control releases from hazardous waste landfills *ad infinitum* – for as long as the wastes have the potential to generate leachate – those who dispose of wastes and waste residues in such landfills need to consider the potential long-term liabilities that they could face in funding postclosure care for as long as wastes in the landfill will be a threat. In an effort to eliminate long-term liability exposure, some waste generators are exploring or attempting treatment of their wastes, prior to disposal, in such a way that they would permanently be rendered unable to leach components that could adversely affect public health/welfare or environmental quality if exposed to liquid or other buried wastes. The actual reduction in their liability for post-postclosure care and remediation costs for the landfill receiving those waste residues, however, is not yet defined, and may well be decided by the courts in the future when problems arise.

In 2015, the American Bar Association released its nearly 500-page reference, "The RCRA Practice Manual 3rd Edition" (Garrett, 2015), in which attorneys who are active in the application of RCRA requirements discussed various aspects of hazardous waste management from a legal perspective. Chapter 9 of that book, devoted to Closure, Postclosure and Financial Responsibility, contains a section entitled, "Liability Requirements, Implications, Financial Assurance and Conclusions." That Conclusions states:

"*Conclusion*

The closure and postclosure requirements, though reasonably objective and straightforward at first glance, are often more arduous than they appear. It often takes a considerable amount of time to complete what otherwise might appear to be a fairly simple closure. In addition, postclosure requirements can be difficult to negotiate and may take considerably longer to complete than originally planned. Owners and operators should be aware that closure and, if required, postclosure care can be difficult and time-consuming processes. EPA's new regulation providing for the use of enforceable documents to meet closure and postclosure requirements can offer a reasonable alternative, particularly for facilities that already face corrective action or CERCLA remediation obligations.

The financial assurance requirements, largely unchanged over the past several years, offer very detailed requirements that, in nearly all cases, must be carefully observed. The potentially staggering costs of corrective action, coupled with drops in the business and economic cycles for various companies, have placed some pressure on the ability to make the required demonstration. Perhaps the increased availability of insurance for demonstrating financial assurance can provide some relief."

The Hoover Institution, an American public policy think tank and research institution located at Stanford University in CA, is often involved in conducting detailed reviews of major issues of public policy in the US; its reviews are recognized for their quality and technically reliability. Excerpts from the Hoover Institution (1999) research analysis report entitled, "Reforming Hazardous Waste Policy," follow:

"*Public policies for hazardous waste are an important part of environmental regulation in the United States. Complex regulations address hazardous wastes under the federal Resource Conservation and Recovery Act (RCRA).*"

"*Hazardous waste regulation, however, has not received as much critical attention as other major environmental policies. This lack of attention does not indicate success. Indeed, there are serious problems with the current policy. The regulations do not prioritize risks and thus fail to direct resources toward the worst environmental contamination. The most important example of this problem is a rule that severely restricts land disposal of all wastes, regardless of the costs and benefits. Such lack of prioritization is unfortunately common in U.S. environmental policy. The problem is particularly severe for hazardous waste regulation because of the diversity of the substances and waste management methods regulated."*

"In addition to their failure to prioritize risks, the current hazardous waste regulations also create strong incentives for illegally disposing of hazardous waste. Illegal disposal can damage the environment much more severely than legal waste management, so policies may even be counterproductive."

"*Although some small changes would improve the policy, fundamental reforms are necessary to address these problems fully. Such fundamental reforms include a switch to economic incentive policies. In particular, taxes on environmental releases for waste management facilities provide the most robust way to make the hazardous waste policies responsive to the differential risks from different types of wastes and methods of waste management. Better* *still, a modified deposit/refund policy could implement the same desirable incentives, without the enforcement problems that plague taxes as well as current regulations*."

"*This essay begins with an overview of current hazardous waste regulations and then documents their problems. After this discussion, I propose policy reforms, beginning with a simple modification of current policies and moving on to more radical changes. The essay focuses on policies that address the current management of hazardous wastes by industrial and commercial generators.*"

"Current Policies for Hazardous Waste
The Resource Conservation and Recovery Act regulates currently generation and management of hazardous wastes. When Congress initially passed RCRA in 1976, it gave the Environmental Protection Agency great flexibility in designing a program for hazardous waste regulation. The EPA struggled with the task. It did not issue the first set of regulations until 1980 and had not issued many permits to facilities when Congress significantly amended RCRA in 1984."

Both the EPA's speed and approach dissatisfied Congress, which decided to take matters into its own hands. In the 1984 amendments, Congress specified extraordinarily detailed regulatory requirements and fixed timetables for the EPA to issue regulations. The changes greatly increased the stringency of the regulations but maintained much of the earlier regulatory framework."

"Standards for Treatment and Disposal Facilities
Wastes classified as hazardous are subject to two important types of regulations. First, the regulations set standards for facilities that manage hazardous wastes. Standards for these treatment, storage, and disposal facilities began with the interim regulations issued in 1980 and were replaced by final regulations in 1982. Although the requirements have changed over time, they continue to have the same basic structure.

For most treatment facilities, the regulations set standards for removing contaminants from the waste and for emissions. For example, incinerators--facilities that burn waste--must destroy 99.99 percent of the principal organic constituents (and a larger percentage of dioxin-bearing wastes). They must also achieve certain air emissions standards, which the 1990 Clean Air Act Amendments have strengthened. Finally, incinerators must manage their ash as a hazardous waste."

"*In addition, all treatment, storage, and disposal facilities face financial responsibility requirements. They must either carry insurance against sudden and accidental pollution incidents or provide assurances that they have adequate assets to cover such incidents. Disposal facilities must also have liability insurance for gradual releases, as well as sudden and accidental releases, and guarantee that they can finance care of the facility after it closes (such care may include monitoring the groundwater for contamination and maintaining structures that contain the waste)."*

"*Land Disposal Restrictions*

> *"The EPA had only begun to implement the first standards for treatment, storage, and disposal facilities when Congress decided to restrict waste management more severely. In the late 1970s, widespread concern developed about the health effects of abandoned hazardous waste sites. This concern, which also prompted the Superfund program, led Congress to tighten RCRA's regulation of land disposal. Trying to prevent a repeat of the past, it ordered the EPA to eliminate nearly all land disposal of untreated wastes.*
>
> *The land disposal restrictions prohibit any land disposal--including landfilling, land treatment (spreading waste on land), surface impoundment (containing liquid waste in lagoons), and underground injection--unless facilities first treat the wastes. If possible, treatment must destroy hazardous constituents, for example, by incinerating them. When destruction of the hazardous constituents is not possible, the treatment must reduce the mobility of hazardous substances*."
>
> "*Even with the RCRA standards for landfills in place by 1987, land disposal appears much less expensive than many alternative management methods. By precluding this option, the land disposal restrictions dramatically increased waste management costs for many facilities*."

The Hoover (1999) report also discussed "Problems with Hazardous Waste Policies," "Failure to Prioritize Risks," and "Incentives for Illegal Disposal."

Part II of Hoover (1999) addresses "*Policy Reforms"* and stated:

> *"Policymakers have shown little interest in modifying the RCRA program for hazardous waste management. Although Congress has repeatedly attempted major reforms of Superfund, RCRA's companion program, RCRA itself has no drawn no attention. As the discussion above suggests, however, RCRA is broken in significant ways. This section suggests ways to fix it, from simple changes to fundamental restructuring*."

Other sections of the discussion made suggestions for RCRA reform unrelated to issues of concern in our report.

In 2006, the Canadian Council of Ministers of the Environment, *"the major intergovernmental forum in Canada for discussion and joint action on environmental issues of national, international and global concern,"* released its updated "National Guidelines for Hazardous Waste Landfills" (CCME, 2006); excerpts are presented below.
The abstract described the document as follows:

> "*This guideline document has been commissioned by the Canadian Council of the Ministers of the Environment to establish current guidelines for engineered hazardous wastes landfill facilities. The guidelines are intended to provide a reference on the basic design, operating and performance requirements for use by the various federal, provincial and territorial regulatory agencies, and designers, owners and operators of engineered hazardous waste landfill facilities in Canada*."

Page iv of the Executive Summary of that report summarizes challenges in providing long-term protection from landfilled hazardous wastes for as long as the wastes are a threat (the *"contaminating lifespan"*):

> "*The contaminating lifespan of some hazardous wastes pose significant challenges to landfill design and operation. Contemporary landfill designs are thought to need effective lifespans approaching 1,000 years, which is an estimated contaminating lifespan for persistent hazardous wastes. Estimated contaminating lifespan for a specific hazardous waste landfill will be dependent on the hazardous wastes the facility is designed for. Such longevity is difficult to achieve in landfill designs, but this is nonetheless an important factor in the design of an engineered hazardous waste landfill facility as an integrated hazardous waste management system."*

Executive Summary page v:

> "*In terms of the engineered components, the limited service lives of such components are an important consideration in the facility design. Engineered components need to be used in combination with natural protection of the site setting to contain or control the escape of contaminants for the contaminating lifespan of all wastes*."

Page 1: *Introduction*

> *1.1 Scope*
>
> *"These Guidelines are for the use of regulatory agencies and of hazardous waste management system designers, owners and operators. The topics considered include:*
>
> - *wastes characteristics affecting landfill design,*
> - *site selection,*
> - *design and construction,*
> - *operations and performance monitoring,*
> - *closure and post-closure care,*
> - *contingency and mitigation planning, and*
> - *financial assurances and record keeping.*

Pages 33-34: *Section 7 – Closure and Post-closure*

> "*7.3 Post-Closure Post closure plans deal with period from the closing of the last active area of the facility until the point when the facility no longer poses any significant threats to the environment or human health*."
>
> "*Performance monitoring will continue for the contaminating lifespan of the engineered hazardous waste landfill facility or until the jurisdiction of authority is satisfied the facility no long poses any concern to the environment and human health*."
>
> "*The post-closure care plan should provide a description of operational activities that will be conducted after final closure of the site (including their frequencies). As a minimum, these activities should include*
>
> - *maintaining the function and integrity of the final cover,*
> - *maintaining and operating the leachate and gas collection systems, along with any treatment systems still installed,*
> - *maintaining the required site monitoring,*

- *protecting and maintaining survey benchmarks,*
- *controlling access to the site consistent with its approved post-closure use, and*
- *long-term contingency plan*."

Page 35: *Section 8 – Financial Assurance*

> "*The owner of an engineered hazardous waste landfill facility should provide financial assurance for the lifetime needs of the facility, including construction, operation, maintenance, replacement, closure and postclosure care, monitoring and reporting, and implementation of contingency measures*."

These Canadian hazardous waste landfill guidelines are considerably more comprehensive and protective than the US EPA regulations covering the development of hazardous waste landfills in their requirements and responsibilities for postclosure monitoring, maintenance, and remediation for as long as the wastes in the landfill will be a threat. Recommendations made in those guidelines follow the same approach that we have recommended for developing municipal and hazardous wastes landfills (see Lee and Jones-Lee, 2013, 2015a and other papers/reports on our website at http://www.gfredlee.com/Landfill_Impacts.html).

As discussed in the literature reviewed above, there is considerable uncertainty about the long-term liability faced by generators of hazardous waste who deposit their wastes or waste residues in US EPA Subtitle C landfills or their equivalent. However, there is no doubt that ultimately, as the liner and other components of the landfill containment system fail and the groundwater becomes polluted with leachate that has escaped, those whose wastes were deposited in the landfill will be held liable to help pay for attempts to remediate the polluted groundwater and pay for alternative water supplies for those whose wells are no longer reliable water supplies.

Evaluation and Remediation/Management of
Impacts of Hazardous Chemicals

The significance of inadequate containment of landfill leachate is compounded by the fact that once groundwater has been polluted with landfill leachate, it cannot be fully recovered to serve as a reliable source for people and animals. The classification of a waste or material as not "hazardous" does not mean that the material cannot cause significant water quality problems. Of the thousands of chemicals in use today and end up in hazardous and non-hazardous waste landfills, only a comparative few are considered in that classification. Further, the area and implications of unrecognized pollutants in waste leachate has not yet been addressed. Finally, even if a landfill leachate contained no "hazardous" chemicals, it still would contain chemicals that, in a water supply, would render it unsuitable for domestic, animal, and some other uses.

While leachate-polluted groundwater is "remediated" by pumping the groundwater, purging of the groundwater will not render the aquifer reliable for domestic and certain other uses; after purging there will continue to be slow leaching of substances adsorbed in the aquifer. Pollution by landfill leachate fundamentally condemns the affected aquifer area.

Drs. Lee and Jones-Lee have developed several papers and reports that discuss important issues for investigating and remediating areas that contain hazardous or otherwise deleterious chemicals. Information is provided on evaluating the adequacy of site investigation and remediation relative to the long-term threats that hazardous and otherwise deleterious chemicals may represent to public health, groundwater resources, and the environment. A list of recent publications and further information on their activities on this topic are available.

Summary of Background, Experience & Activities
G. Fred Lee and Anne Jones-Lee

Background
G. Fred Lee & Associates is a specialty environmental quality consulting firm of which Drs. G. Fred Lee and Anne Jones-Lee are the principals. Through this firm they assist clients in the evaluation and management of impacts of chemical contaminants on water quality, aquatic life, and public health. This work includes problems associated with water supply water quality, water and wastewater treatment, control of water pollution in fresh and marine waters and groundwaters, and solid and hazardous waste impact evaluation and management. Their expertise and experience extend to work on impacts of chemical contaminants in fresh waters, marine and estuarine waters, sediments, saturated and unsaturated groundwater, and on solid and hazardous waste evaluation and management.

Dr. Lee earned his BA degree in environmental health science from San Jose State College in San Jose, CA in 1955. He earned a Master of Science in Public Health degree in 1957 from the School of Public Health at the University of North Carolina, Chapel Hill with emphasis on environmental science and environmental chemistry. The focus of his work there was water quality evaluation and management for the protection of public health and environmental quality from chemical constituents and pathogenic organisms. Dr. Lee earned his PhD degree in environmental engineering from Harvard University in 1960. A major area of his specialization there was aquatic chemistry, which focused on the transport, fate, transformation, and control of chemical constituents in aquatic (surface and groundwater) and terrestrial systems, as well as in waste management facilities. Additional information on his academic background is available at www.gfredlee.com/Education/GFL-Education.pdf.

For 30 years Dr. Lee held graduate-level faculty positions, teaching and conducting research in departments of civil and environmental engineering at several major US universities, including the University of Wisconsin, Madison (Professor of Water Chemistry, Department of Civil & Environmental Engineering; Director, Water Chemistry Program), University of Texas at Dallas (Professor of Environmental Engineering & Sciences; developed and Director of the Center for Environmental Studies), Colorado State University, and the New Jersey Institute of Technology (Distinguished Professor of Civil & Environmental Engineering; Director Site Assessment & Remedial Action Division of Cooperative Center for Research in Hazardous & Toxic Substances). During that time he conducted more than $5-million in research and published approximately 500 professional papers and reports based on his investigations. In 1989, he relinquished his position as Distinguished Professor of Civil and Environmental Engineering to expand his part-time consulting into a full-time endeavor.

He is a registered professional engineer in the state of Texas, a Board Certified Environmental Engineer in the American Academy of Environmental Engineers, and a Fellow of the American Society of Civil Engineers.

Dr. Jones-Lee earned a BS degree in biology in 1973 from Southern Methodist University in Dallas, TX. She earned MS and PhD degrees (1978) in environmental science from the University of Texas at Dallas where she focused on aquatic toxicology and aquatic biology. Dr. Jones-Lee taught and conducted research in graduate university environmental engineering programs for 11 years prior to relinquishing her tenured Associate Professorship in Civil and Environmental Engineering in 1989 to join Dr. Lee in full-time consulting.

Dr. Lee's background in aquatic chemistry, environmental engineering, and public health, combined with Dr. Jones-Lee's background in aquatic toxicology and aquatic biology, creates a unique depth and breadth of expertise to offer to clients in identifying, assessing, managing, and preventing environmental quality problems. For more than 30 years Drs. Lee and Jones-Lee have been an effective team, working with governmental agencies, industry, citizens' groups, and others in developing technically valid, cost-effective approaches for managing contaminants in aquatic and terrestrial systems. They have published more than 1,100 professional papers and reports on their research results and professional experience.

Experience & Activities

Dr. G. Fred Lee began his work on assessing impacts of hazardous chemical sites and municipal/industrial landfills in the mid-1950s while he was an undergraduate student in environmental health sciences at San Jose State College. His academic course and field work involved review of impacts of municipal and industrial solid waste landfills on public health and the environment. An area of his specialization during his PhD work was aquatic chemistry with additional formal education on the fate, effects, and significance of, and development of control programs for, chemical constituents in surface and groundwater systems, as well as in water management facilities. In the mid to late 1960s, Dr. Lee became involved in the review of the impacts of municipal solid waste landfills on groundwater quality. In the 1970s he reviewed a number of municipal solid and industrial (hazardous) waste landfill situations, focusing on the impacts of releases from the landfill on public health and the environment.

Dr. Lee’s pioneering work on the impacts of organic solvents on clay liners for landfills and waste piles/lagoons in the 1970s; his involvement in that and related areas continues to present. In the early 1980s Dr. Lee served as an advisor to the town of Brush, Colorado on potential impacts of a proposed hazardous waste landfill on the groundwater resources. Based on that work, he published a paper in the Journal of the American Water Works Association discussing the ultimate failure of the liner systems proposed for that landfill in preventing groundwater pollution by landfill leachate. In 1984 that paper was judged by the Water Resources Division of the American Water Works Association as the “Best Paper” published in the journal for that year.

While holding the joint positions of Director of the Site Assessment and Remediation Division of a multi-university consortium hazardous waste research center and a Distinguished Professorship of Civil and Environmental Engineering at the New Jersey Institute of Technology, Dr. Lee was involved in numerous investigations concerning the impact of landfilling of municipal solid waste on public health and the environment. He conducted a comprehensive review of the properties of HDPE liners of the type being used today for lining municipal solid waste and hazardous waste landfills. Attention was focused on the compatibility of such liners with landfill leachate and their expected performance for containing waste-derived constituents for as long as the waste in the landfill will be a threat.

Dr. Lee has served as an advisor to the states of California, Michigan, New Jersey and Texas on solid waste regulations and management. He was also involved in evaluating potential threats to groundwater quality posed by uranium waste solids from radium watch-dial-painting, that were to be disposed of by burial in a gravel pit. The public in the area of the disposal site proposed by the state of New Jersey objected to the state's proposed approach. Dr. Lee provided testimony in litigation, which caused the judge reviewing this matter to prohibit the State from proceeding with the disposal of uranium/radium waste at the proposed location.

While serving as a full-time university professor, Dr. Lee was also active as a part-time, private consultant to governmental agencies, industry, and community and environmental groups on water quality, and solid and hazardous waste and mining waste management issues. His work in that capacity included evaluating the impacts of a number of municipal and industrial solid waste landfills. Much of that work was done on behalf of water utilities, governmental agencies and public interest groups who were concerned about the impacts of a proposed landfill on their groundwater resources, public health and the environment.

Since retiring from his academic work and focus on full-time consulting, Dr. Lee has focused a major portion of his work on assisting water utilities, municipalities, industry, community and environmental groups, agricultural interests and others in evaluating the potential public health and environmental impacts of proposed or existing hazardous, as well as municipal solid waste landfills. He has been involved in the review of approximately 80 different landfills in various parts of the United States and in other countries (see list at http://www.gfredlee.com/exp/areawork.htm). He and Dr. Jones-Lee have continued to publish extensively on the issues that should be considered and addressed in developing and evaluating new and expanded municipal solid waste and hazardous waste landfills in order to protect the health, groundwater resources, environment, and interests of those within the sphere of influence of the landfill. Their more than 150 professional papers and reports on landfilling issues provide guidance not only on the problems of today's minimum US EPA Subtitle D landfills, but also on how landfilling of non-recyclable wastes can and should take place to better protect public health, groundwater resources, the environment, and the interests of those within the sphere of influence of a landfill. Their work on landfill issues has particular relevance to Superfund site remediation, since regulatory agencies often propose to perform site remediation by developing an onsite landfill or capping waste materials that are present at the Superfund site. The proposed approach frequently falls short of providing true long-term health and environmental protection from the landfilled/capped waste. Many of their publications and reports prepared on behalf of clients are available as downloadable files from their website (www.gfredlee.com) in the Landfills-Groundwater Hazardous Chemical Sites, Mine Waste Impacts, and Contaminated Sediment sections.

In the early 1990s, Dr. Lee was appointed to the California Environmental Protection Agency's Comparative Risk Project Human Health Subcommittee that reviewed the public health hazards of chemicals in California's air and water. In connection with that activity, he and Dr. Jones-Lee developed a report entitled, "Impact of Municipal and Industrial Non-Hazardous Waste Landfills on Public Health and the Environment: An Overview" (Lee and Jones-Lee, 1994, available at http://www.gfredlee.com/Landfills/cal_risk.pdf), that served as a foundation for the human health advisory panel to assess public health impacts of municipal landfills. Drs. Lee and Jones-Lee also developed a comprehensive review of the "Flawed Technology of Subtitle D Landfilling" for protecting public health, groundwater resources and the environment for as long as the municipal solid wastes in a "dry tomb"-type landfill are a threat. It includes a discussion of how municipal landfills can be developed to better protect public health and environmental quality. Updated approximately annually, that report is available from their website at http://www.gfredlee.com/Landfills/SubtitleDFlawedTechnPap.pdf.

Dr. Lee is a registered professional engineer in the state of Texas, and a Diplomate in the American Academy of Environmental Engineers and Scientists (AAEES). Membership as a Diplomate in the Academy recognizes his leadership role in the environmental engineering field. For more than 20 years he served as a Chief Examiner for the AAEE, first in New Jersey and then for a decade in north-central California. In that capacity he was responsible for administering examinations for professional engineers with extensive experience and expertise in various aspects of environmental engineering, including solid and hazardous waste management, who desired admission to the Academy. In December 2009 Dr. Lee was elected an ASCE Fellow in recognition of his five-decade-long career as a national/international leader in the field, a university graduate-level educator, and an environmental consultant. In November 2010 the Sacramento Section of the ASCE selected Dr. Lee as the "Outstanding Life Member." Dr. Lee has served on the editorial boards for several professional publications, and currently serves on the editorial board for the Journals Stormwater and Remediation. Dr. Lee created and authored an email-based Stormwater Runoff Water Quality Newsletter that he distributed about monthly for 13 years, at no-cost, to about 8,000 subscribers.

For many years Dr. Lee developed and presented two-day short courses devoted to landfills and groundwater quality protection issues. Those courses have been presented through the American Society of Civil Engineers; the American Water Resources Association; the National Ground Water Association in several United States cities, including New York, Atlanta, Seattle and Chicago; and the University of California Extension Programs at several of the UC campuses, as well as through other groups. Dr. Lee has also participated in a mine waste management short-course organized by the University of Wisconsin-Madison and the University of Nevada. Dr. Lee also served for many years as an American Chemical Society tour speaker, through which he was invited to lecture on landfills and groundwater quality protection issues, as well as domestic water supply water quality issues throughout the US. Additional information on the qualifications of Drs. Lee and Jones-Lee to undertake reviews of the potential impacts of landfills and landfill expansions on public health, groundwater resources and the environment is available from their website gfredlee.com or by contacting Dr. Lee at gfredlee33@gmail.com.

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