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GROUNDWATER POLLUTION BY MUNICIPAL LANDFILLS: LEACHATE COMPOSITION, DETECTION AND WATER QUALITY SIGNIFICANCE

Anne Jones-Lee, Ph.D. and G. Fred Lee, Ph.D., P.E., D.E.E.
G. Fred Lee & Associates
El Macero, CA 95618 USA

SUMMARY: Municipal solid waste landfill leachate contains a wide variety of hazardous chemicals, conventional contaminants, and non-conventional contaminants. Contamination of groundwater by such leachate renders it and the associated aquifer unreliable for domestic water supply and other uses; "remediation" treatment does not restore their quality. Focus must be placed on prevention of pollution of groundwater by MSW landfill leachate.

INTRODUCTION

Increasing recognition is being given to the pollution of groundwaters by municipal and industrial "non-hazardous" solid waste landfills. The US EPA estimates that there are about 55,000 landfills in the US, on the order of 75% of which are polluting groundwaters. The majority of those landfills are what are called "sanitary" landfills in which there was little or no regard given in their siting, construction, operation, and closure for the potential impact of leachate generated within the landfill on groundwater quality. Today the US EPA and state pollution control agencies are recommending and/or requiring that sanitary landfills be situated above the watertable. According to recent federal regulations (US EPA, 1991), the minimal municipal solid waste (MSW) landfill requirements include a composite liner of compacted soil and plastic membrane, a leachate collection and removal system (LCRS) designed in concept to remove leachate generated in the landfill, and a low-permeability cover to be placed on the landfill when filled. While widely being adopted and used in some parts of the US, this approach is widely recognized as a stopgap measure which will only postpone the day in which groundwater pollution occurs by leachate generated within the landfill. Lee and Jones (1991a, 1992a) and Lee and Jones-Lee (1993) reviewed many of the numerous mechanisms which prevent "dry tomb" landfills from providing long-term protection of public health and groundwater quality.

Proponents of the "dry tomb" MSW landfill approach often assert that groundwater pollution by such landfills will not be a significant problem. However as discussed by Lee and Jones (1991a, 1992a), such assertions are based on an inaccurate description of the nature of the materials and processes that occur within MSW landfills that lead to leachate generation. This paper reviews the landfill processes that lead to leachate formation, the pollutional tendencies of leachates associated with MSW landfills, and the inability of the typical groundwater monitoring programs to provide reliable detection of leachate migration from the landfill and groundwater pollution by it before widespread pollution has occurred.

CHARACTERISTICS OF CONTAMINANTS IN MSW LANDFILL LEACHATE

There is a common misconception that since the materials placed in MSW landfills are basically household wastes, they are relatively "safe" and would not likely adversely affect public health and groundwater quality. One need only consider the proposition of drinking the ooze that develops at the bottom of a garbage can or the water used to clean a garbage can to understand that it is not desirable to have municipal solid waste leachate in one's drinking water. Even adding a drop of such garbage-can-derived liquid to a glass of drinking water, i.e., highly diluted leachate, would not be considered desirable. Yet this is what happens when municipal solid waste landfill leachate is allowed to contaminate water that is or could be used for domestic supply. A similar comparison can be made with regard to construction and demolition debris and rubble (sometimes classified as inert wastes) that some try to advocate as "safe" for land burial with minimal restriction.

There are three broad types of contaminants present in municipal landfill leachate that need to be considered in evaluating the public health and groundwater quality impacts of MSW landfills. These are the group of what are called "hazardous chemicals," "conventional contaminants," and "non-conventional contaminants." Table 1 (from Lee and Jones, 1991b) presents a compilation of information from the literature on the chemical composition of municipal landfill leachates focusing on many of the conventional, more common contaminants.

Table 1. Concentration Ranges for Components of Municipal Landfill Leachate

Parameter	"Typical" Concentration Range	"Average"*
BOD	1,000 - 30,000	10,500
COD	1,000 - 50,000	15,000
TOC	700 - 10,000	3,500
Total volatile acids (as acetic acid)	70 - 28,000	NA
Tota Kjeldahl Nitrogen (as N)	10 - 500	500
Nitrate (as N)	0.1 - 10	4
Ammonia (as N)	100 - 400	300
Total Phosphate (PO4)	0.5 - 50	30
Orthophospate (PO4)	1.0 - 60	22
Total alkalinity (as CaCO3)	500 - 10,000	3,600
Total hardness (as CaCO3)	500 - 10,000	4,200
Total solids	3,000 - 50,000	16,000
Total dissolved solids	1,000 - 20,000	11,000
Specific conductance (umhos/cm)	2,000 - 8,000	6,700

pH	5 - 7.5	63
Calcium	100 - 3,000	1,000
Magnesium	30 - 500	700
Sodium	200 - 1,500	700
Chloride	100 - 2,000	980
Sulfate	10 - 1,000	380
Chromium (total)	0.05 - 1	0.9
Cadmium	0.001 - 0.1	0.05
Copper	0.02 - 1	0.5
Lead	0.1 - 1	0.5
Nickel	0.1 - 1	1.2
Iron	10 - 1,000	430
Zinc	0.5 - 30	21
Methane gas	60%	
Carbon dioxide	40%	

All values mg/L except as noted
NA - not available
After: Lee et al. (1986) *From CH2M Hill based on 83 landfills (1989)

Regulations and regulatory agencies give primary attention to the so-called "hazardous chemicals" which are typically represented by the "Priority Pollutants." The group of Priority Pollutants was somewhat arbitrarily selected as part of a court order, by representatives of environmental activist groups and several individuals within the US EPA associated with the litigation. The list was not peer-reviewed within the US EPA, much less by the technical community as a whole and focused heavily on chemicals that were suspected of having the potential to cause cancer in man; largely ignored was a wide variety of chemicals that are known to have significant adverse impacts on domestic water supply water quality. It is widely recognized by professionals in the water quality management field that the chemicals included on the Priority Pollutant list did not then, and do not now, represent a consensus list of the most important chemicals posing the greatest threats to surface and groundwater quality. However, that list has diverted attention from destruction of groundwater quality by other contaminants.

There is a misconception that the prevention of disposal of what are classified as "hazardous wastes" prevents the disposal of hazardous chemicals in an MSW landfill. The currently prescribed TCLP leaching test used to define "hazardous waste" incorporates arbitrarily defined conditions which may not appropriately resemble key environmental conditions that exist in landfills. US EPA prescribes an arbitrary determination of the amount of leaching that can occur in the test before a material is classified as "hazardous;" Until a chemical is leached in concentrations at least 100-times the drinking water standard, a material is not classified as a "hazardous waste." Thus, the fact that a material processed through the TCLP is not classified as "hazardous waste" (i.e., is classified as "non-hazardous") does not mean that the material is not hazardous or otherwise deleterious to public health or welfare or groundwater quality. Lee and Jones (1981) have described an approach that should be followed to develop site-specific leaching tests to determine whether components in a solid waste are potentially leachable in the specific landfill environment in which they will be placed.

Conventional contaminants include parameters such as total dissolved solids, hardness, alkalinity, chloride, sulfate, iron, manganese, and hydrogen sulfide. In addition, this group includes a variety of non-differentiated organics measured as COD (chemical oxygen demand), BOD (biochemical oxygen demand), and TOC (total organic carbon). These are common components of a waste stream, traditionally analyzed to provide an overview characterization of the waste stream. They are typically present in elevated concentrations in landfill leachate and can thus often indicate the presence of leachate in unsaturated or saturated groundwaters. However, if present in sufficient amounts, conventional contaminants can cause severe degradation of groundwater quality and preclude its use for domestic water supply purposes. For example, organics measured as BOD, COD, or TOC can cause taste and odor problems and oxygen depletion in the groundwater. The chemicals that comprise those parameters may also adversely affect public health. Some of those organics can serve as co-substrates for microorganisms that can facilitate the conversion of hazardous chemicals to even more hazardous forms. An example of the latter is the conversion of TCE, a suspected human carcinogen, to vinyl chloride, a highly potent, known human carcinogen. The contamination of groundwaters by municipal landfill leachate contributes to the anoxic (oxygen-free) conditions that promote the conversion of TCE to vinyl chloride. Under anoxic conditions, bacteria in groundwater systems convert TCE to vinyl chloride.

Non-conventional contaminants are largely organic chemicals that have not been defined, and whose potential hazards to public health and groundwater quality are not known. Typically the organic Priority Pollutants, those organics that are identified and quantified, represent a very small fraction of the total organic matter present in leachate as measured by chemical oxygen demand and total organic carbon. It is estimated that from 90 to 95% of the organic materials in municipal landfill leachate are of unknown composition. Those chemicals have not been identified and obviously their potential impacts on public health and groundwater quality are unknown.

While there are some who attempt to minimize the significance of contamination of groundwater by MSW landfill leachate of the type generated today since large amounts of highly hazardous industrial chemicals are prohibited from being disposed of in municipal landfills, such a position is not based on technical facts. Most monitoring programs measure only about 200 of the more than 60,000 chemicals in commerce today, many of which could be present in municipal solid waste. Gintautas *et al*. (1992) reported finding a phenoxyalkanoic acid herbicide in municipal landfill leachate which had not be previously reported. They concluded that the chlorinate 2-phenoxypropionic herbicides are ubiquitous in MSW landfill leachates in the US. There are likely to be many other potentially hazardous or otherwise deleterious chemicals yet to be identified in MSW landfill leachate. It is clear that today's society has not found all of the highly hazardous chemicals that can cause cancer (carcinogens), birth defects (teratogens), and mutations (mutagens). It is highly likely that hazardous chemicals or hazardous transformation products that are now part of the non-conventional contaminants in MSW landfill leachate will be found in the future.

As discussed by Lee and Jones (1991a, 1992a), it is prudent public health policy to consider any groundwater contamination by MSW landfill leachate to be a significant public health and environmental threat that should trigger immediate efforts to stop the spread of the pollution and address the groundwaters that are or could be used for domestic water supplies. This action should be taken independent of whether any of the Priority Pollutants and conventional contaminants exceed water quality standards or objectives. Further, it is erroneous to assume, as is done by many who advocate the construction and operation of a municipal landfill at a certain location, that at the end of a few decades after landfill closure the landfill and its leachate will not represent a threat to public health and groundwater quality. Freeze and Cherry (1979) have reported that landfills constructed by the Romans some 2000 years ago are still producing leachate. Belevi and Baccini (1989) estimated that unlined sanitary landfills in a fairly wet climate will leachate hazardous chemicals such as lead at concentrations above drinking water standards for several thousand years. Thus lined landfills would be expected to follow a similar pattern once the liners fail to prevent significant leachate migration.

CONTROLLING LEACHATE CHARACTER BY CONTROL OF WASTE STREAM

It is estimated that each person contributes about 4 L/yr of hazardous chemicals to their MSW stream. Lee and Jones (1991a) listed a wide variety of household products, which eventually reach an MSW landfill, that contain Priority Pollutants; Brown and Nelson (1990) also discussed sources of hazardous chemicals in MSW leachate. "Hazardous" chemicals such as chlorinated solvents and other cleaning compounds, gasoline, waste oil and other hydrocarbons, lead-based paint residues, soil-lead residues, mercury in fluorescent tubes and batteries, etc. are contributed to MSW landfills from residences and commercial establishments. As discussed by Lee and Jones (1991a), anyone can go to the local hardware store and purchase a gallon can of TCE, use half of it and put the remainder on the shelf for future use, only to later discard the half-gallon of TCE in the trash as part of household or garage clean-up. The TCE will not be degraded in the landfill to innocuous products; rather there is a high probability that it will be converted to vinyl chloride in the landfill environment. TCE or vinyl chloride can pass through intact flexible membrane landfill liners as well as compacted clay liners, and be transported to the groundwater (Lee and Jones, 1992a). A half-gallon of TCE or vinyl chloride can cause millions of gallons of groundwater to exceed the US EPA's drinking water standard. A similar scenario is readily conceivable for gasoline; gasoline-derived benzene in groundwater represents a significant human health hazard due to increased cancer risk. Waste automobile oil with its elevated heavy metals and hydrocarbons is also routinely thrown into the household trash, as are various types of batteries such as mercury-based and nickel-cadmium batteries. It is estimated that on the order of 47 tons of mercury were used in the US in 1988 in mercury batteries with consumer applications (Waste Not, 1990). The disposal in MSW landfills of burned-out fluorescent tubes used for home or commercial lighting also adds mercury to the landfill. Further, the disposal of the electrical transformers used in fluorescent lighting systems adds PCB's to MSW landfills since until recently, PCB's have been widely used in such electrical transformers.

In addition to the household and commercial sources of hazardous chemicals, the US EPA and many states allow "small generators" to each dispose of up to 100 kg/mo of hazardous wastes in MSW landfills. Large municipalities typically have many thousands of small generators of hazardous wastes, each of which can be contributing highly hazardous chemicals to the MSW stream. Even in those areas without small-generator exemptions there will inevitably some illegal disposal of such materials because of the significantly greater cost for "hazardous waste" disposal. Another potentially significant source of highly hazardous, persistent chemicals to MSW landfills is street sweepings that are routinely placed in MSW landfills. It is well-known that street sweepings have greatly elevated concentrations of cadmium, lead, as well as other heavy metals and potentially hazardous organics.

Another source of highly hazardous chemicals for MSW landfills is Superfund site residue. The common practice in many states is to require that soils at a Superfund site that are contaminated with Priority Pollutants above a certain level be treated or taken to a hazardous waste landfill. If the concentrations of contaminants are below some arbitrarily established concentration, the contaminated soils may be disposed of in an MSW landfill. As noted above, the fact that a material is classified as a "non-hazardous" waste does not mean that it will not leach significant quantities of chemical contaminants. In association with "remediation" of some Superfund sites with which the authors are familiar, many tons of soils highly contaminated by Priority Pollutants such as lead are disposed of in MSW landfills.

Organized household hazardous material collection programs can reduce the amounts of hazardous chemicals discarded by the homeowner, that are deposited in an MSW landfill. However, it is clear that even with aggressive collection of obvious sources of hazardous chemicals in household waste, it is unlikely that complete control of household sources of Priority Pollutants can be achieved. Landfill owner/operators frequently assert that they will operate a load checking program designed to prevent hazardous chemicals from being deposited in MSW landfills. Basically, those programs involve visual inspection of selected waste loads. Typically, such programs, if carried out adequately, will detect some of the large drums and other large obvious containers of wastes, but they will not detect small containers. While load checking should be practiced, it will not prevent highly hazardous chemicals from entering MSW landfills. Neither of these approaches addresses the legal deposition of hazardous chemicals into an MSW landfill from other sources.

Even if complete control of Priority Pollutants in MSW could be established, MSW landfill leachate contains conventional contaminants and non-conventional contaminants that can have a significant adverse impact on groundwater quality. Increasing the concentrations of total dissolved solids (TDS), hardness and many other constituents of this type which are typically found in municipal landfill leachate at very high concentrations can prevent the use of the groundwater for domestic water supply purposes. Even if the concentrations do not reach this level of contamination, they cause homeowners greater costs for their domestic water supply as a result of increased water treatment by the utility. If the contaminants are not removed, homeowners and commercial/industrial establishments will experience a less desirable water from a variety of points of view. Typically, waters with increased TDS and hardness are more corrosive for the plumbing fixtures, tend to form scale-coatings in water heaters, etc., require the use of greater amounts of soaps and detergents for cleaning, and shorten the life of clothes, washing machines, dish washers, etc. If the homeowner or municipality softens the water by ion exchange, the softened water will have increased sodium which can be a problem to some individuals with heart disease.

MSW landfill leachate typically contains significantly elevated concentrations of a variety of other chemicals which also represent a threat to groundwater quality. For example, iron is of concern in domestic water supplies at concentrations above 0.3 mg/L. As shown in Table 1, the typical concentration range of iron in municipal landfill leachate is from 10 to 1,000 mg/L. While not shown in Table 1, conventional municipal landfill leachate also contains greatly elevated concentrations of manganese and hydrogen sulfide. Further, the high oxygen demand of municipal landfill leachate can cause depletion of dissolved oxygen from the groundwater contaminated by it. Groundwaters free of dissolved oxygen tend to dissolve iron and manganese from the geological strata of the aquifer material. The iron and manganese are of particular concern since they cause staining of fixtures, clothes and other materials. They have to be removed in the water treatment process which adds to the cost of the domestic water supply contaminated by municipal landfill leachate. Groundwaters contaminated by MSW landfill leachate and depleted of oxygen promote the conversion of sulfate to hydrogen sulfide which is highly obnoxious in water supplies. It causes a "rotten egg" smell at very low concentrations, as well as increases the rate of corrosion of plumbing. While hydrogen sulfide can be removed by individual homeowner or municipal water treatment units, such removal adds to the cost of a domestic water supply. Ammonia and a variety of organic nitrogen compounds are conventional contaminants that are also of great concern in MSW landfill leachate. Oxic groundwaters contaminated by ammonia can have greatly elevated concentrations of nitrate. Nitrate above 10 mg/L as N is a public health hazard in groundwater; it causes methemoglobinemia (blue baby disease).

The presence of non-conventional contaminants is one of the most important reasons for preventing groundwater contamination by MSW landfill leachate. As indicated in Table 1, the typical concentration range of COD in MSW landfill leachate is 1,000 to 50,000 mg/L, and of TOC, 700 to 10,000 mg/L. Since the identified organic compounds in MSW typically represent no more than a fraction of a mg/L to a few mg/L, it is apparent that very little is known about the composition and therefore the hazards of most of the organics present in municipal landfill leachate.

Some of the non-conventional contaminant organics are transformed to methane as part of fermentation-gas production. The majority, however, are not fermentable and will be present in landfill leachate for hundreds to thousands of years depending on the rate of leaching of the organics from the solid wastes. These organics contribute to the high oxygen demand in MSW landfill leachate as measured by BOD_5 of 1,000 to 30,000 mg/L as shown in Table 1. These organics are also responsible for taste and odors in domestic water supplies. Further, it is now well-established that these organics serve as complexing agents for heavy metals which enable their transport in groundwater systems which would not occur in the absence of the organics.

In addition and most importantly, within the non-conventional contaminant organics category is a host of unidentified, potentially highly hazardous chemicals that are not measured as part of the approximately 100 organic Priority Pollutants. There is little doubt that in time new, yet unidentified, highly hazardous chemicals will be found in this group such as the chlorinated phenoxy herbicides noted above. It is for this reason that it is prudent public health policy to not allow domestic use of any groundwater that has been contaminated by MSW landfill leachate, even if the concentrations of contaminants do not exceed drinking water standards or other water quality standard-objectives.

The source of the organics in municipal solid waste leachate that are represented by the non-conventional contaminants is the bulk of the organics that are disposed of in MSW landfills. It is therefore impractical to implement changes in the solid waste stream characteristics as a means of eliminating the known and potential impacts of the non-conventional contaminants in landfill leachate. The organic and inorganic contaminants present in municipal solid wastes which ultimately contribute to the conventional contaminants of concern are derived from essentially all of the major components of municipal solid wastes and therefore their control in the waste stream is also impractical. It is readily apparent that attempting to selectively remove those waste components that contribute conventional and non-conventional contaminants to MSW landfill leachate is an impossible task.

CLEAN-UP OF LEACHATE-CONTAMINATED GROUNDWATER

One of the key issues in the evaluation of the potential impact of MSW landfill leachate on groundwater quality is the ability to clean-up contaminated groundwaters once the landfill liner system has been breached. Much of the volatile organic compounds such as TCE and its transformation product vinyl chloride, can generally be readily removed from groundwater by air stripping or bioremediation. However, the concentrations of those contaminants that are considered accepted in drinking water are near analytical detection; it is being found that many such contaminants continue to leach from contaminated aquifer material in concentrations of concern for drinking water, for exceedingly long periods of time, in some cases projected for tens to hundreds of years (Bredehoeft, 1992; AGWSE, 1992; Rowe, 1991).

The removal of conventional contaminants such as TDS is generally more difficult and would involve ion exchange demineralization or reverse osmosis. For non-conventional organic contaminants, multiple series of activated carbon columns would typically be required. From the information available today it appears that clean-up of groundwaters contaminated by municipal landfill leachate will likely require a combination of reverse osmosis and activated carbon columns; in many instances pre-treatment of the groundwater to remove iron, hydrogen sulfide, and some of the organics will also be necessary. This means that the cost of cleaning up groundwaters contaminated by MSW landfill leachate will typically be far-greater than the cost of clean-up of contaminated groundwater normally associated with Superfund sites. Further, groundwater so treated, and the associated aquifer cannot be relied upon to provide a safe drinking water supply because of the unknown removal of chemicals in the non-conventional group. The high costs associated with trying to clean-up MSW leachate-contamination of groundwater have led the US EPA (1991) to conclude that once a water supply well has been contaminated by MSW leachate, the well has to be abandoned for water supply.

With MSW landfill leachates' being one of the primary causes of deteriorated groundwater quality, particular attention must be given to ensuring that existing MSW landfills do not cause further contamination of groundwaters and that all existing contamination, independent of the imminent threat to an existing water supply, should be cleaned up to as close to background as possible.

GROUNDWATER QUALITY MONITORING

The last line of defense cited by landfill applicants for protection of groundwater quality from pollution by MSW landfill leachate is the groundwater monitoring program. In concept, when the "dry tomb" is breached, incipient leakage would be detected in on-site wells and that detection would enable intervention to prevent further groundwater pollution. Groundwater monitoring programs for landfills typically involve the sampling of one upgradient well and a few dowgradient wells spaced a hundred or more feet apart. As discussed by Lee and Jones (1983a,b; 1991b; 1992b) and Cherry (1990), however, it has become well-recognized that the typical groundwater monitoring programs for new lined landfills are grossly inadequate for detecting landfill leakage before widespread groundwater pollution has occurred. Unlike the leakage from an unlined landfill, leachate from lined landfills would be expected to be initially from point-sources such as holes in the liner. The studies of J. Cherry and his associates at the University of Waterloo's Centre for Groundwater Research (Cherry, 1991) have shown that even in a highly homogeneous sand aquifer system, the vertical and horizontal dispersion of the leachate plume in the groundwater is very limited. Thus leachate would be expected to migrate as "fingers" rather than as the classical "fan" shape plume. In order for a well to detect leakage from a landfill the leachate finger must be intercepted by the zone of water capture for the well. In a typical monitoring well, the zone of capture of water after well purging is on the order of a tens of cm about the well. With such typical zones of capture, it is clear that hundreds of downgradient monitoring wells are needed in order to provide any significant probability of detecting incipient leakage from a lined landfill (Parsons and Davis, 1992).

As discussed by Lee and Jones (1992b) the real conditions encountered at landfills complicate groundwater monitoring further. Groundwater monitoring for landfill leakage in fractured rock is very difficult to do with any significant degree of reliability (Haitjema, 1991). Leachate moving through fractures can readily pass, undetected, by a monitoring well system; such conduits can allow rapid transport of leachate compared to the general movement of groundwater in the region, over considerable distances. MSW landfill leachate typically contains sufficient salts so that it will tend to sink in the aquifer. Thus, depending on the horizontal velocity of the groundwater and the characteristics of the aquifer, the leachate finger may be somewhat below the watertable. This situation necessitates an array of monitoring wells screened to various depths at each monitoring well location to achieve a significant probability of detecting incipient leakage-pollution of groundwater by a landfill. The typical three-depth monitoring well array (near surface, mid-depth, and near-bottom) used in groundwater monitoring systems, or fully-screened wells, cannot be relied upon for many saturated aquifers tens of feet thick, to detect landfill leakage near the landfill. The typical groundwater quality monitoring program assumes that the release of contaminants from a landfill is a steady stream once the liners are breached. In arid climates with a moderate degree of cover integrity, the release of leachate from the landfill will more likely occur through holes in the liner in discrete, short-term pulses. The typical quarterly groundwater monitoring program will likely be inadequate to detect such pulses.

Commonly used indicator parameters (e.g., pH, TOC, TOX, TDS) do not provide adequate sensitivity to detect incipient landfill leakage. Typically, but not always, the VOC's, such as TCE and its transformation product vinyl chloride, are better indicators of leakage than the indicator parameters that are often used. A monitoring program must include routine measurement of a wide variety of chemicals that are known or suspected to be present in the landfill that can be measured at very low concentrations.

Groundwater quality monitoring programs being developed today typically have a low probability of detecting leakage from lined MSW landfills before significant aquifer pollution occurs. These monitoring systems provide little or no public health and groundwater quality protection. Until such time as an appropriate groundwater monitoring system is developed to detect incipient leakage of a landfill, it is essential that landfills of the "dry tomb" type being developed today not be sited where the inevitable leakage will pollute groundwater that is or could be used for domestic or many other water supply purposes.

There is increasing recognition that a single or even a double-composite-liner system will at best only postpone groundwater pollution; it will not prevent it. Double-lined dry tomb landfills can be used for storage of untreated MSW for tens to possibly a hundred years or so, provided that incipient leakage through the upper liner can be reliably detected and addressed when it occurs. The lower composite "liner" should not be considered to be a "liner" but rather should function as a full-landfill-area pan lysimeter; when leachate appears in the full-landfill-area pan lysimeter, corrective action must be taken to stop leachate production through either repair/replacement of the cover or waste exhumation. If properly designed, constructed, operated, and closed, a single composite-lined landfill with full-landfill-area pan lysimeter has the potential for long-term storage of untreated MSW provided sufficient funds are available in a dedicated trust derived from disposal fees to exhume the wastes if the source of moisture that causes leachate generation cannot be effectively prevented in a short time after first detected in the pan lysimeter. The leak detection system between the two composite liners (the lower of which is the pan lysimeter) should not be considered a secondary leachate collection and removal system because it will also allow transport of leachate through it to pollute the groundwater in the vicinity of the landfill.

CONCLUSION AND RECOMMENDATIONS

The composition of the solid waste stream controls the composition of the leachate produced at an MSW landfill. Despite waste stream restrictions, MSW landfill leachate still has a high probability of containing potentially significant concentrations of hazardous chemicals arising from household and commercial use of these chemicals and through illegal dumping. Even if all hazardous chemicals which are typically assessed by measuring the Priority Pollutants could be excluded from the MSW stream to a landfill, the leachate from such a landfill would still render the groundwater unusable for domestic water supply and many industrial purposes. Conventional pollutants derived from a wide variety of MSW stream components are present in high concentrations in MSW landfill leachate. Their presence in a groundwater at elevated concentrations down groundwater gradient of an MSW landfill is an indication that the landfill leachate is contaminating the groundwaters, and can themselves cause considerable water use impairment.

More than 90% of the organics present in MSW landfill leachate are not identified or quantified; their public health implications are unknown. The efficacy of groundwater "remediation"-treatment methods in removing such non-conventional contaminants to "safe" levels cannot be determined. These organics also contribute to the oxygen demand of MSW landfill leachate that leads to increased concentrations of iron, manganese, hydrogen sulfide, etc. It is therefore prudent public health policy to assume that all groundwater contaminated by MSW landfill leachate, independent of whether a water quality standard is exceeded for any contaminant derived from the landfill whether considered hazardous or not, represents a significant threat to public health and groundwater quality that requires that immediate steps be taken to stop further contamination of the groundwater. Groundwaters that are or could be used for domestic water supply purposes that have been contaminated by such leachate should be cleaned up to as close to background levels as possible. In situations where an existing landfill cannot be managed in such a way as to prevent further groundwater contamination where such contamination has important implications for adjacent property owners' individual as well as municipal wells, the landfill owner/operator should be required to stop accepting wastes, close the landfill, and effect the cessation of leachate generation and further migration of polluted groundwater. That may require waste exhumation.

"Dry tomb" landfills should incorporate reliable groundwater monitoring programs that would in fact be able to detect incipient groundwater pollution before off-site contamination of groundwater occurs. Financial assurance instruments should be developed as part of the MSW landfill permitting to unequivocally assure that funds will be available *ad infinitum* to clean-up all groundwaters contaminated to background levels of all contaminants, to prevent further contamination of groundwaters by leachate, and to provide alternative water supply. Since the wastes in a "dry tomb" MSW landfill will remain a threat to groundwater quality for as long as they remain buried, it is very important to not site "dry tomb" landfills in areas where domestic water supply water quality is threatened. Landfills sited where groundwater pollution is of potential significance should be constructed and operated as fermentation/leaching wet cell landfills of the type described by Lee and Jones-Lee (1993) to produce treated waste residues that would not be a long-term threat to groundwater quality.

REFERENCES

AGWSE (1992) Conference Abstracts, "Aquifer Restoration: Pump-and-Treat and the Alternatives" Association of Ground Water Scientists and Engineers, Dublin, OH, September.

BELEVI, H., and BACCINI, P. (1989) "Long-Term Behavior of Municipal Solid Waste Landfills" Waste Mgt. & Res. 7:43-56.

BREDEHOEFT, J. (1992) "Much Contaminated Ground Water Can't Be Cleaned Up" Editorial, Journ. Ground Water 30:834-835.

BROWN, K. W., and NELSON, L. D. (1990) "An Assessment of the Potential for Continued Contamination of Groundwater by the Expansion of the Azusa Reclamation Co. Landfill, Azusa, California" K. W. Brown & Associates, Inc., College Station, TX, March.

CHERRY, J. (1990) "Groundwater Monitoring: Some Deficiencies and Opportunities" IN: Hazardous Waste Site Investigations; Towards Better Decisions, Proc. 10th ORNL Life Sciences Symposium, Lewis.

CHERRY, J. (1991) presentation at ASTM Subcommittee D18.21 Proc. Symposium on Ground Water and Vadose Zone Investigations, San Diego, CA Jan (in press).

FREEZE, R. A., AND CHERRY, J. A. (1979) Groundwater Prentice-Hall, Inc., Englewood Cliffs, NJ.

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

HAITJEMA, H. (1991) "Ground Water Hydraulics Considerations Regarding Landfills" Water Resources Bull. 27:791-796.

LEE, G. F., and JONES, R. A. (1981) "Application of Site-Specific Hazard Assessment Testing to Solid Wastes" IN: Hazardous Solid Waste Testing: First Conference. ASTM/STP 760. American Society for Testing and Materials, Philadelphia, pp. 331-344.

LEE, G. F., and JONES, R. A. (1983a) "Water-Quality Monitoring at Hazardous Waste Disposal Sites: Is Public Health Protection Possible through Monitoring Programs?" Proc. National Water Well AssociationSymposium, Aquifer Restoration & Groundwater Monitoring, Worthington, OH, pp. 189-200.

LEE, G. F., and JONES, R. A. (1983b) "Guidelines for Sampling Groundwater" Journ. Water Pollut. Control Fed. 55:92-96.

LEE, G. F., and JONES, R. A. (1991a) "Municipal Solid Waste Management: Long-Term Public Health and Environmental Protection" Notes for Short Course on Landfills and Groundwater Quality, University Extension, University of California, Davis, Davis, CA, April.

LEE, G. F., and JONES, R. A. (1991b) "Groundwater Pollution by Municipal Landfills: Leachate Composition, Detection and Water Quality Significance" Proc. National Water Well Associations's Fifth Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring, and Geophysical Methods, NWWA, Dublin, OH, pp. 257-271.

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

LEE, G. F., and JONES, R. A. (1992b) "Groundwater Quality Monitoring at Landfills: It's Time to Stop Deceiving Ourselves and the Public" Presented at Workshop, "'Dry Tomb' Landfills: Problems and Suggested Alternative Approaches," National Ground Water Association Outdoor Action Conference, Las Vegas, NV, May.

LEE, G. F., and JONES-LEE, A. (1993) "Landfills and Groundwater Pollution Issues: 'Dry Tomb' vs F/L Wet-Cell Landfills" Proc. Sardinia '93 IV International Landfill Symposium S. Margherita di Pula, Italy, 11-15 October.

PARSONS, A. M., and DAVIS, P. A. (1992) "A Proposed Strategy for Assessing Compliance with RCRA Ground Water Monitoring Regulations" Current Practices in Ground Water and Vadose Zone Investigations, ASTM STP 1118, ASTM, Philadelphia, pp. 39-56.

ROWE, W. (1991) "Superfund and Groundwater Remediation: Another Perspective" Environ. Sci. & Technol. 25:370-372.

US EPA (1991) "Solid Waste Disposal Facility Criteria; Final Rule." 40 CFR Parts 257 and 258, Federal Register Vol. 56, pp. 50978-51119, October 9.

WASTE NOT (1990) "EPA Conference on Mercury Batteries" Work on Waste USA, Inc. Canton, NY.

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