Evaluation of the Potential for a Proposed or Existing Landfill to Pollute Groundwaters[1]

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One of the issues of greatest concern on the impacts of an existing or a proposed landfill is the pollution of groundwaters by landfill leachate. Small amounts of landfill leachate can pollute large amounts of groundwater, rendering them unusable for domestic and many other purposes. Presented herein is a discussion of the issues that need to be considered in evaluating the potential for a proposed or existing landfill to pollute groundwaters that could at any time in the future be used for domestic or other purposes. This evaluation is based on a risk assessment approach that the authors developed in the early 1980s. At that time, the authors published a paper, "A Risk Assessment Approach for Evaluating the Environmental Significance of Chemical Contaminants in Solid Wastes" (Lee and Jones, 1982). This paper was the first paper published on how to conduct a risk assessment on a proposed or existing landfill. It discussed the issues that need to be considered in evaluating the risk-hazard of a landfill to impair groundwater quality at a particular location. Today, risk assessments of this type are routinely done in connection with industrial hazardous chemical sites, such as superfund sites, and should be conducted as part of developing a new or expanded landfill.

Risk Assessment Approach

The basic components of a landfill-groundwater pollution risk assessment are:

- a source of hazardous and deleterious chemicals, i.e. a proposed or existing landfill;
- a transport path from the source, i.e. groundwater, which may include as part of the pathway gas phase transport of potential pollutants; and
- a receptor, i.e. humans, animals and/or plants that may be potentially adversely impacted by the chemicals derived from the source.

Source of Pollutants

Municipal solid waste, industrial "non-hazardous" waste and industrial hazardous waste landfills contain a variety of potentially significant chemical constituents and pathogenic organisms that could be adverse to public health, groundwater quality, environment and other interests of those within the sphere of influence of the landfill. These constituents are not

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necessarily just those that are classified today as "hazardous" waste. They include the regulated hazardous chemicals that are a threat to public health, such as the Priority Pollutants (heavy metals, VOCs, chlorinated solvents, etc.); the unregulated hazardous chemicals which are a threat to public health but for which there are no regulatory limits established and which are not measured in an investigation of the characteristics of landfill leachate and groundwaters polluted by landfill leachate; and the conventional pollutants, such as BOD, TOC, chemicals that cause taste and odors, H_2S, Fe, Mn, TDS, hardness, alkalinity, Cl, etc. Of concern, but often ignored, are a variety of constituents that are adverse to a homeowner's or industrial/commercial concern in terms of shortening the life of plumbing and appliances through scale formation or corrosion. While not a health hazard, such constituents represent a significant economic burden to the user of the groundwaters polluted by landfill leachate. Jones-Lee and Lee (1993) have discussed the potential for municipal landfill leachate to pollute groundwaters, rendering them unusable for domestic water supply purposes.

Even today's so-called "treated" hazardous wastes that are placed in US EPA RCRA Subtitle C landfills are not sufficiently treated to eliminate the hazards of the regulated, hazardous components in the wastes to polluting groundwaters. While normally hazardous waste landfills are only assumed to be of concern because of the hazardous wastes (Priority Pollutants) present in them, they are also of significant concern because of the non-conventional, unregulated hazardous chemicals and the wide variety of other chemical constituents present in the wastes that can render a groundwater unusable for domestic water supply purposes. These wastes also contain many conventional pollutants as well as unregulated chemicals that are a threat to public health, groundwater resources, the environment and the interests of those who use groundwaters in the vicinity of the landfill for domestic and other purposes. Even if all of the regulated so-called hazardous chemicals present in a municipal, industrial non-hazardous or hazardous waste landfill leachate-polluted groundwater occur at concentrations less than drinking water standards, these groundwaters should still not be considered safe-appropriate for use for domestic water supply purposes because of the unregulated chemicals and the conventional pollutants present therein.

The authors find that frequently landfill owners and their consultants as well as some regulatory agency personnel do not understand the full range of potential impacts that chemical constituents present in landfill leachate may have on the use of a leachate-polluted groundwater for domestic or other purposes. The landfill permit applicant should be required to provide a detailed discussion of the potential adverse impacts of each of the constituents potentially present in the landfill leachate on the use of the groundwaters for domestic water supply or other purposes.

Contaminating Lifespan. While landfill applicants often assert that the contaminating lifespan of a proposed landfill will be less than 30 years, i.e. the minimum post-closure care period specified by RCRA, it is more appropriate to conclude that the contaminating lifespan of today's "dry tomb" landfills (plastic sheeting and clay lined landfills) will more likely be on the order of a thousand or more years. As discussed by Lee and Jones-Lee (1992, 1993a) the 30-year post-closure care period dictated by Congress was a significant error in developing RCRA. Those who assume that municipal and industrial hazardous waste landfills will only be a threat for 30 years did not properly distinguish between the period of time that classical unlined sanitary landfills tend to produce significant amounts of landfill gas and the leaching of waste constituents in the landfill that cause landfill leachate to be a threat to groundwater quality.

The classical, unlined, permeable cover sanitary landfill allowed appreciable moisture to enter the landfill's wastes and thereby promote landfill gas production through bacterial fermentation processes. This moisture also produced leachate through leaching of the soluble waste components. As discussed in Lee and Jones (1992) and Lee and Jones-Lee (1996a), in today's "dry tomb" landfills where there is an attempt to keep the wastes dry, the fermentation and leaching of the wastes to produce landfill gas and leachate will take place over a very long period of time. From a conservative-protective perspective, it should be assumed, unless it can be convincingly demonstrated otherwise, that the contaminating lifespan of an existing or proposed landfill will be at least several hundred years, and likely, a thousand or more years.

The landfill owner/operator should be required as part of permitting the landfill and evaluating the potential for the landfill to pollute groundwaters to reliably estimate the potential contaminating lifespan of the landfill.

Transport Mechanism

A key issue of concern with respect to the potential for a landfill to pollute groundwaters is whether there is a transport mechanism via groundwater by which hazardous and deleterious chemicals present in the landfill could, at some time in the future, be transported from the landfill to the wells of interest to a downgradient property owner-user at sufficient concentrations and for sufficient duration to be adverse to the use of this water for domestic or other purposes.

The transport of hazardous and deleterious chemicals from landfills can occur for considerable distances via gas phase transport in the unsaturated (vadose) zone. Such transport does not require direct hydraulic connection between the landfill and the groundwaters of the region. Prosser and Janechek (1995) have described appreciable up/downwatergradient pollution of groundwaters by gas phase transport of VOCs at landfills. Landfill applicants should be required to evaluate the potential for gas phase transport of hazardous and deleterious chemicals that can lead to groundwater pollution as part of permitting the landfill. Of particular concern is how the landfill owner will detect such transport, what steps will be taken when found and the amount and source of funds needed to control further transport by this mechanism as well as to remediate the contaminated vadose zone and groundwaters arising from it.

Typically, landfill applicants assert that even if the landfill liners fail to prevent leachate from migrating through the liner, the natural strata will prevent the transport of leachate-derived constitutes from the base of the landfill to off-site (adjacent or nearby properties within the sphere of influence of a landfill) groundwaters. However, it is the experience of the authors that these assertions are based on a superficial analysis of the real risk that a landfill represents to the pollution of groundwaters hydraulically connected to it for as long as the wastes in the landfill represent a threat. It is important in making this evaluation to assume that, except under very rare situations, if there is a hydraulic connection between the base of the landfill and off-site groundwaters, that based on today's landfilling approach it is only a matter of time until the off-site groundwaters are polluted by leachate, rendering them unusable for domestic and many other purposes.

Receptor

The domestic, commercial/industrial, agricultural and other water supply wells of a region are the points at which there is concern about the potential impacts of leachate pollution of groundwaters that could impair the use of these waters for human consumption and the support of agricultural and other activities. Municipal and industrial landfill leachate contains a wide variety of hazardous and deleterious chemicals at high concentrations that could cause a water supply well to have to be abandoned. The US EPA (1988a) concluded as part of promulgation of its municipal landfilling regulations that any water supply well that is contaminated to any extent with municipal landfill leachate must be abandoned and a new well constructed as an alternative water supply source. The same situation would apply to wells contaminated by today's hazardous waste landfill leachates. In areas with large amounts of surplus groundwaters, abandoning a well, while costly, is possible. However, in many areas, especially during droughts, there is no surplus groundwater and therefore all groundwaters must be protected from pollution by landfill leachate for as long as the wastes represent a threat.

Plausible Worst-Case Polluted Groundwater Transport Scenario

One of the key issues that needs to be addressed by landfill applicants/owners is an evaluation of plausible worst-case conditions where the landfill containment system (cover, liners, leachate collection and removal system, and groundwater monitoring) fails to prevent leachate-contaminated groundwaters that arise at the edge of the landfill from trespassing into adjacent properties. It is suggested that a landfill owner/applicant should develop a plausible worst- case scenario evaluation of how long it would take for leachate-polluted groundwaters arising at the landfill to reach adjacent groundwaters and wells of importance to adjacent and nearby property owners and users.

It is our experience that normally groundwaters do not move more than a few feet per day. This experience, however, is based on sand and gravel aquifer systems. In fractured rock and limestone systems, the rates of groundwater movement can be significantly different. It is important in making a plausible worst-case scenario evaluation to assume the fastest possible transport based on the measurements made, rather than the mean or some other approach that is used to try to convince regulatory agencies and others that a landfill is "safe" for a region.

If there are significant gaps in information needed to reliably make an estimate of plausible worst-case transport of leachate-polluted groundwaters to a region, then these information gaps should be defined and a program should be developed to obtain the necessary information as part of additional studies of the environmental assessment for the existing or proposed landfill.

It should not be assumed, as is often done, that the landfill liner systems of the type being used today under RCRA Subtitle C and D (single or double composite-lined landfills) will prevent leachate from passing through the liner system and entering the underlying groundwater system. The US EPA (1988a) as part of developing Solid Waste Disposal Criteria with reference to composite-lined (plastic sheeting and compacted clay) landfills stated,

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

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

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

While these statements were made with reference to the development of municipal solid waste Subtitle D single composite liner systems, they are applicable to Subtitle C and D double composite liner systems. Therefore, landfill liner systems of this type cannot be relied on to protect groundwaters from pollution by landfill leachate. At best, they only postpone for a period of a few tens of years when pollution occurs. Lee and Jones (1992) and Lee and Jones-Lee (1996a) have reviewed the properties of landfill liner materials and liner systems with respect to their ability to prevent leachate passing through them for as long as the wastes in the landfill represent a threat. While there are some consultants, such as Fluet *et al.* (1992) and Tisinger and Giroud (1993), who claim that today's landfill liner systems using plastic sheeting (flexible membrane liners) and compacted clay will be protective of groundwater resources, the facts are that this protection will be for a limited period of time compared to the time that the wastes in the landfill will be a threat.

This issue has been discussed by Lee and Jones-Lee (1993b) and Lee (1994) where they point out that statements about how the "protection" provided by flexible membrane liners represents superficial, inadequate assessment of the issues of concern to those who own or use adjacent or nearby properties to a landfill. They and all future generations who may own or use those properties want and should be entitled to groundwaters free from leachate pollution for as long as the wastes in a landfill will be a threat, i.e., forever. Lee and Jones (1992) have discussed the fundamentally flawed technological approach that was adopted by Congress and implemented by the US EPA as part of RCRA of attempting to develop protective "dry tomb" type landfills for any landfill that is sited where there are groundwaters hydraulically connected to the base of the landfill that could be used in the infinite future for domestic water supply purposes.

Haxo and Lahey (1988) have discussed the transport of organic solvents through intact (without holes) flexible membrane liners. This process is described as "permeation" where the solvents dissolve into the plastic liner material and exit the liner material on the downgradient side (outside the landfill). Sakti *et al.* (1991) have provided information on the rate of penetration of HDPE geomembrane liners by a variety of dilute aqueous solutions of organic solvents. Common organic solvents that are often disposed of as wastes in landfills can quickly pass through an HDPE liner. This is of particular importance since these chemicals are significant threats to groundwater pollution through their high mobility, persistence and potential to cause cancer in those using domestic water supplies containing these solvents.

Attenuation of Chemical Pollutants in Leachate

In making the estimate of the plausible worst-case (fastest) travel time between when the landfill liner containment system fails and off-site groundwater pollution occurs, consideration should be given to estimating the amount of attenuation based on the dilution and dispersion that could occur in the geological strata in the transport from the landfill to a potential off-site well. If there are no wells currently located near the landfill-adjacent property owner property line, it should be assumed for the risk assessment that an adjacent property owner at some time in the future should have the right to construct a well near the property line that would be able to pump groundwaters that are free of landfill leachate. This issue is not just having the few regulated chemicals currently regulated by RCRA Subtitle C and D at concentrations below drinking water MCLs. Because of the health hazards of the non-regulated chemicals and the frequent finding of additional chemicals that need to be regulated associated with municipal and industrial wastes (non-conventional pollutants), the groundwaters at the adjacent property line should be free of all constituents present in municipal solid waste (MSW) leachate independent of whether their concentration exceeds a current drinking water MCL.

It is important not to assume any adsorption, biological transformations and chemical reactions as part of this attenuation since they are likely to be small for a variety of constituents in the landfill leachate that could be adverse to water supply interests. For these types of chemicals, the only mechanism for decreasing the concentration of leachate-derived pollutants with travel distance that should be assumed to be important are dilution and dispersion.

An important issue that should be addressed as part of evaluating the potential for leachate leakage from a landfill to pollute the groundwaters is the expected concentration of leachate-derived constituents in these groundwaters. Since the groundwaters in the vicinity of a landfill are derived to a considerable extent from upgradient sources, there will be a mixing-dilution process that occurs between any leachate-polluted groundwater arising from the landfill and the groundwater in the vicinity of the landfill that ultimately will be transported off-site. Landfill applicants/owners should estimate the worst-case concentrations of leachate-polluted groundwaters that could arise within the vicinity of the landfill that would be transported off-site. These would be the initial concentrations of constituents that could, through off-site transport, pollute downgradient wells.

One of the issues of concern is the level of knowledge in the literature about dilution and dispersion in fractured rock and limestone systems. This is an area that needs to be better understood. If it can be reliably concluded that during the transport from the landfill to the off-site area that sufficient dilution and dispersion of the constituents in the landfill leachate would occur to reduce the concentrations below any critical levels, then the likelihood of the landfill being adverse to downgradient wells would be small. In making this assessment, typical leachate concentrations of hazardous and deleterious chemicals should be assumed to occur in leachate at the landfill. Further, it should be assumed that a critical concentration of 0.01 μg/L is appropriate for the unregulated, potentially hazardous organics that are present in landfill leachate. From this critical concentration it would be possible to back-calculate to the landfill using the estimated dilution and dispersion to determine what concentrations of unregulated hazardous chemicals could be present in the leachate and still not be hazardous to public health.

It is important to understand that most landfill leachate, whether hazardous or non-hazardous, has hundreds to thousands of mg/L of total organic carbon whose characteristics and therefore health hazards are unknown and which could contain yet unrecognized or unregulated hazardous chemicals. Today about 70,000 chemicals are used in the US; only about 200 of these are regulated. There is, therefore, a wide arena of potentially hazardous chemicals that could be present in industrial and municipal landfill leachate that represents a threat to groundwater quality and public health. Any credible review of the potential of a landfill to pollute groundwaters must consider the potential for the unregulated chemicals in the wastes to be adverse to those who use the groundwater for domestic or other purposes.

Groundwater Water Quality Monitoring

One of the issues that must be addressed in connection with assessing the hazard that a landfill represents to groundwater quality is the ability of a groundwater monitoring system to detect pollution of groundwaters by landfill leachate before widespread pollution occurs. While landfill owners/operators often assert that a groundwater monitoring system would be established to detect leachate-polluted groundwaters if the landfill containment system fails, landfill owners typically provide little or no information on the reliability of the groundwater monitoring systems proposed to detect leachate-polluted groundwaters before widespread pollution occurs. Landfill owners/operators should be required to provide detailed information on the ability of the groundwater monitoring system in place and/or proposed to reliably detect leachate-polluted groundwater at the point of compliance for groundwater quality protection.

Cherry (1990) and Lee and Jones-Lee (1994) have discussed the highly unreliable nature of Subtitle C and D landfill monitoring programs which involve the use of vertical monitoring wells located at the point of compliance at or just groundwater downgradient of the edge of the landfill waste deposition area to detect leachate-polluted groundwaters before widespread pollution occurs. These monitoring wells are often spaced hundreds to a thousand or so feet apart. Each well has a zone of capture of a radius of about one foot. As Cherry (1990) points out, the initial leakage of landfill leachate from plastic sheeting-lined landfills will produce finger-like plumes of leachate of a few feet in width at the point of compliance. This means that today's RCRA landfill groundwater monitoring systems have a very low probability of detecting leachate-polluted groundwaters before widespread pollution occurs. The landfill owner/operator, as part of evaluating the potential of a landfill to pollute off-site groundwaters, should be required to estimate how reliably their groundwater monitoring system could detect leakage of leachate through the liners near the downgradient edge of the landfill, i.e. plausible worst-case liner failure scenario.

It is well-known that groundwater monitoring in fractured rock is virtually impossible to carry out reliably. The basic problem is that the flow occurs through fractures-cracks in the rock. This means that monitoring wells spaced even a few feet apart may not be able to detect leachate transport through the bedrock unless they happen to intercept the fracture(s) that are principally responsible for leachate transport. Haitjema (1991) characterizes monitoring groundwaters for leachate leakage in fractured rock systems near landfills as,

> *"Monitoring wells in the regional aquifer* [consisting of fractured rock] *are unreliable detectors of local leaks in a landfill."*
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> * * *
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> *"The design of monitoring well systems in such an environment is a nightmare and usually not more than a blind gamble."*

Great caution must be exercised in permitting landfills sited within or above complex geological strata where the hydrogeology of the region is not adequately defined to be able to predict with a high degree of certainty the ability of a groundwater monitoring well(s) to detect leachate pollution of groundwaters at the point of compliance before passage of this leachate beyond this point occurs.

Production Well Water Quality Monitoring

Because of the fundamental inherent unreliability of groundwater monitoring systems for lined landfills, additional monitoring is mandatory in order to protect the health, welfare and interests of those potentially impacted by the pollution of groundwaters by landfill leachate. Such an approach could involve the landfill owner committing to monitor production wells within the potential sphere of influence of the polluted groundwaters that could be developed under plausible leakage conditions associated with the development of the landfill. A production well is defined as any well that is used by a property owner as a water supply source for any purpose. This monitoring program would be designed to detect incipient (initial) contamination by leachate-derived constituents before significant harm is done. It would need to be carried out effectively forever where on a quarterly basis, samples would be taken of all existing and any future developed off-site production wells and analyzed for constituents that would indicate that landfill leachate is being found in the well at low concentrations.

Typical municipal solid waste and industrial hazardous and non-hazardous waste leachates have a characteristic signature (chemical composition) for a group of conservative (non-reactive) chemicals that can be used to indicate when leachate first begins to contaminate a well. Lee and Jones (1983) in their discussion on groundwater monitoring point to the importance of utilizing changes in concentrations of conservative chemicals as an indicator of incipient groundwater pollution. As a result of appropriately conducted chemical analyses of groundwater, it is possible to detect when leachate contamination of groundwater first begins to occur before significant harm is done to the users of the groundwater. At that point, the use of the groundwater can be terminated provided that an alternative water supply is available to meet the needs of the well owner.

When sufficient data have been collected from the quarterly monitoring of production wells so that small changes in water quality can be reliably detected, the frequency of monitoring could be reduced to semi-annually and then possibly, annually. However, the development and implementation of this program will require a much more sophisticated approach toward groundwater monitoring than is typically done in monitoring groundwaters for landfill leachate pollution. Such a program should be carried out by experts and should be conducted by a third-party independent consultant who would report the results to a citizens advisory committee overseeing the landfill operations and impacts. The funding of this monitoring program should be provided by the landfill owner where there is *ad infinitum* assured funding.

The potential worst-case sphere of influence would be judged by the shortest possible time that leachate-polluted groundwaters could travel from the landfill to the location of a production well. Once, the projected worst-case plume could have possibly passed the location of a production well, then the monitoring of that well would be initiated and continued *ad infinitum*.

Liner Leakage in Double Composite Lined Landfills

Lee and Jones-Lee (1994) have discussed an alternative approach for monitoring liner leakage for double composite lined landfills than vertical monitoring wells at the point of compliance. This approach is patterned after the state of Michigan's Rule 641 monitoring where for double composite lined landfills the lower composite liner serves as a leak detection system for the upper composite liner. When leachate is found in the leak detection system between the two composite liners at sufficient concentrations to pollute the groundwaters underlying the landfill if the lower composite liner were not present, then the upper composite liner should be judged as having failed. Under these conditions, it is only a matter of time until the lower composite liner fails, if it has not already failed, and groundwater pollution occurs or will soon occur.

It is important to point out that typically landfill permitting agencies today allow liner leakage rates for upper composite liners well above those that could cause significant groundwater pollution if the lower composite liner were not present. Often, liner action leakage rates are based on what can be achieved with plastic sheeting and compacted clay liners rather than what is needed to protect groundwaters from pollution by landfill leachate. At some sites, leakage of leachate through a composite liner at a rate of more than a few gallons per acre per day is sufficient so that, in time, groundwater pollution will occur when the lower composite liner and the associated leak detection system between the two composite liners are no longer effective in collecting leachate that leaks through the upper composite liner. The landfill owner/operator should be required to conduct a plausible worst-case scenario evaluation of the liner action leakage rate that should be allowed at a particular landfill in order to protect groundwaters from leachate pollution associated with the eventual failure of the lower composite liner in a double composite lined system.

Lee and Jones-Lee (1995a, 1996c) have provided information on how municipal solid waste and hazardous waste landfills can be developed to provide for true protection of public health, groundwater resources, the environment and the interests of those within the sphere of influence of the landfill. As they discuss, when the upper composite liner fails to prevent leachate from passing through it, the landfill owner/operator must then take corrective action which will stop leachate generation, such as the installation and/or maintenance of a leak detectable cover on the landfill and, if necessary, exhumation of the wastes. A key component of this suggested approach for monitoring liner leakage is the availability of sufficient funds to operate and maintain a leak detectable cover for as long as the wastes in the landfill will be a threat, i.e. effectively forever, as well as to exhume the wastes if leachate leakage through the upper composite liner cannot be stopped.

With respect to maintaining the integrity of the landfill cover, the landfill owner should define how they will detect areas of the cover where moisture could pass through the cover and generate leachate within the landfill, how the repairs will be made, cost of such repairs and the sources of funds needed to detect and make these repairs for as long as the wastes in the landfill represent a threat. Lee and Jones-Lee (1994) report that the only reliable approach to ensure that adequate funding will, in fact, be available for landfill cover leak detection operation and maintenance when needed is to require that the owner/operator of the landfill develop a dedicated trust fund of sufficient magnitude to provide for *ad infinitum* landfill cover maintenance and, if necessary, waste exhumation, treatment and management.

Commitment to Provide Alternative Water Supply Sources

Because of the high probability of the pollution of groundwaters by landfill leachate from today's "dry tomb" landfills, the landfill owner should commit to a program of providing the funds necessary to provide alternative water supplies to those potentially impacted by leachate-polluted groundwater for as long as the wastes in the landfill, and any polluted groundwaters that could develop from it, represent a threat. For planning purposes, it should be assumed that this period of time is forever. A well-defined program for the development of alternative water supplies for those potentially impacted by the landfill should be formulated with the development of the landfill or its continued operation. Of key importance is the source of the funds that will be available *ad infinitum* to implement this alternative water supply program. This source should be discussed and evaluated with respect to its reliability as part of the permitting of the landfill.

Evaluate Possible Remediation Approaches

While the pollution of groundwaters by landfill leachate can never be assumed to be completely remediable where the once- polluted groundwater "after remediation" would be considered "safe" for human consumption, it is possible to provide high degrees of treatment of leachate-polluted groundwaters so that these waters may be used for a variety of purposes. Landfill owners should discuss in detail the remediation approaches that could, and would if necessary, be implemented should an off-site production well be found to be threatened or contaminated by landfill-derived leachate.

The primary purpose of groundwater remediation would be to stop the spread of leachate-polluted groundwaters. The remediation program should be conducted at two locations: near the polluted production well as well as near the landfill. The latter should be designed to stop the off-site transport of leachate-polluted groundwaters. The landfill owner should define as part of permitting the landfill how they would proceed to accomplish groundwater quality remediation in both areas. Particular attention should be given to how such remediation would be funded at any time in the future when the wastes in the landfill could be a threat to pollute groundwaters.

Further, if it should develop that it proves to be difficult, if not impossible, to stop the landfill-derived off-site transport of leachate-polluted groundwaters, then the landfill owner should be required to exhume-mine the wastes in the landfill as a possible remediation activity that eliminates the landfill as a future source of polluted groundwater. Landfill mining is now being accomplished at a number of locations in the US. One of the purposes of such mining is the stopping of further groundwater pollution by the landfill.

Funding of Groundwater Quality Protection

The magnitude of the funding for landfill cover leak detection operation and maintenance, alternative water supplies for leachate-polluted groundwaters and plausible worst-case remediation programs for contaminated groundwaters near production wells and near the landfill as well as waste exhumation should be defined, and a dedicated trust fund of sufficient magnitude to address all plausible worst-case scenario situations should be established by the landfill owner at the time of the permitting of the landfill. It is important to note that while current regulatory approaches allow other financial instruments to be used to fund post-closure landfill monitoring and maintenance. As discussed by Hickman (1992, 1995), the financial arrangements not involving a dedicated trust are often unreliable and should not be used.

This trust fund would be paid for by the people/firms who generate the wastes as part of landfill disposal fees. This fund should be established for an infinite period of time. If, at some time in the future, hundreds to a thousand or more years after landfill closure it is found that the landfill no longer represents a threat to cause groundwater pollution and no pollution of the unsaturated zone as well as the groundwaters has occurred, then it would be possible to return these funds those in the area who generated the fund.

Resolution of Conflict Between Experts

One of the issues associated with the development of landfills and in conducting a risk assessment for the potential for an existing or proposed landfill to pollute groundwaters at any time in the future while the wastes in the landfill represent a threat is a conflict between technical experts on groundwater pollution issues. Frequently, non-expert public groups responsible for formulating policy face trying to determine which experts' presentation of information is most reliable. Far too often, decisions of this type are based on a non-technical assessment, such as the demeanor of the expert, rather than a critical in-depth review of technical issues.

This is an issue that has been of concern to the authors for a number of years. The American Society of Civil Engineers has published a review of this issue developed by the authors (Lee and Jones-Lee, 1995b) entitled, "Environmental Ethics: The Whole Truth." This article is based on a report that the authors developed entitled, "Practical Environmental Ethics: Is There an Obligation to Tell the Whole Truth?"

In the authors' discussions of this issue, they have recommended that should a situation develop where disputes occur between experts in a topic area that the dispute should be resolved by a panel of experts who require that each of the opposing experts presents the technical basis for their position on an issue in a full peer-review arena where all information in support of an expert's opinion is available for review by the panel and the public. The panel of experts would then recommend to the public body responsible for formulating a decision on an issue the appropriateness of each of the opposing experts' positions on the issue in dispute. This peer review process would be paid for by the landfill applicant.

The burden of proof for demonstrating the safety of a landfill should be on the landfill applicant. In those situations where there is a lack of adequate information to properly define the risk of a landfill, the landfill applicant must obtain the needed information before further consideration of permitting the landfill can be conducted.

Adoption of this approach can lead to a better resolution of the "whole truth" concerning the potential of a landfill to pollute groundwaters in a region by landfill leachate for as long as the landfill will be a threat to groundwater pollution.

Summary of Issues in the Characterization of the Risk of a Landfill to Pollute Groundwaters

The landfill permit applicant as part of permitting the landfill and its continued operation-expansion should be required to conduct a comprehensive, in-depth risk assessment of the potential of the landfill to pollute groundwaters associated with the landfill with landfill leachate-derived constituents and landfill gas for as long as the wastes in the landfill will be a threat. This risk assessment should include the following components:

- It should not be assumed that the only chemicals of concern in landfill leachate are the small number of regulated hazardous chemicals currently considered by US EPA RCRA Subtitle C and D. All chemicals and pathogenic organisms present in the landfill that could potentially adversely impact the beneficial uses of a groundwater for domestic or other purposes should be evaluated.

- It should be assumed that the waste in a "dry tomb" type landfill will be a threat to groundwater quality, effectively forever.

- It should be assumed that the groundwaters of concern for pollution by landfill leachate are the groundwaters that exist at the point of compliance for groundwater monitoring and at the landfill-adjacent property owner's property line.

- It should be assumed that the landfill containment system consisting of a landfill cover and a single or double composite liner will eventually fail to prevent leachate from passing through it that could pollute groundwaters hydraulically connected to the landfill.

- The landfill permit applicant should be required to reliably estimate the potential contaminating lifespan of the landfill, i.e. how long the wastes in the landfill will be a threat to cause impairment of the uses of the groundwater.

- The landfill permit applicant should be required to estimate the composition of leachate that could be developed in the landfill considering all constituents in the wastes that represent a threat to groundwater quality from any perspective, including regulated hazardous chemicals, unregulated hazardous chemicals, conventional pollutants and all other constituents that could be detrimental to the use of a groundwater for domestic or other purposes, including those that represent economic burdens to groundwater users.

- The landfill permit applicant should be required to provide a detailed discussion of the potential adverse impacts of each of the constituents potentially present in the landfill leachate on the use of the groundwaters for domestic water supply or other purposes.

- The landfill permit applicant should be required to estimate the expected service life of the landfill cover, liner system and leachate collection and removal system. With respect to maintaining the integrity of the landfill cover in order to prevent leachate generation, the landfill permit applicant should define how they will detect areas of the cover where moisture could pass through the cover and generate leachate within the landfill, how the repairs will be made, the cost of such repairs and the sources of funds needed to detect and make these repairs for as long as the wastes in the landfill represent a threat.

- The landfill permit applicant should estimate the amount of permeation of dilute solutions of organic solvents that could occur through the intact landfill liner and the potential consequence of the permeated solvents on groundwater quality.

- The landfill permit applicant should be required to evaluate the potential for gas phase transport of hazardous and deleterious chemicals that can lead to groundwater pollution as part of permitting the landfill. The magnitude of this pollution should be estimated as well as information should be provided on how gas phase transport of VOCs would be detected and controlled.

- The landfill permit applicant should develop a plausible worst-case scenario evaluation of how long it would take for leachate-polluted groundwaters arising at the landfill to reach adjacent groundwaters and wells of importance to adjacent and nearby property owners and users.

- If natural strata and dilution and dispersion are to play any significant role in protecting off-site groundwaters from pollution by landfill leachate, the landfill applicant should be required to reliably define, using worst-case scenario evaluation approaches, the magnitude of protection provided by the natural strata, dilution, dispersion and any other attenuation mechanism that is thought to be potentially important in reducing the concentrations of constituents in landfill leachate that passes through the liner system at the point of groundwater monitoring compliance and at the point where a production well could be constructed at any time in the future on adjacent property owners' lands.

- The landfill permit applicant should be required to provide detailed information on the ability of the groundwater monitoring system in place and/or proposed to reliably detect leachate-polluted groundwater at the point of compliance for groundwater quality protection. This estimate should be based on a plausible worst-case liner failure scenario in which failure of the liner occurs near the downgradient edge of the waste deposition area.

- The landfill permit applicant should be required to fund an off-site production well incipient groundwater pollution detection program that would be active for as long as the wastes in the landfill would be a threat. The details of this program should be provided and the source of funds needed to carry out this program for as long as the wastes in the landfill represent a threat should be defined.

- The landfill permit applicant should be required to conduct a plausible worst-case scenario evaluation of the liner action leakage rate that should be allowed at the proposed landfill or landfill expansion in order to protect groundwaters from leachate pollution associated with the eventual failure of the lower composite liner in a double composite lined system.

- The landfill permit applicant should commit to a program of providing the funds necessary to provide alternative water supplies to those potentially impacted by leachate-polluted groundwater for as long as the wastes in the landfill, and any polluted groundwaters that could develop from it, represent a threat. The details on how this program would be implemented and the sources of funding that will be used for the implementation should be defined for as long as the wastes in the landfill represent a threat.

- The landfill permit applicant should commit to conducting groundwater remediation should pollution of groundwaters be found at any time in the future. The details of the remediation approaches, magnitude of funding needed and the source of the funds that would be used to develop the groundwater remediation program should be provided.

- The landfill permit applicant should define the magnitude of the funding needed for landfill cover leak detection operation and maintenance, alternative water supplies for leachate-polluted groundwaters and plausible worst-case remediation programs for contaminated groundwaters near off-site production wells and near the landfill as well as waste exhumation. If an alternative financial instrument to a dedicated trust fund is proposed, the reliability of this financial instrument should be evaluated by the landfill permit applicant considering the time that the wastes in the landfill will be a threat. For planning purposes, this period of time should be considered to be infinite.

- The landfill permit applicant should develop a public peer review approach for resolution of any disputes among qualified experts on issues associated with assessing the potential for the proposed landfill or landfill expansion to pollute groundwaters for as long as the wastes in the landfill represent a threat. The landfill permit applicant should discuss the amount of funds that they will make available for proper independent peer review of technical issues associated with landfill development.

Summary

Today the permitting of landfills and landfill expansions typically does not lead to a credible review of the potential for a landfill to pollute the groundwaters with landfill leachate for as long as the wastes in the landfill will represent a threat. Frequently, landfill applicants assert as part of permitting a landfill and/or its continued operations that the landfill location, design, operation, closure and post-closure care meet the regulatory requirements of Subtitle C or D, dependent on the type of the landfill. However, they do not discuss the fact that US EPA RCRA Subtitle C and D landfills using plastic sheeting and clay composite liners will eventually fail to prevent leachate from migrating through them and, at best, will only postpone when groundwater pollution occurs. Current RCRA landfilling regulations are badly out-of-date and are largely based on an early 1980s understanding of the ability of plastic sheeting and compacted clay liners to prevent leachate from passing through them and thereby polluting groundwaters in the vicinity of the landfill. As discussed by Lee and Jones-Lee (1996d), there is an urgent need to revise RCRA so that the highly significant deficiencies in today's Subtitle C and D landfilling approaches are eliminated.

With few exceptions, today's "dry tomb" landfills will represent a threat to the groundwater resources within a region, effectively, forever. A properly conducted risk-hazard assessment of the type described herein would provide a technical base of information that would enable the public, regulatory agencies and the landfill owner/operator to evaluate the potential that a landfill has to pollute groundwaters in the vicinity of the landfill for as long as the wastes in the landfill represent a threat. It is urged that all permitting of landfills require that the landfill applicant conduct this type of review and present the information in sufficient detail so that it can be subjected to a public peer review of the issues of concern. Adopting this approach will enable the development of appropriate landfill regulations and landfill design, operation, closure and post-closure care to truly protect the groundwaters hydraulically connected to a landfill from pollution by landfill leachate for as long as the wastes in the landfill represent a threat.

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