Evaluation of the Adequacy of Hazardous Chemical Site Remediation by Landfilling[1]

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Abstract

Ultimately, hundreds of billions of dollars of public and private funds will be spent in the US in hazardous chemical site (Superfund and closed RCRA facilities) investigation and remediation. A critical review of the adequacy of remediation of many of these sites that are closed in accord with RCRA and/or CERCLA requirements as being interpreted by regulatory agency staff/boards and principle responsible parties (PRPs) and their consultants shows that the residues of hazardous and deleterious chemicals left at the site after current required remediation represent significant long-term threats to public health, groundwater quality, the environment, and those that live on or use properties within the sphere of influence of the remediated site. A major fundamental problem with current hazardous chemical site investigation/remediation is that the long-term threats of residual chemical constituents left at the site after remediation is not adequately or reliably evaluated and managed. This situation will mean that many closed hazardous chemical sites will have to be re-remediated at some time in the future under conditions where there is inadequate funding available to adequately investigate and remediate the site. This chapter reviews some of the longer-term issues that need to be evaluated as part of determining the adequacy of hazardous chemical site investigation and remediation relative to evaluating the long-term threats that remediated site residual chemical constituents represent a threat to public health and the environment.

The deficiencies in the use of on-site or off-site landfills that meet current interpretation of RCRA Subtitle C and D requirements for site remediation is the major area addressed in this chapter. Today s RCRA Subtitle C and D landfills, with a single or double composite liner and vertical groundwater monitoring wells spaced hundreds to a thousand or more feet apart at the point of compliance for groundwater monitoring, at best only postpone when off-site groundwater pollution will occur. The composite liner and cover systems used in RCRA Subtitle C and D landfills have a limited finite period of time compared to the time that the waste residues will be a threat during which the containment system components can be expected to function effectively to prevent groundwater pollution by landfill waste residues. The groundwater monitoring systems allowed at today s Subtitle C and D landfills have a low probability of detecting groundwater pollution by landfill leachate before off-site pollution occurs. Basically, today s Subtitle C and D landfills represent a fundamentally flawed approach for managing hazardous and/or deleterious waste chemicals that only postpones when there will be need for re-remediation of the hazardous chemical site.

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Introduction

Hundreds of millions to ultimately billions of dollars are being spent across the country in Superfund and Resources Conservation and Recovery Act (RCRA) hazardous chemical site investigation and remediation. In the past few years, there has been a considerable emphasis on re-developing so-called brownfield properties as part of this effort. This redevelopment will result in the public and/or the environment being exposed to hazardous/deleterious chemicals left at the site as part of site remediation/closure. While initially in the Superfund program the primary focus of remediation was cleanup to background, today the emphasis is changing to the use of remediation technologies that leave waste residues at the hazardous chemical site. In general, it is being assumed that an on-site waste management area that is covered with a landfill cover that meets minimum RCRA specifications, on-site RCRA landfills, solidified waste residues, naturally attenuated groundwater pollution plumes and other on-site remediation technologies that leave appreciable quantities of hazardous or deleterious chemicals at the site upon site closure will, after a 30-year period, require no further monitoring and/or maintenance of the waste residues left at the site. However, a critical review of the adequacy of such remediation technology shows that in many instances the residues will be a threat to public health and the environment for a long, if not infinite, period of time.

Typically, some type of use-deed restrictions are placed on future uses of the remediated property which presents at least a superficial appearance that future users of the property and nearby properties will not experience problems due to the waste residues present at the site upon closure. The adequate implementation of the use-deed restrictions, however, by public agencies and future property owner/users is tenuous at best. At this time, as part of closure of a hazardous chemical site, inadequate attention is being given to ensuring that the PRPs, as well as any new owners or users of the remediated hazardous chemical site property, will adequately monitor and maintain the waste residues left at the site upon closure for as long as the waste components represent a threat to public health, groundwater resources and/or the environment.

This chapter reviews a number of the issues that need to be addressed in evaluating the adequacy of hazardous chemical site remediation relative to long-term liabilities and potential public health and environmental impacts associated with residual waste/chemical components left at the closed site. Particular attention is given to:

- the adequacy of using RCRA landfill-type covers to reduce infiltration of moisture into the waste that leads to the transport of pollutants to the underlying groundwater system,
- the adequacy of US EPA Subtitle D and C RCRA landfills in protecting groundwaters from pollution by landfill leachate for as long as the residual wastes at the site will be a threat,

the adequacy of current waste characterization procedures in determining the potential for residual waste components to endanger public health, groundwater resources and the environment for as long as the waste residues at the site will be a threat,

the potential problems with the use of natural attenuation as an approach for remediating contaminated groundwaters, and

the issues that need to be addressed in the redevelopment of brownfield properties to protect public health, the environment, groundwater resources and the financial interests of the property redevelopers/purchasers/users.

While the discussion of examples of problem areas given are presented in a generic form, they are based on the authors experience on these topics and the literature.

Liability for Site Clean-up

One of the commonly made statements by PRPs for hazardous chemical sites, such as areas where chemicals have been inadequately - improperly stored or were inappropriately managed through landfilling or waste disposal ponds, is that those who deposited chemicals or wastes in these areas were following regulatory requirements of the time when the environmental contamination first occurred. The implication is that they should not be responsible for having to clean up the contaminated soils or groundwaters since they met regulatory requirements. A critical review on what was known or should have been known by PRPs about the potential hazards associated with depositing wastes on the ground, in lagoons or in sanitary landfills shows that, since the 1950s, there is substantial literature demonstrating that the management of chemical wastes by means that now lead to inadequately closed RCRA sites and/or Superfund sites would lead to groundwater pollution. The issue often becomes one of whether the PRPs knowingly manage hazardous chemicals and hazardous chemical wastes in accord with both regulatory and appropriate professional expertise that was available at the time that the hazardous chemicals/wastes were deposited at the location that ultimately led to the hazardous chemical site that requires remediation.

Adequacy of Regulations Relative to Protecting Public Health and the Environment

Those familiar with how regulatory agencies develop regulations relative to protection of public health and the environment know that, with few exceptions, the adoption and appropriate implementation of regulations lags behind the professional recognition of the need for regulations by often decades or more. This situation has existed throughout time, where usually the only way that regulations are adopted is through the occurrence of a major crisis. An example of this kind of situation is the regulation of waterborne pathogens in domestic water supplies. It has been well known in the professional literature since the mid-1980s that the current treatment of domestic water supplies for consumption has been inadequate to prevent significant human disease and deaths associated with the consumption of treated water that meets water supply public health standards. It took a Milwaukee *Cryptosporidium* outbreak, where 400,000 people became ill and 100 people died, to get the national and state regulatory agencies to begin to meaningfully address what was a well-known problem by those familiar with the topic area well before the Milwaukee incident occurred.

In the mid-1980s, the Center for Disease Control published information which indicated that approximately 1,000 people per year in the US die from consuming what is accepted as adequately-treated domestic water supplies. Millions of US residents become ill every year because of inadequately disinfection of water supplies that meet the fecal coliform standard. This is not the situation where there is inadequate treatment, but one of inadequate technical procedures and incorporation of basic information into the regulatory process. It has been known since the 1940s that the approach that is used for evaluating the sanitary quality of domestic water supplies was inadequate for enteroviruses and parasitic protozoan cyst-forming organisms, such as *Cryptosporidium*. The fecal coliform standard that has been and continues to be used was known since the 1940s work of a number of individuals, principally Dr. Chang at Harvard University, to be inadequate for determining the safety of a water that contains protozoan cyst-forming parasitic organisms such as those that cause amoebic dysentery, *Cryptosporidosis*, and giardiosis. These and other disease-causing organisms of this type are not killed by conventional water supply or wastewater chlorination practices. The conventional domestic water supply and wastewater treatment/chlorination are designed primarily for the control of organisms that respond to disinfection like fecal coliforms, such as the salmonella-type organisms that cause bacterial enteric diseases. Even today, while it is now well-known that the fecal coliform standard is inadequate to protect domestic water supply consumers from disease, the regulatory agencies at the federal and state level have still not established monitoring programs for enteroviruses and protozoan parasites as part of the routine monitoring of the safety of a treated domestic water supply.

Lee and Jones [1,2,3] have discussed how inadequate development and implementation of regulations that are being used as requirements for remediation for hazardous chemical sites create conditions where inadequate long-term protection of public health and/or the environment is occurring. The major problems that exist are associated with failure to establish well-defined, appropriately funded evaluations of the adequacy of site remediation and monitoring relative to existing and new information that develops on the potential hazards of residual chemicals left at the site as part of remediation. This situation will cause many so-called remediated Superfund/RCRA sites to require additional remediation at some time in the future. Because of inadequate long-term funding to address these issues, it is likely that both the public and the environment will be unnecessarily exposed to hazardous or deleterious conditions associated with current remediation approaches for hazardous chemical sites.

Inadequate Approaches for Landfilling of Wastes

The regulation of chemicals in waste with respect to the potential to pollute groundwaters has been and continues to be woefully inadequate. Beginning in the 1950s, there were a number of reports in the professional literature about groundwater pollution by various types of wastewater lagoons, sanitary landfills and other areas where hazardous or deleterious chemicals or wastes are located. In 1959 the American Society of Civil Engineers [4], issued a landfill design manual which discussed the potential for sanitary landfill waste to pollute groundwaters with waste-derived constituents. It was known by many professionals in the 1950s that the approach that was being used for managing industrial and municipal solid wastes could readily lead to groundwater pollution rendering the groundwaters unusable for domestic purposes. This situation was not begun to be addressed, however, until the mid-1970s with the passage of the Resource Conservation Recovery Act (RCRA). Even today, the US EPA and state regulatory agencies are still allowing the development of municipal and industrial so-called non-hazardous and hazardous waste landfills that, at best, will only postpone for a short period of time compared to the time that the wastes in the landfill will be a threat when groundwater pollution occurs.

Lee and Jones-Lee [5] have recently summarized the significant technical problems associated with today s minimum Subtitle D landfills in protecting groundwaters from pollution by landfill leachate for as long as the wastes in the landfill will be a threat. Basically, a minimum Subtitle D dry tomb type landfill which uses a single composite liner consisting of a 60 mil HDPE plastic sheeting layer in contact with two feet of compacted clay with a permeability at the time of development of less than 1 x 10^{-7} cm/sec will prevent groundwater pollution for a small period of time relative to the time that the waste in the landfill will be a threat. The landfill liner system allowed in Subtitle D landfills will be a significant barrier to leachate passing through the liner into the underlying groundwater system for those landfills hydraulically connected to usable groundwaters for a short period of time relative to the time the waste in the landfill will be a threat. The HDPE liner, if it is properly constructed and there are no holes punched into it at the time of waste deposition, will be effective in collecting leachate generated in the wastes through infiltration of precipitation until the HDPE begins to disintegrate. While no one can reliably predict how long HDPE layers of the type being used in municipal landfills will last, it is certain that they will not be effective barriers for leachate migration through them, for as long as the wastes in the landfill will be a threat.

Eventually, through breakdown of the polymeric HDPE, the leachate will come in contact with the underlying clay layer and start to pass through it. If the original 1 x 10^{-7} cm/sec permeability still exists at that time, then the leachate will pass through this layer in about 25 years. There are, however, a wide variety of well-known mechanisms for the permeability of the clay layer to increase significantly over time, the most important of which are desiccation cracks [5,6]. Clay layers are compacted with a certain optimum moisture content. Over time, the moisture will migrate out of the clay, causing the permeability to increase significantly, likely leading to cracking. Therefore, holes that develop in the HDPE layer, if they intersect cracks in the clay layer, could result in quite rapid transport of large amounts of leachate through the liner system into the underlying groundwater system.

Another current example of inadequate regulation implementation that has applicability to some of the technologies that are used to remediate/close hazardous chemical sites occurs with the monitoring of liner leakage from solid waste landfills. In 1988 the US EPA [7], in its promulgation of Subtitle D municipal solid waste regulations, 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 Criteria for Municipal Solid Waste Landfills released in July 1988 [8] 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.

The information available today, 10 years later, strongly supports the US EPA s position of the inevitable failure of the landfill liner system.

The Agency, however, in promulgating the final version of Subtitle D regulations in 1991 [9] established groundwater monitoring requirements that stipulate that,

The design must ensure that the concentration values listed in Table 1 of this section not be exceeded in the uppermost aquifer at the relevant point of compliance…

and specify that,

(a)A ground-water monitoring system must be installed that consists of a sufficient number of wells, installed at appropriate locations and depths, to yield ground-water samples from the uppermost aquifer (as defined in §258.2) that: (2)Represent the quality of ground water passing the relevant point of compliance…

(c) The sampling procedures and frequency must be protective of human health and the environment.

In support of this requirement, the Agency required a three-phase monitoring program which consisted of detection monitoring where groundwater monitoring wells are to be placed at the point of compliance for the monitoring of the landfill in sufficient number and characteristics to detect leachate-polluted groundwaters in order to protect human health and the environment.

When leachate is detected by the monitoring wells, the landfill owner/operator is required to determine the extent of groundwater pollution that has occurred. This requires a site-specific investigation where a number of additional monitoring wells are constructed to determine the characteristics of the pollution plume. After defining the magnitude of the pollution plume, then the Subtitle D regulations require that the pollution be cleaned up to the extent possible, typically through a pump and treat operation, where the polluted groundwaters are pumped to the surface and treated before discharge to surface waters or reinjected into the groundwater system. Verification monitoring is required to confirm that the pollution has been cleaned up and that no further pollution occurs.

While in principle, the Subtitle D groundwater monitoring system and the associated remediation requirements should be effective in preventing off-site groundwater pollution by landfill leachate, in practice as being implemented today in many states across the US, the Subtitle D monitoring system has a low probability of detecting groundwater pollution at the point of compliance for groundwater monitoring before significant off-site/adjacent property groundwater pollution occurs. Subtitle D landfill siting requirements do not preclude placing a Subtitle D landfill immediately next to the adjacent property owner s property line. The monitoring requirements established that the point of compliance for groundwater monitoring shall be no more than 150 meters from the downgradient edge of the waste management unit, i.e. where wastes are deposited, and must be on the landfill owner s property. For many landfills, there is a few hundred yards of bufferlands between the edge of the landfill and adjacent properties. This means that within a short time, once the leachate plumes pass the point of compliance, the polluted groundwaters will be trespassing under adjacent properties.

Lee and Jones-Lee [10] have recently reviewed the 1990 work of Cherry [11] and others on the adequacy of monitoring groundwater pollution at lined landfills. They point out that the work of Cherry discusses the unreliability of the typical groundwater monitoring systems that are being used for lined landfills. Figure 1 adopted from Cherry [11] shows the situation that will typically occur where the initial leakage through the flexible membrane liner and underlying clay layer will produce finger-like plumes of leachate which can be a few meters in width at the point of compliance for groundwater monitoring. Typically, groundwater monitoring wells are located hundreds to a thousand or so feet apart at the point of compliance. This means that a three-meter wide plume at the point of compliance has a low probability of being detected by typical groundwater monitoring wells since each well has a zone of capture of about one foot associated with the sampling event.

Basically, today s groundwater monitoring systems for Subtitle D and C landfills evolved from the groundwater monitoring systems that were used for unlined landfills which leaked leachate into the underlying groundwaters across the entire bottom of the landfill. For that type of landfill, it was relatively easy to locate monitoring wells that would readily detect leachate-polluted groundwaters. However, with lined landfills, where the initial leakage would be through holes, rips, tears, points of deterioration of the liner which produce finger-like plumes of leachate of limited lateral dimensions at the point of development and limited lateral spread along the groundwater flow path downgradient from the landfill, the monitoring systems for unlined landfills is highly unreliable for detecting leachate-polluted groundwaters before widespread off-site pollution occurs.

In order for today s Subtitle D landfills to be effectively monitored to comply with Subtitle D regulations for detecting leachate-polluted groundwaters for many types of geological formations, groundwater monitoring wells would have to be placed about 10 feet apart. There are some types of geological formations, such as fractured rock, cavernous limestone, where groundwater monitoring by vertical monitoring wells at the point of compliance is highly unreliable. Haitjema [12] states,

> *An extreme example of Equation (I) (aquifer heterogeneity) is flow through fractured rock. The design of monitoring well systems in such an environment is a nightmare and usually not more than a blind gamble.*
>
> *Monitoring wells in the regional aquifer are unreliable detectors of local leaks in a landfill.*

There are alternative monitoring approaches that could be used to more reliably detect when the composite liner for a Subtitle D landfill fails to prevent leachate from migrating through the liner that could pollute groundwaters. As discussed by Lee and Jones-Lee in 1998 [10], the state of Michigan adopted a double composite-lined landfill for municipal solid wastes where the lower composite liner is a leak detection system for the upper composite liner. This design is the same as that used for a double composite-lined Subtitle D landfill as well as the US EPA s Subtitle C landfills for hazardous waste where there is a leak detection layer of highly permeable materials that is designed to take leachate that passes through the upper composite liner to a sump where it can be sampled and removed.

In accord with the Michigan regulations, whenever leachate is detected in the leak detection system between the two composite liners then action must be taken to stop leachate generation within the landfill. As discussed in the next section, this can be done through improving the quality of the landfill cover. If that approach is not taken, then it is only a matter of time until leachate passes through the lower composite liner and pollutes groundwater. The double composite-lined system also will ultimately fail to prevent groundwater pollution since the lower composite liner is subject to the same types of failure mechanisms as the upper liner.

The double composite-lined landfill, operated where the lower composite liner is a leak detection system for the upper liner and where action is taken to stop the leakage into the leak detection system between the two liners shortly after it is detected, provides a far more reliable groundwater monitoring system than is typically used today. The key to the operation of this system, however, is the availability of funds to continue to remove leachate in the leachate collection system and to operate the leak detection system between the two composite liners for as long as the wastes in the landfill will be a threat. For funding planning purposes, it should be assumed that the wastes in almost all landfills will be a threat, effectively forever. Therefore, there should be an adequate funding mechanism to achieve in perpetuity funds that could be used to monitor the landfill for liner leakage.

Hickman [13,14] and Lee and Jones-Lee [10] have come to the conclusion that the only reliable funding mechanism to ensure that funds will be available when needed for plausible worst-case scenario failures of a landfill waste management system is a dedicated trust which is established at the time that the wastes are placed in the landfill. Lee and Jones-Lee [15] have discussed the long-term liabilities associated with hazardous waste landfills, pointing out that there is inadequate assurance of long-term funding being developed today as part of permitting Subtitle C landfills to ensure that the funds that will eventually be needed to remediate these landfills when the liner and other components of the containment system ultimately fail, will, in fact, be available. For municipal solid waste landfills or hazardous waste landfills, the trust can be developed from part of the disposal fees. For hazardous chemical site remediation, the trust should be established at the time of closure of the site from funds provided by the PRPs. It is important not to rely on the various financial instruments that the US EPA and states allow for providing financial assurance associated with Subtitle D and C landfills. Many of these are unreliable in assuring that funds will be available in perpetuity, i.e. for as long as the wastes are a threat. A dedicated trust, however, where the only way that the funds can be used is for meeting monitoring, maintenance and remediation needs associated with the landfill is a significantly far more reliable funding mechanism than many of the approaches allowed today by the US EPA and the states in closing hazardous chemical sites that allow residual waste components/chemicals to be left at the site in on-site landfills or under RCRA covers of a waste deposition area.

While there are eight states or parts of states that now require double composite-lined landfills for municipal solid waste management and all Subtitle C landfills are double composite-lined, neither the US EPA nor the state regulations require the development of a reliable funding mechanism to ensure with a high degree of reliability that funds will be available to implement the double composite-lined landfill leak detection system and remediation approach for as long as the wastes in the landfill will be a threat.

A dedicated trust established to address plausible worst-case scenario failures over the time that the wastes in the landfill will be a threat should also be required for minimum Subtitle D landfills. However, for a single composite-lined landfill which relies on vertical monitoring wells at the point of compliance for detection of groundwater pollution, the magnitude of the trust needs to be considerably larger to eventually address the groundwater pollution plume that will occur. For Subtitle C or for double composite-lined landfills, the trusts could be somewhat smaller since there is a high probability of detecting leakage through the upper composite liner before groundwater pollution occurs. It is important, however, that the closure plan for a landfill or waste management unit clearly define that effective action must be taken to stop leachate from entering the leak detection system between the two composite liners, or else even the double composite-lined landfill system will eventually pollute groundwaters.

Lee and Jones [16,17] have discussed the significant technical problems with Subtitle C hazardous waste landfills as they are being permitted today. Basically, they are the same problems as Subtitle D landfills, with the exception that there is an opportunity for Subtitle C landfills to provide for higher degrees of protection because of a double composite liner and the fact that many of the hazardous wastes are treated before being placed in the landfill to reduce the potential for constituent migration. This treatment, however, is not adequate to produce residues in a Subtitle C landfill that represent no significant threat to public health, groundwater resources or the environment. The treatment reduces the hazards to groundwater pollution and public health but does not eliminate them.

Period of Time that Wastes In Landfills or Contaminated Soils Are Likely to Be a Threat

For most situations where remediation of a hazardous chemical site is needed, the wastes have already been in the soil/landfill area for considerable periods of time. Any readily decomposable/leachable components have likely been removed from the wastes, with the result that less readily leachable, more resistant to transformation residues are present. Under these conditions, there will be few situations where a hazardous chemical site remediation should be planned for anything less than an infinite period of time. The 30-year post-closure care period and site-remediation monitoring period that is specified in RCRA and CERCLA represents an infinitesimally small part of the real time over which the waste residues at remediated-closed hazardous chemical sites or at a landfill will be a threat to public health, the environment and groundwater resources.

The 30-year post closure care period arose out of a significant error made by Congress in the 1970s where Congress received inappropriate advice from individuals on how long wastes in a classical sanitary, unlined landfill were a threat. Thirty years was the period that typically classical sanitary landfills produced landfill gas. Those advising Congress did not understand that landfill gas production, which is often stated to be landfill stabilization, does not address the leaching properties of the wastes. As discussed by Lee and Jones-Lee [18], Belevi and Baccini [19] have conducted investigations that show that classical sanitary landfills in Switzerland would be expected to produce leachate that would contain hazardous chemicals, such as lead. From their review, it is concluded that lead above drinking water MCLs could be leached from a classical sanitary landfill for over 2,000 years. According to Freeze and Cherry [20] Roman Empire landfills are still producing leachate approximately 2,000 years after they were developed.

These periods of time represent the fermentation and leaching characteristics of wastes in classical sanitary landfills in relatively wet climates where there is appreciable infiltration of precipitation into the wastes which promotes landfill gas production through bacterial fermentation processes and leaching of the wastes. Lee and Jones-Lee [18] have discussed that the classical sanitary landfill groundwater pollution and landfill gas production characteristics are significantly different than today s Subtitle D and C landfills where there is an attempt to create a dry tomb of plastic sheeting-entombed waste. As long as the tomb s (plastic) integrity is maintained, and the wastes are, in fact, kept dry, then no landfill gas production or leaching of the wastes will occur since both of these processes are dependent on moisture. However, eventually under current landfill cover regulatory requirements, today s landfill covers will fail to keep the wastes dry; it is only a matter of time until a closed landfill or waste management area that stopped producing leachate at the time of a cover installation starts to produce leachate again when the integrity of the cover is no longer maintained. This issue is discussed further in a separate section of this chapter. Therefore, for today s dry tomb type landfills where there is an attempt to isolate the wastes from moisture which can provide treatment of the wastes, the period of time that waste monitoring, management and maintenance activities must be conducted should be based on for as long as the wastes in the landfill are a threat. The state of California Water Resources Control Board Chapter 15 regulations adopted this approach in 1984. However, the State Water Resources Control Board and regional water quality control boards have continued to permit municipal solid waste landfills, largely ignoring this requirement of the regulations.

Landfill and Waste Management Area Covers as a Site Remediation Technology

One of the commonly considered methods of remediation of hazardous chemical sites is to develop a RCRA or a sometimes less than RCRA landfill-type cover over the waste containing area, such as a burial pit, former lagoon, old landfill, etc. It is reasoned that if the supply of moisture to the landfill through precipitation can be stopped, then it should be possible to stop the leaching of the waste components that are leading to groundwater pollution. The same type of reasoning is used for on-site Subtitle D for non-hazardous waste components of a hazardous chemical site and Subtitle C for hazardous waste components of a hazardous chemical site remediation program where on-site landfills are constructed and the wastes present at the site are managed in the landfills. Such landfills suffer from all of the same characteristics as the classical Subtitle D and C landfills.

There is widespread recognition that landfill covers for Subtitle C and D landfills have limited periods of time over which they can be expected to function effectively in preventing moisture from entering a landfill and generating leachate. Lee and Jones [21] have discussed the inadequacies of today s landfill covers in keeping wastes dry in a dry tomb type landfill for as long as the wastes represent a threat. While landfill owners and operators and some regulatory agency staff, as part of permitting landfills, will claim that the integrity of a landfill cover can be maintained through visual inspection and maintenance of the cover, the facts are that often such claims are superficial and unreliable. The basic problem with visual inspection of the cover which can be readily accomplished by walking over the surface, only detects surficial problems with the soil cover layer, such as major cracks caused by erosion, differential settling, etc. They also detect major areas of landfill gas release and typically the release of landfill gas through uncontrolled conditions of the cover leads to the killing of the vegetative layer where the gas release occurs.

It is not possible to determine the integrity of the low permeability layer in the landfill cover since this layer, whether it is compacted clay, an HDPE layer or combination of the two is buried below several feet of topsoil and a drainage layer. The net result is that for minimum Subtitle D landfills, there can readily be cracks, holes, rips, tears, etc. in the key layer of the cover which is designed to keep the wastes dry that will not likely be detected for a minimum Subtitle D landfill until off-site pollution of a neighboring property s well occurs. For double composite-lined Subtitle D or C landfills, it will be possible to detect the failure of the cover to keep moisture out through detecting leachate in the leak detection system between the two composite liners.

The situation of special concern is the low rate of leakage through the landfill cover that does not produce sufficient leachate to cause leachate generation to occur in sufficient amounts to lead to the need for leachate collection systems to operate effectively and remove the leachate. As discussed by Lee and Jones-Lee [6], leachate collection and removal systems, however, are well-known to clog due to build-up of chemical and biological precipitates and the accumulation of fine particulates in the leachate collection system. Therefore, especially in older systems, the detection of leachate in the leachate collection system is not necessarily a reliable indicator of leachate production in a landfill. There can readily be leachate production that would pass through the deteriorated liner system that would not be detected in the leachate collection system.

Lee and Jones-Lee [5,21,22,23] have discussed how a hazardous chemical site or a Subtitle C or D landfill can be covered using a leak detectable cover that has a high degree of reliability if the system is operated and maintained as designed, of preventing moisture from entering or passing through the cover into the underlying wastes. As they discussed, there are several commercial systems available. One is based on the Robertson vacuum system [24]. Another is based on the electrical discharge system[25,26]. Both indicate the location of where the cover low permeability layer no longer maintains its integrity and therefore, moisture could pass through the cover into the underlying wastes. While there are a number of other kinds of landfill covers being developed, none of them thus far have the ability to provide a high degree of assurance that moisture will not enter the underlying landfill wastes or chemical management area and leach the chemicals transporting them into the groundwater system.

In order to make a leak detectable cover system work to keep wastes dry for as long as the waste components represent a threat to public health, groundwater resources and/or the environment, it will be necessary to have a highly reliable funding mechanism to ensure that funds will, in fact, be available for as long as the wastes in the area under the cover are a threat. Again, the reliable funding approach for this type of a situation is a dedicated trust which is of sufficient magnitude to cover plausible worst-case failure scenarios for as long as the waste residues represent a threat. Recently, there have been increasing efforts on the part of public agencies who have gained the support of the US EPA to relax long-term funding requirements associated with post-closure care activities for landfills or other waste management units. This approach is strongly contrary to the future generations interests and, at best, only passes the inevitable costs of monitoring and maintenance and eventual remediation on to future generations.

It is time to stop passing on the real costs of landfills, waste covered areas and clean-up of hazardous chemical sites to future generations and start using the technologies and funding mechanisms that are readily available to ensure that existing Superfund, closed RCRA facilities and/ or other sites or Subtitle C or D landfills do not become future Superfund sites. Today s hazardous chemical remediation approaches often virtually ensure that there will not be adequate funding available to address what can be readily expected to be significant problems in the future associated with how hazardous chemical sites and landfills are being closed today. Often, legitimate concerns can be raised about the financial stability of private companies in the waste management business being able to meet the long-term liability that is being developed in the closure of landfills and Superfund/hazardous chemical sites. Hickman [13,14] has pointed out that public agencies, such as county boards of supervisors, etc. are no better, and in fact may be less reliable than some private interests in meeting the financial obligations associated with funding closure and post-closure activities on former landfills and waste management areas. The future funding of operation and maintenance of leak detectable covers cannot be left to the whims of public agencies or private entities. It should be addressed in a reliable way as part of closure of the site as one of the components of site closure costs.

Overall, on-site Subtitle C or D landfills or RCRA or less than RCRA covers for waste management areas as being developed today are not reliable approaches for managing hazardous or deleterious chemicals for as long as these chemicals represent a threat to public health, groundwater resources and/or the environment. It is possible through alternative approaches, using available technology, to develop on-site landfills or waste covered areas that will have a high reliability of protecting the resources of a region from further pollution by releases from the waste management area. The key components are adequate and reliable groundwater monitoring to detect failure of the waste/hazardous chemical management system. All on-site waste management areas where there is a potential for leaching of constituents by precipitation that infiltrates the waste area should include closure with a leak detectable cover and a dedicated trust of sufficient magnitude to operate and maintain this cover for as long as the wastes - residual chemicals represent a threat. For planning purposes, the funding needs should be considered to be for an infinite period of time.

Monitoring of Capped Waste Management Units

There are two kinds of situations that can readily occur associated with hazardous chemical site remediation. One of these is where the chemicals of concern are distributed fairly evenly over the site and therefore under unmanaged conditions, precipitation infiltrates through the waste management area and it leaches some of the chemical, carrying it into the underlying groundwater system. The other situation which is likely more common is that the hazardous chemicals are not evenly distributed across the site, but there are pockets of more hazardous chemicals or certain types of hazardous chemicals in localized areas. While the overall site may have generated a fairly large plume of contaminated groundwaters, there may be one or more smaller, more intense plumes due to the disposal of a particular type of chemical at a certain location within the overall site. An example of this type of situation occurred at the University of California, Davis national Superfund site where the University attempted to manage its own campus wastes by disposal in shallow pits located in campus landfills. Certain pits within a part of the landfill received certain types of wastes over considerable periods of time. An example was the waste chloroform apparently developed from veterinary medicine that was apparently dumped into one pit in the corner of a landfill. This practice resulted in a chloroform plume over one mile with concentrations well above those that are considered acceptable risk for unchlorinated domestic water supplies. This occurred at two different campus landfill chloroform dumping areas. This kind of situation points to the importance of evaluating the potential hazards of a hazardous chemical site to contain small - limited dimension plumes that carry high concentrations of constituents for considerable distances down groundwater gradient.

Once the site is remediated through capping, then the plume characteristics will likely change significantly since no longer will there be the potential for generalized pollution. The pollution plumes that arise from a capped landfill or waste management area will, at least initially and for considerable periods of time, produce limited dimension plumes that will not likely be detected by the broad-brush type monitoring systems where a few downgradient wells are used to characterize groundwater quality. Basically, the characteristics of the waste deposition area and the characteristics of the groundwater hydrologic regime should be understood sufficiently well to develop a site-specific monitoring program that will reliably detect the groundwater pollution plumes that were generated prior to the site remediation and those that will be generated after remediation. Because of the change in the character of the infiltration and the associated plume characteristics, far more monitoring wells will likely be needed to monitor failure of the remediation approach system to prevent further groundwater pollution by waste-derived constituents than were needed for the initial characterization of the site.

Adequacy of Solid Waste Hazard Classification

One of the frequently explored and sometimes used procedures for remediation of hazardous chemical sites, such as Superfund sites, is the addition of reagents to the waste containing soils or waste residues to solidify - stabilize the constituents in the treated wastes. These so-called stabilized/solidified wastes are typically placed in an on-site or off-site landfill. A variety of solidification/stabilization reagents/materials are used for this purpose ranging from lime/cement-based materials through various petroleum derivatives, plastics, etc. The Association for Environmental Engineering Professors (AEEP) is publishing a review of many of the procedures that can be used for this purpose which discusses some of the potential benefits associated with stabilization/fixation of various types of wastes with various reagents/materials. The focus of the AEEP review is on short-term compliance with the US EPA Toxicity Characteristic Leaching Procedure (TCLP). This section reviews the appropriateness of using the TCLP-based short-term evaluations of the adequacy of stabilization/fixation as a measure of the threat associated with long-term potential problems for public health, groundwater resources and the environment by the chemical constituents in the stabilized/fixed waste. It also addresses the reliability of the TCLP procedure to properly characterize the hazards that contaminants in soils and wastes represent to public health and the environment.

Reliability of TCLP. The Toxicity Characteristic Leaching Procedures (TCLP) evolved from the US EPA Exaction Procedure toxicity test that was specified in RCRA. Basically, this test was contrived by the US EPA as a political test designed to minimize the size of the hazardous waste stream that would have to be managed as part of implementing the initial RCRA requirements for managing hazardous waste. The test was not then, nor is the TCLP which evolved from the EP-tox test, now a reliable assessment of the potential for chemical constituents present in a waste stabilized and/or fixed to cause public health, groundwater quality or environmental problems. The conditions of the EP-tox/TCLP test were arbitrarily selected without reference to the physical conditions of the EP-tox/TCLP test such as solid-liquid ratio, leaching times, physical degree of dispersion of the waste, leaching solution characteristics, etc. As discussed by Lee and Jones, [23, 24], many of the conditions of the hazardous waste leaching test were arbitrarily selected and bear no reality to the real world in which the leaching of constituents present in a soil or waste or fixed by various stabilization/fixation reagents would take place. The test is alleged by the US EPA to simulate the conditions of leaching that would occur if the materials were placed in a municipal solid waste landfill. The only characteristic of the TCLP that begins to resemble a municipal solid waste leaching environment is the use of a dilute acetic acid solution to establish a pH during the leaching test similar to that encountered in some municipal solid waste landfills.

At the time of development of the EP-tox test, Lee and Jones [27] provided a detailed discussion of the unreliability of this test as a true measure of the leaching potential of constituents in waste or contaminated soils with reference to their potential impact on public health, groundwater resources and/or the environment. They report on a number of significant problems with the test that still have not been adequately or reliably addressed today.

The EP-tox test was arbitrarily somewhat patterned after the elutriate test that was developed by the US Army Corps of Engineers for leaching of dredged sediments to determine what might be released when dredged sediments are dumped in open waters. Lee and Jones [28] have reviewed the development and evaluation of the elutriate test that is used by the US EPA and Army Corps of Engineers to evaluate the potential for chemical constituents in contaminated dredged sediments to be leached to the water column during open water disposal of the dredged sediments. The 1:4 solid to liquid ratio used in the elutriate tests was selected based on the typical pumping ratio that is used in hydraulically dredging sediments. The 1:4 solid to liquid ratio in the EP-tox and now TCLP test has no technical foundation; it is completely arbitrary. Leaching is for many substances influenced by liquid - solid ratios.

In the elutriate test, the sediments are slurried to resemble what might happen under worst-case conditions where release of constituents associated with the interstitial water in the dredged sediments, as well as the actual release upon any leaching that would occur in the receiving waters for the dredged sediment disposal, is assessed. In the EP-tox/TCLP tests the wastes are ground to a fine powder. Such an approach can significantly distort the release of constituents in a leaching test. For some constituents in some types of solids, the grinding will expose additional waste components that would not be leached otherwise. In other situations, the grinding exposes surfaces which could serve to take up the constituents of concern in the wastes and therefore actually reduce the amount of release that would occur compared to that which would occur in the landfill.

In a landfill the liquid to solid ratio can vary from unsaturated conditions where the transport through the wastes occurs as a thin film of moisture moving on the surface of the particles with no fluid between the waste particles to a saturated condition where the wastes are fully saturated with moisture. The one-hour period of leaching in the elutriate test resembles the period of time over which leaching would typically occur in an open water disposal of hydraulically dredged sediments. The period of leaching in the EP tox/TCLP test has no relationship to the leaching time over which there is concern in a municipal landfill.

The EP-tox and now TCLP tests were designed for a specific purpose, namely to determine whether a waste placed in a classical, municipal solid waste landfill could leach sufficient materials to produce a leachate that represented a significant threat to groundwater quality for use of the groundwaters as a domestic water supply. Any waste that leaches more than an arbitrarily defined amount (100 times the drinking water MCL) is classified as a hazardous waste and must be managed in a hazardous waste landfill. Waste that leaches less than this amount could be placed in a municipal solid waste landfill. This test was never designed to be used as it is widely used today to determine whether a contaminated soil or other medium was hazardous or not and therefore required remediation. Lee and Jones [29] discuss the appropriate approach that should be used to determine whether constituents at a particular location represent a significant hazard to public health and the environment to require remediation. This involves a site-specific hazard assessment approach where the leaching characteristics of the materials under the conditions that will be encountered at a particular location are evaluated and the transport/fate of the leached materials is determined to assess whether concentrations above critical levels for various beneficial uses of a water receiving the materials of interest occurs.

In the elutriate test, the receiving waters for the dredged sediment disposal are used to leach the dredged sediments since this is where leaching will occur. In the EP-tox/TCLP test a dilute acetic acid solution is used. While at one time leachate produced in the classical sanitary landfill would tend to have the pH of dilute acetic acid solution, today that situation is changing. First, the classical sanitary landfills had a certain moisture content dependent on the amount of infiltration into the wastes through the landfill cover. The landfill covers were not designed and constructed to keep moisture out. Moisture that did not run off from the landfill cover surface penetrated into the waste. Today upon closure of the landfill and the application of the low permeability cover, the moisture supplied to the waste is shut off or significantly reduced, and to the extent that the cover maintains its integrity, the wastes will be kept dry. This is in accord with the dry tomb type landfilling that was adopted in the USA for hazardous waste in the mid-1980s and municipal solid wastes in the early 1990s. While eventually because of the inability to maintain the low permeability layer within the cover of a dry tomb type landfill, appreciable moisture can enter the wastes again. The amount of moisture entering the wastes will likely be less than that of the classical sanitary landfill. The situation therefore could become one of not having as low a pH in the leachate generated within today s and tomorrow s dry tomb landfills as occurred in the classical sanitary landfill.

Another factor that influences the pH in a municipal solid waste landfill leachate is the fact that green wastes such as yard wastes are now, as the result of recycling efforts, being diverted from municipal solid waste landfills. As a result, the readily fermentable components of the municipal solid waste stream which are the precursors of the acid that decreases the pH in leachate are no longer being added to the landfill to the same degree that they were a few years ago. Recently, the state of California Environmental Protection Agency Department of Toxic Substances Control (DTSC) [30] has conducted some fairly comprehensive studies on the characteristics of leachates from a variety of landfills in California where it was found that the pH in these landfills was not 5 or so as is typically assumed, but was around 7 or 8. Changing the pH from 4 or 5 to 7 or 8 significantly changes the leaching characteristics for many constituents.

While the TCLP is now being used to determine the leaching characteristics of waste components in a hazardous chemical on-site or off-site landfill, the use of this test for that purpose is technically invalid from several respects since the test conditions are not designed to mimic in any way the leaching characteristics that would occur in a hazardous chemical site type landfill where there may be little or no municipal solid waste components which determine the characteristics of the leaching solution. Many of the hazardous chemical site on-site landfills will have low fermentable organic content. As a result, the pH of the leaching solution and its complexing tendencies will be significantly different from those that would occur in a municipal solid waste landfill or those of the TCLP test.

The Cal EPA DTSC studies [30] on the leaching of various types of industrial solid wastes which were potentially hazardous wastes included leaching with acetic acid in the typical TCLP procedure and with citric acid under the California Waste Extraction Test (WET). It was found, as expected, that for most metals, the citric acid because of its stronger complexing tendencies for metals, tended to leach more heavy metals from the wastes than the TCLP. Also used in this study was actual leachate from several municipal solid waste landfills. It was found that the leaching characteristics of the most aggressive of the municipal solid waste landfill leachate that was tested was similar to the leaching characteristics of the TCLP for many of the heavy metals investigated. There were a number of leachates, however, that leached significantly less heavy metals than the TCLP test, indicating that TCLP tends to over-estimate the amount of leachable heavy metals in many landfill settings.

Definition of Excessive Leaching. As part of developing the EP-tox political test for classifying wastes as hazardous or non-hazardous, the US EPA arbitrarily, without a technical foundation, decided that a 100-fold leaching above the drinking water MCL (maximum contaminant level - standard) represented an excessive leaching of constituents that when present in municipal solid waste landfill leachate, should cause the wastes to be placed in a so-called hazardous waste Subtitle C landfill. The Agency has described this 100-fold factor between the drinking water MCL and the allowable leaching in the EP-tox/TCLP test as the attenuation factor that typically occurs in municipal solid waste landfills between when leachate leaves the landfill and when the groundwaters which contain the leachate in a diluted form could be used for domestic water supply purposes. The US EPA as part of promulgating the TCLP test as a revision of the EP-tox test initially proposed to abandon the use of the arbitrary 100-fold attenuation factor in favor of a site-specific evaluation that would consider the characteristics of the aquifer system into which the leachate is being added. This was along the lines of those recommended by Lee and Jones [27,28]. However, in adopting the final TCLP regulations without providing any technical justification, the US EPA abandoned what could become a technically valid approach, if appropriately implemented, of site-specific evaluation of attenuation factors and reverted back to the technically invalid approach of using a 100-fold attenuation factor.

Following this action, several years ago, the authors attempted through contacts with EPA administration to ascertain any technical basis for this action. They were informed that a group within the Agency had done some groundwater transport modeling which justified the 100 attenuation factor. When an attempt was made to obtain a copy of the models and reports on this, the authors were told that there were no reports covering this work. This was then followed up by a request to contact the people doing the work, and the authors were told by the US EPA administration member responsible for this area that those individuals had left the Agency and had left no records of their work with the Agency.

This situation does not give a lot of confidence to the Agency ever having any technical justification for the 100-fold attenuation factor. It was a political decision without technical merit. A critical examination of this issue shows that there can readily be conditions within the landfill and in aquifer systems where 100-fold attenuation is under-protective of domestic water supply wells located near the landfill or over-protective of the groundwaters used for domestic purposes. The amount and location of deposition of wastes within a municipal landfill that is of concern because of the leaching of potentially hazardous constituents will influence the concentration of the constituents of concern in the groundwaters underlying the landfill. Further, the characteristics of the aquifer through precipitation - solid formation, sorption, dilution, biological transformations, etc. will influence the transport of waste derived constituents and their transformation products.

In addition, certain kinds of aquifers, such as fractured rock and cavernous limestone, where there can be substantial transport of leachate with limited dilution along fractures or in solution channels, can lead to concentrations of leachate in groundwaters intercepted by a well where there is certainly less than 100-fold attenuation between the point of release of the leachate from the landfill and the point of interception of the leachate-polluted groundwaters by a domestic water supply well. The deposition of wastes in an on-site landfill from a hazardous chemical site can readily result in parts of the wastes that are placed in the landfill having significantly different characteristics, therefore causing leachate generated in those areas to have different characteristics than other parts of the landfill which receive wastes with different characteristics.

It can be concluded that the 100-fold attenuation factor typically used to determine whether a waste is hazardous or not is unreliable in characterizing whether constituents in a waste that is placed in a municipal landfill or a hazardous waste landfill represents significant threats to public health, groundwater resources or the environment. The same, even to a greater extent, can be said about the use of this factor to characterize the potential for leaching constituents from a hazardous chemical, on-site remediation landfill. The appropriate approach in evaluating the potential for constituents in an on-site remediation landfill is to conduct detailed site-specific leaching and leachate transport characteristic evaluations to predict prior to the construction of the landfill, whether constituents in the on-site landfill could likely lead to groundwater pollution with the inevitable failure of a dry tomb type landfill of either Subtitle D or C characteristics, as well as a waste management area which is covered with a RCRA landfill cover. If it appears feasible to manage the hazardous chemical site wastes in an on-site landfill, then a comprehensive groundwater monitoring and landfill gas monitoring program should be implemented, operated and maintained for as long as the constituents in the landfill represent a threat to public health, groundwater resources and/or the environment.

This threat should be evaluated not just for the Priority Pollutants as is typically done today which focus on a limited number of potentially hazardous constituents compared to the vast arena of hazardous constituents present in most landfill leachates and hazardous chemical site wastes, but should include consideration of unknown hazardous constituents which are a threat to public health through drinking water consumption as well as the so-called non-hazardous components which are not a threat to health, but are a threat to the quality of the groundwater used for domestic purposes. Constituents that cause taste and odors or high dissolved solids which either lead to scaling or corrosion in municipal water supply systems and in the residences/commercial establishments are as important to the public as the hazardous constituents which receive the focus of attention. Tastes and odors or unusable waters because of their aesthetic or other characteristics typically require abandonment of the domestic water supply well and the development of alternative water supplies. While this musical wells approach is possible in some areas where the total demand for water supplies is less than the available supply, there are areas, especially in the arid west as well as the more humid east, where the total water supply, especially in drought years, is inadequate to meet the needs of the populations in the region. The destruction of a groundwater resource by pollution by landfill leachate is strongly contrary to the public s interests.

As discussed herein, it is essential that a dedicated trust be developed by private and public entities or Responsible Parties to ensure that reliable groundwater monitoring will be conducted to detect with a high degree of certainty any subsequent releases of constituents from the on-site landfill or covered waste management area for as long as the wastes represent a threat. The magnitude of this trust should be sufficient so that if those responsible for managing the on-site wastes cannot terminate the migration of constituents from the landfill, then the wastes in the on-site waste management unit will have to be removed (mined). Failure to provide this level of protection will mean that future generations will face the same problems as the current generation in adequately managed hazardous waste.

In summary, the current TCLP test which is widely used to characterize the leaching potential of constituents in a waste for deposition in a municipal solid waste Subtitle D landfill, a hazardous waste Subtitle C landfill or an on-site hazardous chemical site remediation landfill, which could be C or D dependent on the materials placed in the landfill, is not a reliable test to assess the potential mobility of the constituents in the landfill. This test should not be used for anything other than a political test to determine whether wastes can be placed in a municipal solid waste landfill or a hazardous solid waste landfill. The results of the TCLP test bear no relationship to reliably assessing the potential threat that constituents in the waste represent to public health, groundwater resources or the environment.

Natural Attenuation

Natural attenuation for remediation of groundwater pollution is becoming an increasingly popular approach toward remediation of hazardous chemical sites. The basic premise of this approach is that if the source of the constituents that is causing groundwater pollution is removed and the pollution plume has apparently stabilized, then rather than trying to pump and treat the polluted groundwaters for their remediation, the plume should be allowed to naturally attenuate. While this approach saves PRPs considerable funds, it, in general, must be more carefully implemented than is being done in some areas today.

It should be remembered that in most cases the pollution of groundwaters is the result of the PRP failing to follow common sense and/or good business practice with respect to leaking tanks which is one of the major causes of groundwater pollution. In most cases, it should have been obvious to those responsible for management of inventories of tanks of stored materials that the tanks were leaking as the result of more material being purchased than was actually used or sold. Further, in the case of pollution by landfills or waste disposal facilities, the potential to pollute groundwaters by such facilities has been well understood since the 1950s. While regulatory agencies then and unfortunately in some cases, still today, are not taking the action required by regulations to ensure that groundwater quality is protected with a high degree of certainty, the manager of the waste should have been aware and acted on controlling the disposal of wastes in landfills, pits, etc. so that groundwater pollution would not occur or would have a low probability of occurring. One of the basic problems is that companies, commercial establishments, public agencies, etc. have for years provided inadequate funds to hire appropriately trained individuals who would become familiar with and understand the literature that has been available since the 1950s on the potential to cause groundwater pollution. Further, there has been and continues to be a chronic problem where the management of the industrial or commercial facilities or agencies opt for a short-term economic gain for reduced spending in the case of an agency compared to the funds that should be spent to properly manage wastes so they do not cause long-term problems of groundwater pollution.

Basically the long-term costs of pump and treat or other active groundwater remediation approaches represent part of the costs that will have to be borne by the industry, commercial establishments, public agencies that manage wastes, etc. arising out of the cheaper-than-initial-cost approach that was used at the time of waste deposition. The public and future generations are entitled to clean-up of polluted groundwaters to the maximum extent practicable to ensure that no further spread of pollutants will occur which would further damage the groundwater resources, health, welfare and interests of those within the sphere of influence of the polluted groundwater. If this can be achieved through a properly developed, implemented and most importantly, monitored natural attenuation approach, then natural attenuation is a viable option that should be considered.

Natural attenuation arises from a variety of factors which limit the size of a groundwater pollution plume. These factors include the dilution of this plume through lateral and vertical mixing with unpolluted groundwaters. One of the sources of dilution, especially of the upper parts of the plume, is the infiltration of precipitation along the plume path which adds additional water to the aquifer which tends to dilute the plume. Further, there are several chemical and biochemical reactions (precipitation, sorption, oxidation reduction, volatilization, biochemical transformations) which for some constituents tend to remove one or more constituents from the plume. Not all these reactions, however, especially chemical and biochemical transformations lead to non-hazardous transformation products.

One of the areas in which there has been considerable interest in natural attenuation of polluted groundwaters is associated with the pollution of groundwaters by gasoline from service stations. However, it is inappropriate to assume, as has been done by Lawrence Livermore National Laboratory (LLNL) and the State of California Water Resources Control Board staff, that removal of benzene, xylene and toluene from a gasoline plume leads to the conversion to carbon dioxide and water. There could readily be a variety of transformation products formed which are hazardous or otherwise deleterious to groundwater quality, public health, and/or the environment where the groundwater has become part of the surface water system.

One of the areas of particular concern that is often ignored is the presence of unidentified hazardous or deleterious chemicals in groundwater plumes. At this time, only from about 50 to a couple of hundred chemical constituents are routinely monitored - regulated in groundwater pollution investigation and remediation programs. There are over 75,000 chemicals in use today with about 1,000 new chemicals being developed each year. Further, there is a large, unknown number of transformation products from chemicals that could readily be present in groundwater plumes arising from pollution of groundwaters by various types of wastes, waste spill materials, or tank or transmission line leaks. Frequently, measurement of total organic carbon or dissolved organic carbon in a plume and/or waste shows that the concentrations of total organics far exceed the identified organic components. This can lead to a significant potential for there being unknown/unidentified constituents in the groundwater plume that can be hazardous/deleterious to public health, groundwater quality and the environment.

With increasing frequency today, risk-based approaches are being used to establish clean-up objectives for groundwater systems and soils. These approaches are typically significantly deficient when these objectives are applied to situations where there are complex mixtures of chemicals in the source or where the source chemicals can be transformed into a variety of hazardous and deleterious chemicals within the soil aquifer system. An appropriately conducted risk-based approach for establishing clean-up objectives for hazardous chemical mixture polluted groundwaters or soils is to establish a surrogate hazard level for an unknown/unidentified constituent(s) that could be present and be transported in the groundwater plume at the same rate as water. It is suggested that the surrogate be assigned a hazard concentration - MCL of 0.01 times that of vinyl chloride and that it is assumed to move as readily in groundwater systems as vinyl chloride. This would make the critical MCL for the unknown constituents about 0.01 μg/L.

There is a situation where vinyl chloride does not persist in groundwaters as far as other constituents. This occurs with municipal landfill systems where the groundwater plume which originally contained TCE in the landfill disposed of as a waste from industrial or residential/commercial use, converts to vinyl chloride in the landfill environment . At the leading edge of the groundwater plume from municipal solid waste there is a conversion from anaerobic to aerobic conditions. Under these conditions, there is the potential for methane that could be present in the groundwaters where the conversion of methane to CO_2 under aerobic conditions leads to the removal of vinyl chloride to the groundwater plume.

A prime example of the significant errors that can occur is the LLNL s assessment of the persistence of gasoline derivatives benzene, xylene, and toluene where LLNL ignored the fact that there are other well-known constituents in gasoline that can be polluting groundwaters as well. For example, MTBE has been found to be a common component of gasoline that is far more resistant to biotransformations than benzene, toluene and xylene that moves as readily as water in groundwater systems. It is now known that MTBE is a widespread common pollutant of groundwaters associated with gasoline leaks that is a significant problem to groundwater quality through imparting severe taste and odor problems.

Another example of how assuming that only those constituents that are on the US EPA MCL list or the Priority Pollutants represent the only hazards in a polluted groundwater plume is provided by a situation that has occurred in the Sacramento, California area with the pollution of groundwaters by Aerojet Corp. in connection with its rocket engine testing. Aerojet created a very large plume that is polluting groundwaters over a substantial area by trichloroethylene. For a number of years, the approach toward remediation was to pump the polluted groundwaters, airstrip the TCE and then reinject the pumped and treated groundwaters down-gradient from where they were pumped. About two years ago it was discovered that Aerojet not only polluted the groundwaters with TCE but also with perchlorate which has been found to be highly hazardous to human health. Perchlorate is not on the US EPA drinking water MCL list; it is not normally analyzed for in any groundwater pollution studies. The Aerojet created plume is affecting a number of domestic water supply wells and is threatening many others. Other exotic chemicals associated with Aerojet s mismanagement of its wastes are also being found in this plume.

One of the key aspects of any natural attenuation program is the appropriate monitoring of the pollutant plume. A detailed comprehensive monitoring program should be undertaken as part of any natural attenuation program to assure that the plume is, in fact, being naturally attenuated and that no new situations have developed which would cause the behavior of the plume to significantly change. An area of concern is where new off-site production wells cause the groundwater flow pattern to change which, in turn, alters the natural attenuation plume.

The monitoring program should be designed to be operated for as long as any residual, potentially hazardous constituents are present in the groundwaters. This will likely require that a dedicated trust be established to ensure that funds are available to continue the monitoring program for as long as there are constituents in the groundwater that represent a potential threat. Initially, the monitoring program should be conducted quarterly for at least two to three years. This would provide information on seasonal changes in the characteristics of the plume which is especially important where there are significant changes in the water table elevation and where there are large production wells in the vicinity of the plume that could influence its behavior and characteristics. If after two to three years, depending on the overall plume setting, it is possible to reliably predict the next set of analytical results for sampling the monitoring wells around and within the plume, then the frequency of monitoring can be cut back to semi-annual. The approaches that are being used by some regulatory agencies of monitoring once every year to once every five years are totally inappropriate. There is an insufficient database generated from this approach to determine whether changes in plume characteristics are occurring.

Every five years the overall character of the groundwater monitoring program should be subjected to a public review with appropriate public notice and a hearing where the PRP is to present a comprehensive report of the results of the monitoring report during the past five years. This report should include a listing of parameters being monitored with a critical review of the appropriateness of this list with what is known at that time about constituents of concern. This review should be designed to bring up-to-date the monitoring program relative to new information that has developed during the past five years on the potential hazards of chemicals present in the plume to public health, groundwater resources and the environment. It is important to emphasize that in addition to considering hazardous chemicals which are a threat to human health, also consideration must be given to chemicals that are detrimental to the use of the groundwaters for domestic water supply purposes, including tastes and odors, increased TDS, increased hardness, constituents that cause staining, etc. The monitoring program can be terminated once it has been established after five years of monitoring that there is no residual evidence for any constituent associated with the plume.

Conclusions

The current trend of remediating hazardous chemical sites in which potentially hazardous chemical constituent residues are left at the site as part of site closure is typically not being adequately evaluated with respect to the long-term hazards that the waste residues represent to public health and the environment. Of particular concern is the use of on-site landfills or waste management units covered with a RCRA landfill cover to prevent further groundwater pollution by waste-derived constituents for as long as wastes in the landfill or covered waste management unit will be a threat. Current landfilling approaches allowed by regulatory agencies under RCRA Subtitle C and D, at best, only postpone when further groundwater pollution will occur.

While this approach enables hazardous chemical sites to be cleaned up at initially reduced cost, ultimately the true costs of using landfills or RCRA covered waste management units will have to be borne by future generations. Because of inadequate funding for long-term costs as part of current hazardous waste site remediated closure approaches, future generations will not only have to pay for the cost of remediation, but also they will be exposed to the hazards of the residual chemicals at inadequately remediated hazardous chemical sites.

The current regulatory approach for classification of a waste as hazardous involving the use of the TCLP is significantly deficient in properly assessing the real hazards that constituents in wastes represent to public health and the environment. Site-specific evaluations of leachability, transport and transformations of waste-derived constituents should be used to evaluate the hazards that constituents in wastes represent to public heath and the environment.

Many of the approaches being used today in support of natural attenuation as a remediation approach for polluted groundwaters are deficient in properly evaluating and managing the hazards that constituents in a groundwater plume arising from a hazardous chemical site represent to public health and the environment. Far more comprehensive evaluations of constituents of concern in groundwater plumes should be made as part of developing a natural attenuation approach for remediation of contaminated groundwaters. Also, the PRPs for a groundwater pollution plume should be required to reliably monitor the groundwater plume for as long as the plume contains constituents that are a hazard or are detrimental to the use of the groundwater for domestic water supply purposes.

By far the greatest deficiency in hazardous chemical site remediation is the failure to require that the PRPs develop a dedicated trust fund as part of site closure that is sufficient to address all plausible worst-case scenario failures that could occur at the site for as long as the wastes remaining at the site at closure will be a threat to public health and the environment. For most hazardous chemical sites, the planning period during which the trust fund will be needed should be considered to be infinite and be of sufficient magnitude to monitor and maintain the site in perpetuity for as long as the waste residues and their transformation products represent a threat and be of sufficient magnitude to exhume all waste residues and contaminated soils from the site should this prove to be needed to protect public health and the environment.

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