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RISK MANAGEMENT AND THE LANDFILL IN HAZARDOUS WASTE DISPOSAL

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Summary

Amidst the current dialogue surrounding drives at state and federal levels to ban the use of landfills for certain hazardous wastes, it is easy to lose sight of the simple fact that there is a continuing and necessary role for landfills in overall hazardous waste management.

1. Introduction

Throughout history man has turned to the land as a final repository for his waste. While the modern sanitary landfill looks significantly different from the midden heaps of primitive man and the dust piles of the early industrial era, the technology itself has evolved very little during the intervening centuries. The basic underlying principle has always been to place discarded residues somewhere out of the way and assume that they will take care of themselves. When land was plentiful compared to man's needs, anywhere would do. As the human population density increased, however, there were incentives to put wastes in the less desirable places so that more sought-after areas were left free. In time, even these locations were proximate to man's other activities. This led to the covering of wastes and occasional burning to reduce unsightliness, odors and the concentration of disease vectors. Ultimately, the sanitary landfill design emerged as a preferable way to keep wastes contained in the earth. At the same time, the industrial revolution and more recently the exponential growth in reliance on chemicals changed the nature of many of the wastes. Industrial sludges, tars, slurries and other solid wastes are more hazardous as a result of the toxic, corrosive, flammable and reactive properties of specific constituents contained therein. Associated vapors could migrate through the sanitary landfill's overburden while soluble constituents infiltrate with rain to produce contaminated leachate. As a result, the originally conceived sanitary landfill has been found inadequate for disposal of many hazardous wastes because of the potential concomitant contamination of aquifers and the atmosphere.

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To cope with these new wastes, the sanitary landfill has been transformed into the secure landfill. The latter (Fig. 1) is a surface repository equipped with engineered barriers such as synthetic and clay liners, gas migration barriers, and leachate collection systems intended to prevent all release of waste materials. This objective may be achievable over finite periods. In time, however, all facilities will release contaminants. It is this realization that forces a re-evaluation of landfills and their design.

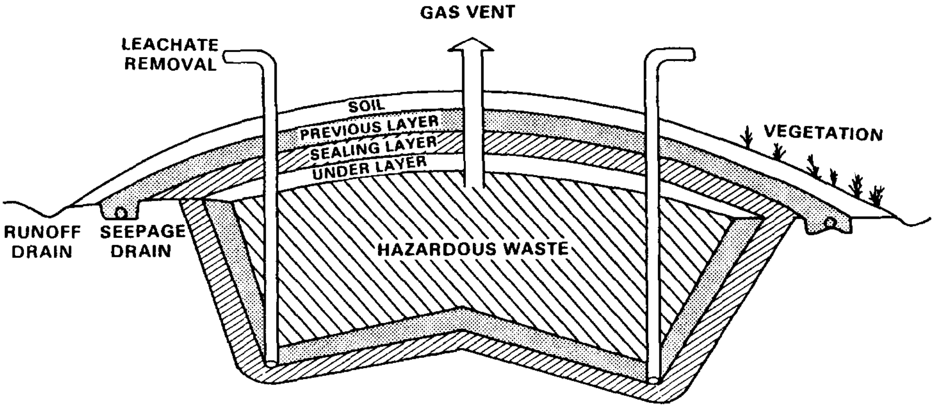

Fig. 1. Design for a secure landfill.

Current U.S. Environmental Protection Agency regulations prescribe acceptable designs for hazardous waste landfill facilities. The design oriented standards mandate use of synthetic membrane liners. While clay underliner systems are recommended as a safety feature, they are not required. This willingness to rely totally on membrane systems is underscored by companion monitoring requirements. Whereas facilities with a single membrane liner are required to have a downflow monitoring well, double-lined facilities need have no monitoring well. The interstitial space between liners is to be monitored for fluids during the operational period, but it is assumed that caps (both clay and membrane layers are prescribed) will prevent post-closure infiltration and, therefore, eliminate concern for subsequent leachate migration. Hence, regulations define the secure landfill of the future as an envelope of synthetic membrane liners and caps with clay layers optional and leachate collection systems functional only during the operational phase and a brief five-year post-closure period.

Land disposal, primarily through surface impoundments, and sanitary and secure landfills, now accounts for the disposal of more than 80% of all hazardous wastes in the United States on a wet ton basis. This reflects a number of factors including: (1) the confidence of many engineers in current repository designs, (2) the interconnection of treatment and disposal options such as the need to landfill residuals from incineration and concentration technologies, and (3) the perception that no cost-effective alternative is available. Recognizing the fallibility of all landfill designs these perceptions are now in question. Certainly, direct operational costs for secure landfills are lower than options such as incineration as is evident from Table 1. However, with the passage of the Comprehensive Environmental Responses Compensation and Liability Act (CERCLA) and with the use of absolute liability doctrines by the courts, the long-term costs of landfill (which include restoration activities and potential damages) may significantly alter comparative economics. It is this perspective that provides the incentive for taking a new look at the role of landfills in hazardous waste management.

TABLE 1

Life cycle cost for management alternatives [1]

	Life cycle cost in $/1000 lb at given capacity (1981 dollars)				
	1000 lb/h	2000 lb/h	3000 lb/h	4000 lb/h	5000 lb/h
Incineration	256.55[a]	246.91	244.34	242.88	243.15
Land disposal	154.34	91.26	68.37	56.86	50.01
Chemical fixation (with solids)	90.00[a]	90.00	90.00	90.00	90.00
Chemical fixation (without solids)	24.00[a]	24.00	24.00	24.00	24.00
Encapsulation	46.62[a]	42.87	—	—	—

[a] Require ultimate disposal of residuals typically by landfill.

2. Issues of risk

By their very nature, when exposure occurs, hazardous wastes pose a risk to man. It follows then that the objective of management programs is to reduce risks to acceptable levels. That is a significantly different objective than the elimination or minimization of risks. The former is not feasible since all of man's activities carry risks at some level. The latter is not cost-effective because marginal reduction of risk becomes exceedingly expensive at lower levels of risk and often fosters activities with higher levels of secondary risk such as transportation over long distances. Hence, meeting the hazardous waste management objective entails a sequence of trade-offs or a balancing of cost and risk.

One of the simplest definitions of risk (R) is that it is equal to the product of the probability of an event (P) and the consequences of that event (C) or:

$$R = P \times C$$

With respect to contaminant risk arising from land disposal activities, the event of concern is the release of or an exposure to toxic constituents. The timing of the event may or may not be critical in determining the level of risk. Many hazardous wastes are organic, and therefore can undergo degradation or transformation to nonhazardous residuals. For these wastes, the consequences of a release are dependent on the stage of degradation of the waste constituents in the landfill. Releases occurring after wastes are fully degraded may be associated with little or no real hazard and hence low risk. On the other hand, many waste constituents, especially toxic elements, have essentially infinite half-lives. For these contaminants, the timing of the releases becomes insignificant, in that the contaminants will forever retain their toxic properties. This creates a waste management dilemma since these same constituents cannot be destroyed through chemical or thermal means. Therefore, internment of some kind is the only available disposal option for wastes with these constituents. In these instances, the integrity of the repository must be maintained forever — but what does "forever" mean in terms of management options and planning?

Proposed regulations under CERCLA address a period of up to five years with no evidence of significant chemical losses and up to 30 years of post-closure maintenance for hazardous waste sites. Nuclear waste management has received more scrutiny than any other segment of the solid waste problem set. Currently, regulatory agencies require that a respository for these materials be shown to pose no unacceptable risks for a period of 10,000 years. This is considerably longer than the five to thirty year post-closure period referenced for chemical wastes. And yet, radiocontaminants have a finite half-life while inorganic hazardous wastes do not. There is no technical justification for the dichotomy. In time, regulations may be changed to reflect the much longer period of risk. Currently, while the disposal site operator may be free from responsibility after closure via the CERCLA Post-Closure Liability Fund, generators are still held ultimately responsible for damages caused by their wastes. As a consequence, landfill design must be directed towards risk reduction over spans of time significantly longer than 30 years.

From the simple definition above, it is apparent that risk reduction can be achieved either by reducing the probability of releases, or by reducing the consequences of any given release.

3. Reduction in probability

In order to develop designs which will reduce both the probability and the consequences of repository failure, it is necessary first to characterize the likely modes under which integrity will be lost. While each possible failure is a unique event with its own discrete probability, it is possible to group failure modes. Experience suggests three classifications are of interest: (1) natural phenomena, (2) engineering or design failure, and (3) human intrusion.

3.1 Natural phenomena

Landfills may fail as a result of inundation or exposure resulting from natural phenomena such as floods, storm events, earthquakes or glaciers.

Probabilities of these events are generally available as a result of past studies on frequency in given locales. This is particularly true for the more acute events; hence, the derivation of 100- and 500-year flood plains and the characterization of 100-year storm events. The longer-term phenomena are more often dealt with in terms of areas of relative susceptibility (e.g. seismic risk zones and probable advance of glacial ice sheets).

For the most part, sites can be selected to reduce the probability of releases arising from natural phenomena in the next 100 to 1000 years. After that point, the possibility of significant climatic or tectonic changes will insert greater levels of uncertainty.

3.2 Engineering or design failure

Ultimate failure of land disposal facilities may result directly from the deterioration or inadequacy of engineered barriers. This is a difficult failure mode to quantify because very little work has been performed to identify failure dynamics. However, a database is emerging on the most commonly employed types of barriers: synthetic liners and clay liners. Experimentation sponsored by the U.S. Environmental Protection Agency has shown that synthetic liners will undergo swelling, elongation and loss of strength when contacted with various hazardous constituents [2, 3]. The degree to which these effects will accelerate liner failure depends upon the specific waste constituents, the liner materials and the period of exposure. Moderate effects were found with nine-year exposure to leachate from a municipal solid waste landfill. When exposed to sunlight and weather, deterioration was much more dramatic. The effects of long-term exposures (>3—5 years) and the presence of hazardous constituents have not been investigated. In general, however, it is likely that liners will ultimately break down in a 10- to 100-year time frame due to chemical and physical effects. Hence, integrity may be good for that time frame if the membrane is intact to begin with. The latter may not be the case, however. Work at the U.S. Corps of Engineers Waterways Experiment Station [4] revealed that when synthetic liners were placed on typical subgrades, covered with bedding materials, and subjected to normal trafficking (placement of wastes and overburden), systems containing gravel evidenced 2 to 50 punctures per 5 ft^2 of surface. Systems with no failures were those where the liners were bedded in sand or finer silts. The implication is that under normal conditions, some degree of failure is probable before a commercial facility is brought to capacity, let alone closed.

Similarly, there are concerns for the long-term viability of clay liners. By their very nature, clay and other soil barriers retard, but do not prevent, the migration of liquids. In fact, clays are normally classified by their hydraulic conductivity (e.g. 10^{-8} cm s^{-1}). The premise is that the low permeabilities will prevent flow rates from being large enough to allow significant losses of contaminants. Selection of a specific clay and a given thickness establishes the rate at which leachate will be lost and the time

TABLE 2

Approximate effective change in permeability of various clays exposed to hazardous constituents $(P_n/P_0)^a$ [5, 6]

Clay	Acetic acid	Aniline	Heptane	Xylene	Ethylene glycol	Acetone	Methanol
Smectite — lufkin	0.1[0.3]	100[3]	100[1.0]	1000[1.0]	—	—	—
Smectite — houston black	0.1[0.3]	10[2.5]	100[1.5]	1000[1.5]	—	—	—
Smectite — oncalcareous	10[2.5]	100[0.5]	100[2.0]	100[2.0]	100[2.0]	1000[1.0]	1000[0.6]
Smectite — calcareous	0.1[0.5]	10[3.0]	100[0.5]	1000[1.5]	10[1.0]	100[3.0]	10[1.5]
Kaolinite — mixed cation	0.001[0.5]	10[2.0]	100[1.0]	100[0.5]	0.1[0.5]	10[1.0]	10[0.7]
Illite — mixed cation	0.1[0.5]	10[0.1]	1000[0.2]	1000[0.5]	0.1[0.5]	100[1.5]	100[1.5]

[a] P_n = permeability after n pore volumes of flow, P_0 = initial permeability, $[n]$ = bracketed value is the number of pore volumes of flow.

at which it will exit the engineered barrier (facility). Recent results of laboratory studies summarized in Table 2 suggest that such estimates may be optimistic because of the interaction of waste constituents with clay materials [5, 6]. Clay materials may evidence permeabilities three orders of magnitude higher after exposure to concentrated organic solvents such as xylene than their measured permeabilities in water. While effects may differ with exposure to more dilute solutions, the results suggest that contaminated leachate may render a liner less protective over time and hence significantly increase the rate of leachate loss. Such effects are both soil- and chemical-specific and therefore necessitate direct testing of proposed wastes and liners when designing a given facility.

If clay liners crack as a result of loading stress or desiccation, the loss rates may be increased substantially over the designed rate. Moore and Ali [7] found that when crack length exceeds 75% of the depths of the clay liner, permeabilities increase by a factor of 2 to 3. As the density of cracks increases, the ratio of effective permeability to initial permeability grows rapidly.

A summary of problems with admix and synthetic liners that have been observed after exposure to flue-gas cleaning sludges is provided in Table 3 [8]. While each liner differed in its response to the waste, all systems displayed changes in physical properties which could lead to earlier-than-anticipated failure. For instance, decreases in breaking strength and elongation suggest a higher probability of tearing. Density increases suggest chemical changes which may result in degradation. The clearest indicators of failure are the results for admixes and AC40 where leachate was observed with elevated contaminant levels.

It has been suggested that redundant design can elimate leakage from clay liners. This approach is illustrated in Fig. 2 where a leachate collection system in porous sand is put between two clay liners. However, if both clays have equivalent permeabilities, the leachate system will never function under most conditions. The sand must become saturated if leachate is to flow to the pipes and be withdrawn. Complete saturation will not occur since the lower clay liner will pass fluids at the same rate as the upper liner. Leachate can be collected if the lower liner has a lower permeability than the upper liner. In this case, the leachate loss rate is merely that of a single liner with the properties of the bottom liner, and the upper liner and leachate collection system represent unnecessary costs.

Alternatively, one can go to combined synthetic and clay liners or more sophisticated combinations of materials. While these may delay losses or reduce them further, they will also entail significantly higher costs than those currently estimated for secure landfill.

3.3. Human intrusion

The third type of repository failure, human intrusion, consists of a number of possible activities which will bring man into contact with the waste

TABLE 3

Effects of flue gas cleaning sludges on liner materials [8]

Liner type	Liner	Composition	Changes		
			Unconfined strong compression (2 mo)	Breaking strength (BS) and elongation (E)	Density
Admix	Lime	Hydrated ASTM C141-67	464% increase	leachate contains 5—20 times the Cr and B	+1.1%
	Portland cement	Type 1 ASTM C150-78	175% increase	leachate contained 7 times the levels of sulfate and sulfite	unchanged
	Cement with lime	4% type 1 Portland Cement, 6% hydrated lime	187% increase	leachate contained 40 times the Cr	+0.3%
	M179	4% polymer, bentonite blend	complete breakdown after 12 months		
	Guartec UF	4% light gray powder	complete breakdown after 12 months		
	Asphaltic concrete	11% asphalt cement, 1/2 in (max.) aggregate	penetration increased 10%, extensive cracking	while properties did not change, leachate passed through carrying Cr, Se, B and sulfate	
	TACSS 020	6% blackish-brown liquid	14% decrease (12 mo), 25% decrease (24 mo)	sludge penetrated the liner 3/8 in	unchanged
	TACSS 025	6% blackish-brown liquid	12% decrease	sludge penetrated the liner 3/8 in	unchanged
	C400	15% finely ground powder	106% increase	leachate had 3 times the As and B, 20 times the Cr and Se, higher Cu, Pb	+0.3%
	CTS	15% finely ground powder	63% increase	leachate had 20 times sulfate, 100 times Ni	+0.3%
Spray-on	DCA-1295	3/4 gal/yd^2 natural rubber	discolored and thin	significant decreases in both BS and E	-3.3%
	Dynatech	3/4 gal/yd^2 natural rubber	discolored	both BS and E unchanged	+17.3%
	Uniroyal	3/4 gal/yd^2 latex	discolored	-40% (BS)	+17.2%
	Aerospray 70	3/4 gal/yd^2 polyvinyl acetate	discolored, decomposition	-57% (BS)	+33.3%
	AC40	3/4 gal/yd^2 asphalt cement	leachate passed through with Cr, Se, B and sulfate		
	Surcoat	As-supplied molten sulphur	One liner burst during tests	-16% (BS), leachate had twice the Mg and sulfate, 5 times the B, 100 times nitrate and nitrite	
Prefabricated	Total liner	As-supplied elasticized polyolefin		-72% (BS)	+26.2%
	T16	As-supplied black chloroprene-coated nylon		no change in BS	+14.5%

or with waste-contaminated resources. These may include mining, drilling of water supply wells, vandalism, agricultural or commercial development, and inadvertent contact during recreation or work in the area. This is the least predictable of the failure modes, and yet may be the most important.

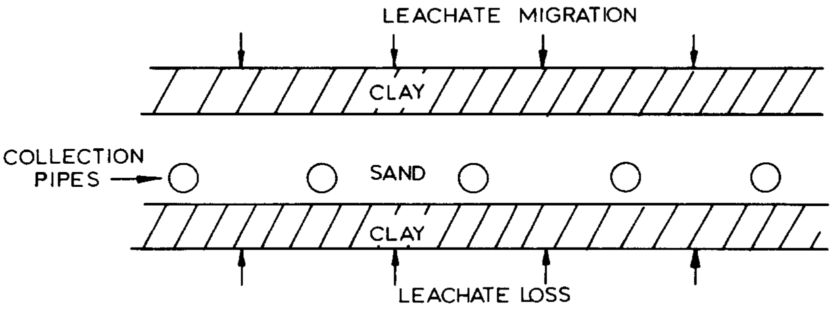

Fig. 2. Redundant clay liner design.

One of the first recorded incidences of hazardous waste damages occurred in Perham, Minnesota, when private wells were sunk into an abandoned disposal site containing arsenic trioxide grasshopper bait [9]. The more recent example of Love Canal indicates that better record keeping will not completely resolve this potential problem. Even though the presence of chemical wastes in the canal was recorded on the deed to the land, within 10 years developers had disturbed the protective clay cap so that precipitation in subsequent wet years could transport contaminants out to the surrounding homes[10]. In a recent evaluation of a Permian Basin salt dome as a potential repository for high-level radioactive waste, it was determined that the most likely mode of failure was the solution mining of the dome for salt with subsequent use of radioactive refined salts by the public [11].

Clearly, the potential for human intrusion is increased when site locations are not recorded or monumented and when land use planning is not exercised. It would appear that RCRA regulations will require such measures in the future. However, their utility is bounded by the assumed viability of the governmental entities involved. While it is convenient to plan in terms of stable government and orderly social evolution, history has proven that such will not be the case. This is particularly true with respect to the infinite time frame associated with toxic metals and other inorganic species. In recognition of the finite life of most social organizations, the U.S. EPA has proposed to constrain the evaluation of nuclear waste repositories with the caveat that all organizational control is lost after 100 years (i.e., all records and means of determining the presence of the wastes is lost after 100 years) [11]. Acceptance of this premise assumes that, over an infinite life,the probability of repository failure is 1.0. All disposal facilities will ultimately fail to the extent that they will release contaminants to man and/or the environment.

3.4. Potential remedies

A short-term solution to the specter of guaranteed failure is the redesign of landfills into storage facilities. By their nature, storage facilities offer two advantages over landfills:

(1) Storage implies a finite lifespan. In this context, the probability of failure can be designed to be much lower than 1.0, thus rendering risks acceptable.

(2) By regulation, storage facilities will entail continued maintenance and routine observation, thus eliminating the "out-of-sight, out-of-mind" mentality that allows closed sites to be "lost" or orphaned.

The first point implies that a definite storage period is selected. Indefinite storage is tantamount to disposal. Storage anticipates some event in the future that will remove the need for further containment. Conceptually, that event may be the development of an economic recovery process or a lower-cost destruction alternative. This approach is being used by General Motors. They have proposed a metal sludge storage facility in Rochester, New York, with a 5-year life. At that time, they anticipate successful conclusion of ongoing research which will allow them to rework the waste and recover metals. The above-ground landfill concepts employed in Europe appear to approach indefinite storage in concept but offer the same added protection provided by the high visibility of such facilities.

Even with storage facilities, however, there will remain the need for land disposal. There are materials such as arsenic which are toxic in most forms and presently have no large-volume use in commerce. For these materials, some method of release to the environment such as land disposal is required. In these cases, risk reduction efforts must revolve around reduction in consequences.

4. Reduction of consequences

The consequences of repository failure will depend on a number of important factors including the intrinsic toxicity of waste constituents, the duration of exposure to those constituents and the strength (concentration) of exposure. These three parameters become the focus of efforts to reduce consequences.

4.1. Intrinsic toxicity

The intrinsic toxicity of a waste constituent may or may not be a controllable entity. Many constituents display different toxic properties depending on their chemical form. For instance, arsenate is generally less hazardous than arsenite. The degree to which waste constituents can be taken to their least toxic forms represents the level of risk control available through addressing intrinsic toxicity. The approach is not broadly applicable, however, since some metals and inorganic species are either toxic in most forms or can be converted in the environment back to more toxic forms. Therefore, the risk reduction arising from conversion is temporal at best, but the risk can be made acceptable.

4.2. Duration

The duration of exposure to toxic constituents is roughly proportional to the level of risk posed in that the longer exposure generally results in greater damage. Duration of exposure is dictated both by the quantity of waste and the specific transport mechanism involved at a given site. If contaminant movement originates in ground-water systems, rates are slow and a receptor at any given point will be exposed for a longer time (i.e. the plume will take longer to pass). Similarly, contaminants which bind to sediments will move slowly in runoff and surface waters. Vapor release to the atmosphere encounters greater velocities and, therefore, is likely to result in shorter exposure duration times. Unfortunately, the slower routes of transport are also the most common route of contaminant loss from repository failure; hence, exposure durations are likely to be long. Therefore, in order to reduce the time a stationary point would be exposed to the contaminated plume for a site, one would have to reduce the quantity of a waste at a given site (i.e. use a great number of small landfills). This approach would appear to be counter-productive. Not only does it drive up costs, it generates the need to site more facilities (something that is increasingly more difficult to do) and it increases the number of sites where failure can occur.

4.3. Concentration

The third and final control factor for reducing the consequences of repository failure is the concentration at which receptors are exposed to waste constituents. For most toxic materials, there is a concentration or concentration range below which no noticeable effects occur. Indeed, with some toxic metals, there is a minimal nutritional intake requirement. Some current theories hold that with carcinogens a threshold may not exist. For such substances, damage potential may start at one molecule of exposure and increase proportionally from there on. Even here, however, it is generally accepted that levels which increase the incidence of cancer to one or fewer cases in 10^6 exposures cannot be differentiated from background risks. Therefore, risks from site failure can be reduced to acceptable levels by controlling the exposure concentration.

Contaminant concentration is generally determined by the availability of the contaminant form. For instance, the more soluble the waste form, the higher the resulting concentration in leachate is likely to be for a given volume of leachate. Hence, risk reduction by concentration control involves efforts to render the waste as immobile as possible and then to put it where releases will gain the maximum possible dilution prior to contact with a receptor of concern. The first of these considerations lies at the heart of waste fixation. Processes and reagents are formulated to put waste in as soluble a form as practicable so that subsequent leachate contains as low a level of toxic constituents as possible. To date, a number of proprietary and nonproprietary materials have been marketed with excellent abilities to fix metal-bearing sludges and some inorganic materials. Little has been done to fix organic contaminants and nonmetallic species. Wastes can also be made less mobile by emplacing them in soils which have a high affinity for chemical constituents in the waste. Whereas a chemical will have a given solubility, when soil is added to the solution, the solubility appears to drop because of the creation of less soluble sorbed or exchanged forms.

The second point, maximizing dilution potential, addresses the area of failure design. Once it is accepted that failure will occur, the repository design should be selected on the basis of minimizing the concentrations in effluents associated with failure (i.e., encourage and augment dilution). This can be accomplished by physical dispersion of the fixed waste in the soil or by selection of a site which will maximize mixing/dilution. While such an approach is politically difficult at this time (dilution is not the solution to pollution) it is in fact implicit in all disposal schemes for nondegradable materials. In fact, proposed NRC criteria for high-level nuclear wastes are being written in terms of allowable quantities of loss in given time frames.

5. A hypothetical case

In order to evaluate the options available for reducing risks associated with hazardous waste disposal, consider the case of an arsenic waste. Waste calcium arsenate, $Ca_3(AsO_4)_2$ is disposed in a remote area landfill where it resides for 150 years. In that time frame, sufficient social change occurs that records are lost and no information is left to identify the nature of buried materials in the area. The diversion of surface water and minor climatic changes have rendered the area suitable for irrigated agriculture. Over time, the ground-water levels rise to the point of contact with the disposal cells. Subsequently, families move to the area and complete shallow wells into the abandoned repository. What is the difference of the residual risks between the hypothesized repository of wastes, the same repository with fixed calcium arsenate, and a site where the arsenic has been dispersed throughout the soil at low levels?

If the wastes themselves are below the water table, the resulting concentrations will depend on the equilibrium solubility of the arsenic and soil attenuation properties. Hence, the highest concentrations will be found in the well associated with the standard landfill approach where the waste will supply arsenic to the ground-water at the level of its maximum solubility, 48 mg l^{-1}. Had the arsenic waste been fixed, it would be in a matrix with much lower solubility than calcium arsenate (CA). Hence, the waters associated with the waste would have comparably lower levels of arsenic. In studies with cement, CA at 25% was found to yield leachate at $\leqslant 2.0$ mg l^{-1} As over a 9000 h period. When heated to form a slag, the leachate contained $\leqslant 0.25$ mg l^{-1} As over an 8000 h period. In cast and cured cement, aresenic levels were reduced to $\leqslant 0.01$ ppm. When the latter was also roasted, leachate levels increased to $\leqslant 0.04$ mg l^{-1} As [12]. Hence, while exposure in the initial scenario would result in potential hazards, fixation would have reduced arsenic levels below the primary drinking water standards of 0.05 mg l^{-1} for arsenic.

Lower concentrations could also have been obtained if the CA was dispersed throughout the soil at low levels so that it could benefit from maximum attenuation. When CA was mixed with clay and roasted in small pellets, leachate was found to contain $\leqslant 1.0$ mg l^{-1} As [12]. Arsenic is known to adsorb onto hydrous iron oxide surfaces as well.

Additional disposal options can be identified which would reduce concentrations and risks below those resulting from the basic landfill design. Had intentional leaching been allowed, little or no arsenic may have been left by the time the human intrusion occurred. Similarly, the wastes could have been injected in an aquifer at levels below drinking water standards with no noticeable effect. Higher levels could have been injected had it been a brine aquifer since it would not be employed as a potable water source and any salt removal treatment to render it potable would remove the arsenic as well. Finally, the waste or the fixed waste could have been dispersed in the ocean at levels essentially nondetectable against background concentrations.

6. Conclusions

Regardless of state and some federal efforts to ban landfilling of certain hazardous wastes, economic factors and the lack of safe uses for some constituents will always necessitate the disposal of these wastes in the environment. For those wastes which do not undergo degradation to nontoxic forms, failure in the way of loss of toxic constituents is virtually assured. In these cases, traditional means of land disposal must be replaced or rethought to reduce risks associated with losses. This may take the form of designed failure to assure effluents are dilute and/or fixation/conversion of wastes to low-mobility forms. Regardless of the specific approach taken, any land disposal scheme for hazardous wastes should contemplate failure and include features which will render the consequences posed by that failure insignificant. Fig. 3 is provided as a means of ordering the options available for safe disposal of wastes. It is designed on the basis of selecting options whose time frames remove hazardous constituents from the facility prior to the time when failure may occur. In this way, the management plan is designed around anticipated failure. Risk considerations have been utilized to consider both the probable timing of events and the potential consequences.

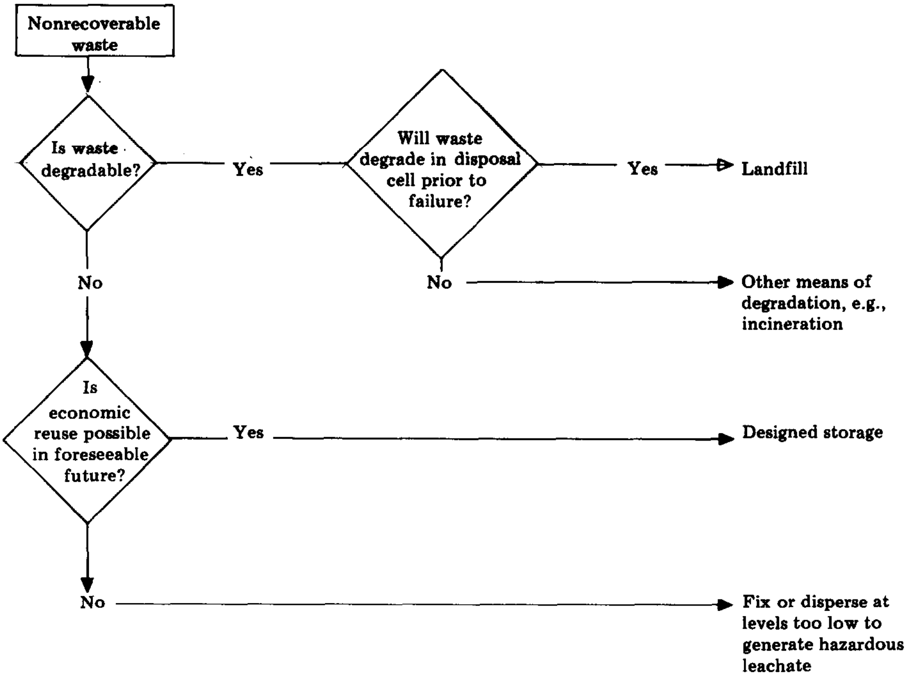

Fig. 3. Decision process for land disposal of wastes.

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