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Elimination of the Hazards from Hazardous Wastes

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The "hazard" associated with a waste essentially controls the overall engineering approach to finding suitable alternatives for solving potential disposal problems. It should be recognized that all factors affecting environmental equilibrium must be considered, including product sales, process design, financing, pre- and end-of-pipe treatment, residuals management, and ultimate bioaccumulation of residuals.

To meet this challenge, a systems approach to waste treatment and residuals disposal provides a logical approach, but this management concept requires a thorough understanding of the important physical and chemical aspects of the problem, as well as many social implications of the resulting decisions. Thus waste management within a plant necessarily involves process control, pretreatment and end-of-pipe treatment. Further, it follows that residuals management from a disposal point-of-view must ultimately embrace what is called the "multi-barrier concept." In essence, hazard elimination occurs in varying degrees during each phase of a properly engineered system.

Introduction

The objective of this presentation is to detail the basic components of a waste management system embracing the "multiple barrier concept" and extensions thereof, such as detoxification and volume reduction methodologies, the intent being a discussion of the elimination of the "hazard" from hazardous solid wastes. The paper briefly summarizes; (a) hazardous waste guidelines, (b) definition of toxic and hazardous wastes, and (c) principles of ultimate disposal. A more detailed discussion follows; (a) separation and waste partitioning, (b) volume reduction, (c) segregation and containerization, and (d) isolation. Finally, an example is presented on how one barrier system, i.e. clay soil, can be evaluated as a disposal site.

Estimates of the annual production of hazardous wastes have ranged upwards to 9 million tons (8 Tg) during 1970 and production is expected to continue increasing (*1–3*). When these numbers are reduced to a per capita basis, the problem becomes manageable. A summary of hazardous waste production by region has been published (*4*). A significant portion of these hazardous wastes are, or eventually will be, a solid waste problem. Representative hazardous materials found in various industrial waste streams are given in Table 1.

The handling of the hazardous materials is complicated by the increasing magnitude of waste generated each year, the variety of materials that become refuse, the vast array of chemicals that may eventually leak from containers and burial sites; the difficulty of monitoring landfill sites for leachates, the difficulty of adequately sequestering waste to inhibit leaching, the variability of soils and their sorption capacities for leachates, the variability of soil permeability, and the cost of safe disposal versus that of assessing real or imaginary risk (*5*).

Due to these complexities, the removal of the hazard from hazardous wastes requires a systems approach. For example, the least cost of an activated sludge and carbon adsorption system is a function of both processes operating simultaneously (Fig. 1). The optimal design range for the least-cost system could not be ascertained by assessing the performance of the two processes independently.

Hazardous Waste Guidelines

An important consideration over the next several years will be the impact of the toxic effluent limitations which are currently being prepared by EPA in accordance with Section 307 of PL 92-500. In a consent decree from the Circuit Court of Appeals in Washington, D. C., the EPA agreed to promulgate toxic effluent limitations for selected constituents

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Table 1. Representative hazardous materials found in industrial waste streams.[a]

Industry	As	Cd	CHC[b]	Cr	Cu	CN	Pb	Hg	Miscellaneous organics	Se	Zn
Mining and metallurgy	x	x		x	x	x	x	x		x	x
Paint and dye		x		x	x	x	x	x	x	x	
Pesticide	x		x			x	x	x	x		x
Electrical and electronic			x		x	x	x	x		x	
Cleaning and duplicating	x			x	x		x		x	x	
Electroplating and metal finishing		x		x	x	x					x
Chemical manufacturing			x	x	x			x	x		
Explosives	x				x		x	x	x		
Rubber and plastics			x			x		x	x		x
Batteries		x					x	x			x
Pharmaceutical	x							x	x		
Textile				x	x				x		
Petroleum and coal	x		x				x				
Pulp and paper								x	x		
Leather				x					x		

[a] Data of Battelle Memorial Institute (*4*).
[b] Chlorinated hydrocarbons.

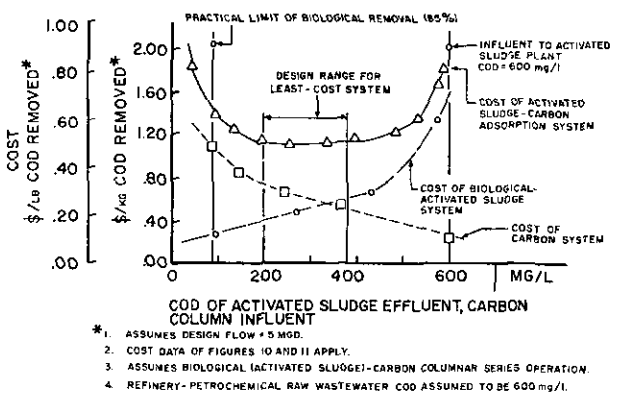

FIGURE 1. Development of design basis for lease-cost biological-carbon system (5 MGD).

from a list of some 65 different classes of compounds. Over 109 different chemical compounds are being studied in detail to determine whether or not toxic limitations should be promulgated under Section 307. A listing of some of the toxic pollutants studied for which effluent limitations will be promulgated is given in Table 2.

The current guidelines dealing with solid wastes are based on the Solid Waste Disposal Act, as amended (SWDA). Section 212 of the Act was the origin of EPA's Report to Congress; Disposal of Hazardous Wastes (1973). Section 204(a) of the SWDA Act provides basic research, demonstration and training mandates. Section 204(b) instructs EPA to collect information. Section 209 is a mandate for guidelines for recovery, collection, separation and disposal systems. Section 211 of SWDA states that all Federal agencies shall ensure compliance with Section 209(a). Section 209(b) calls for model codes, ordinances, and statutes, as well as issuances of data on costs of constructing, operating, and maintaining technical, feasible methods for collection, separation, disposal, recovery, and recycling.

Definition of Toxic or Hazardous Waste

A rational approach to defining toxic and hazardous wastes is to view a biological entity in equilibrium with its environment and attempt to quantify those insults on the biological entity that causes a disequilibrium or negative response. In the study of hazardous substances, two parameters of importance are dose and time.

An important point to note about the tests for acute and chronic toxicity is that, although the tests might isolate the relative toxicity of a substance, they are virtually useless for predicting levels at which no toxic effects will occur. The result is that potentially toxic and hazardous substances can be identified, but criteria for safe exposure are lacking; therefore, these wastes have a special stigma imposed on them because of the possibility of unknown effects. This psychological stigma can often impede rational implementation of treatment and ultimate disposal schemes for these toxic and hazardous wastes.

Principles of Ultimate Disposal

No matter what treatment or ultimate disposal scheme is selected, man-made residuals will eventually reside in the atmosphere, lithosphere, or hydrosphere. An understanding of the reactions and

Table 2. Toxic pollutants for which EPA may promulgate effluent limitations.

Acenaphthene	Endrin and metabolites
Acrolein	Ethylbenzene
Acrylonitrile	Fluoranthene
Aldrin/Dieldrin	Haloethers
Antimony and compounds	Halomethanes
Arsenic and compounds	Heptachlor and metabolites
Asbestos	Hexachlorobutadiene
Benzene	Hexachlorocyclohexane
Benzidine	Hexachlorocyclopentadiene
Beryllium and compounds	Isophorone
Cadmium and compounds	Lead and compounds
Carbon tetrachloride	Mercury and compounds
Chlordane	Naphthalene
Chlorinated benzenes	Nickel and compounds
Chlorinated ethanes	Nitrobenzene
Chloroalkyl ethers	Nitrophenols
Chlorinated naphthalene	Nitrosamines
Chlorinated phenols	Pentachlorophenol
Chloroform	Phenol
2-Chlorophenol	Phthalate esters
Chromium and compounds	Polychlorinated biphenols
Copper and compounds	Polynuclear aromatic hydrocarbons
Cyanides	Selenium and compounds
DDT and metabolites	Silver and compounds
Dichlorobenzenes	2,3,7,8-Tetrachlorodibenzo-*p*-dioxin (TCDD)
Dichlorobenzidine	Tetrachloroethylene
Dichloroethylenes	Thallium and compounds
2,4-dichlorophenol	Toluene
Dichloropropane and dichloropropene	Toxaphene
2,4-dimethylphenol	Trichloroethylene
Dinitrotoluene	Vinyl chloride
Diphenylhydrazine	Zinc and compounds
Endosulfan and metabolites	

forces controlling the movement of a pollutant in the environment is essential if effective treatment and ultimate disposal of toxic and hazardous wastes is to be attained. For example, decisions involving chemical waste disposal will be based on knowledge of chemical form, persistence, acute or chronic toxicity, genetic effect, flammability and reactivity. A study of the natural environmental forces and reactions which maintain equilibrium of systems illustrates quite well the basic principles of handling toxic and hazardous substances by transforming them into less harmful substances or isolating them in a repository such that release into the dynamic parts of the environment occurs at such a low rate that toxic effects are not realized.

The greatest fallacy with the environmental crisis and residuals disposal is that acceptable environment can be obtained by reducing or even abolishing our dependence on "technology" or by neglecting cost considerations. The fact is that residual wastes and their ultimate disposal will require technological solutions—and many of them. Finally, the cost to support waste treatment, recycle, reuse, collection and disposal must be borne by the consumer in the form of higher prices and by the taxpayer in the form of higher taxes.

The handling and disposal of toxic and hazardous wastes is a multipronged problem that involves: (a) separation and waste partitioning, including process control through technological improvement, waste stream separation, and recycling; (b) inplant waste treatment, including chemical, physical, and biological treatment; (c) in-plant waste disposal, involving recycling, containerization, and incineration; (d) volume reduction through drying, incineration, and compaction of end-of-pipe residuals; (e) translocation involving storage, containment, and transportation; and (f) ultimate disposal considering isolation through minimization of water movement, and maximization of passive barriers through which migration of hazardous materials might take place.

Separation or Waste Partitioning

The first step in an approach to eliminating hazardous agents from solid waste is to separate the potentially dangerous substances and provide a means of effectively removing these agents from the waste. This procedure can be as simple as separating the hazardous agents at their source during process control or as complex as using physical, chemical, or biological pretreatment to extract or

detoxify the agents in the waste stream.

Separation and waste partitioning have the distinct advantage of reducing the volume of solid wastes to be handled (*6*). Often, relatively innocuous solid wastes will be combined with the hazardous wastes, thereby increasing the bulk which must be disposed of as a hazardous substance. The methods of separation and waste partitioning to be discussed in this section include process control and various treatment procedures.

Process Control. Process control entails separating the hazardous agents at the source. The initiation of control on the toxic wastes at this point is the most cost effective with respect to minimizing the volume and segregating the hazardous wastes. These concentrated, smaller volume waste streams are more amenable to the use of hazard reduction techniques such as sophisticated and expensive physical and chemical detoxification schemes.

Although process control economics vary from one industrial situation to another, in general, separating the hazardous agents at the source has the economic advantage of reduced treatment system size, reduced chemical cost, and amenability to recycling of valuable by-products (*5*). Thus, regardless of the industry, process control should be investigated for its potential for hazard reduction.

Chemical Treatment Chemical treatment schemes involving techniques based on chemical precipitation, oxidation, photochemical degradation, and pH adjustment can be employed to isolate or detoxify certain hazardous agents. Toxic heavy metals such as lead and cadmium can be isolated by hydroxide precipitation (*7*). Lime precipitation followed by filtration is probably the most dependable method of removing cadmium salts and highly stable hydroxide precipitate at an alkaline pH. The completeness of the reaction is a function of pH, and lime addition to pH 10 is required. The cadmium removal process requires provisions for lime addition, rapid mix, flocculation, sedimentation, filtration, and neutralization to a pH between 6 and 9.

Cyanides can be reduced with appropriate pH control, chlorine dosage, and residence times. This alkaline chlorination process is the most proven treatment technology for removing cyanides from waste streams (*8*). Chromium removal can be effectuated by several treatment techniques. These techniques involve chemical reduction and precipitation, ion exchange, and electrolytic reduction and precipitation. Each of these processes has advantages and disadvantages. However, the electrolytic process is finding increasing application, especially for treating cooling water blowdown (*8*). Table 3 gives a comparison of costs for removal of certain of these toxic metals for a model refinery. Although these costs are for an aqueous waste stream, the metals not detoxified in the aqueous waste stream will eventually reside in sludges.

Numerous toxic metals can be precipitated by the previously cited metal hydroxide technique (*9*). The principle involved in heavy metals removal by hydroxide precipitation is that virtually all metals have a low point in their solubility curve at some alkaline pH value. The hydroxides of the various metals therefore precipitate at different pH's (Fig. 2).

The detoxification of hazardous wastes not only occurs by induced chemical precipitation during pretreatment schemes but also after placement in the shallow land burial site. The precipitation of toxic metals from landfill leachate is well documented (*10*). The dynamic nature of this soil-leachate interaction can be illustrated schematically (Fig. 3). For this reason, the design of the burial site with respect to selection of lining materials and soil geomorphology is an important aspect in the system design for containment of hazardous wastes.

A technique, similar to hydroxide precipitation, for removal of toxic metals is removal by sulfide precipitation; this method utilizes either inorganic sulfide, hydrogen sulfide gas, or sulfide generated by anaerobic organic activity. This technique is based on the principle that virtually all metal sulfides have a low solubility. Mercury is successfully separated by this technique as well as with the addition of ferrous chlorides (*11*).

Extensive work has been done on detoxifying

Table 3. Costs for removal of selected waste constituents from model refinery effluent.

Constituent waste	Amortized capital cost, $/1000 gal	($/m³)	Annual Operation & Maintenance costs, $/1000 gal	($/m³)	Annual total costs $/1000 gal	($/m³)	$/1000 gal removed	($/m³ removed)
Cadmium[a]	0.13	(0.034)	0.27	(0.071)	0.40	(0.11)	—	—
Cyanides[b]	0.22	(0.058)	2.02	(0.53)	2.24	(0.59)	2.68	(0.71)
Chromium[c]	0.23	(0.061)	0.43	(0.11)	0.66	(0.17)	4.06	(1.07)

[a] Cost based on treating entire refinery process effluent.
[b] Assumes only FCC and coker process wastes are treated.
[c] Assumes treatment and cooling tower blowdown only; 190,000 gpd.

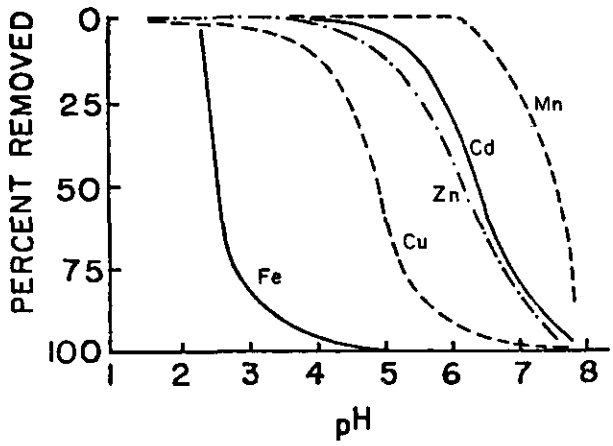

FIGURE 2. Heavy metal behavior as function of pH in mine drainage (9).

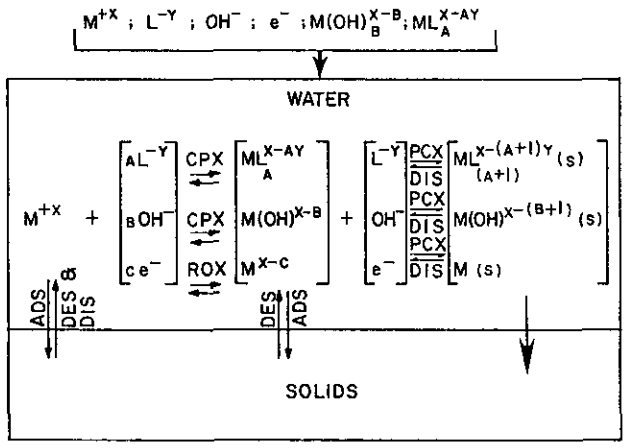

FIGURE 3. Schematic model of metal ions transformation in soil–water system: CPX = complex formulation; PCX = precipitation, DIS = dissolution, ROX = reduction oxidation reaction; ADS = adsorption, DES = desorption (10).

sludges by removing toxic metals using a procedure for fractionating metals by several extractions with chelating agents (12). Table 4 gives the extractability of metal precipitates by various reagents. The retention mechanisms of the sludge for the metals include ion exchange, sorption, chelation, and precipitation.

Certain pesticides when oxidized with potassium permanganate are effectively detoxified. Photochemical degradation can also detoxify some pesticides (13). Highly alkaline conditions render some chlorinated hydrocarbons and organophosphate manufacturing wastes relatively innocuous.

Physical Treatment. In liquid waste streams, numerous physical treatment schemes are possible for separation and partitioning of the hazardous agents. The bulk form of the solid wastes limits the implementation of most physical treatment techniques. However, plausible schemes using activated carbon, which has been found effective for removal of certain pesticides and at low pH's, chromium; and foam fractionation, which also removes pesticides, are viable methodologies for separation of some hazardous agents from solid waste.

Implementation of physical treatment schemes such as carbon adsorption is costly, as shown in Table 5. However, in those cases where these treatment schemes are viable, high removal percentages are realized.

Recently, in a corollary to carbon adsorption, the use of clays for detoxification of hazardous materials has been proposed. Clays, in particular bentonite clays, have exhibited adsorptive capacities 10 to 20 times greater than activated carbon for nonionic surfactants (14). Although the potential for regeneration of clays is not as plausible as for activated carbon, the mixing of clays and hazardous solid wastes prior to shallow land burial as a hazard reduction technique is still a viable alternative.

Foam separation has been used to detoxify bleached kraft mill effluents (15). It exploits the phenomenon that toxic surface-active substances such as resin and unsaturated fatty acids can be foam fractionated and separated. The resulting foam after collection and collapsing is biologically treated.

The role of chemical precipitation in the soils to detoxify hazardous agents has been previously cited. In a similar manner, the sorption and ion exchange capacity of the soils can provide a mechanism for detoxification. The fine particles of soil and sediments have enormous surface areas relative to their sizes, and carry electric charges.

Table 4. Extractability of model metal precipitates by various reagents.[a]

Extractant	Percent of total metal			
	Pb	Zn	Cu	Cd
Carbonates				
Oxalate	1	63	74	10
$Na_4P_2O_7$	79	18	19	1
Citrate	4	96	35	<1
NH_2OH	1	62	27	<1
Acetic acid	33	73	50	7
KF	<1	1	<1	<1
EDTA	91	91	95	68
Sulfides				
Oxalate	<1	1	10	6
$Na_4P_2O_7$	18	2	<1	10
Citrate	1	<1	5	2
NH_2OH	7	3	1	7
Acetic acid	13	6	1	26
KF	<1	1	<1	1
EDTA	29	2	10	3

[a] Data of Stover et al. (12).

Table 5. Case histories of industrial activated carbon treatment.

System	Flow, MGD	Organic removal: BOD_5, lb/day	Organic removal: COD, lb/day	Amortized capital cost[a] ($/1000 gal)	Amortized capital cost[a] ($/lb BOD)	Amortized capital cost[a] ($/lb COD)	Annual operation and maintenance costs ($/1000 gal)	Annual operation and maintenance costs ($/lb BOD)	Annual operation and maintenance costs ($/lb COD)
Petroleum refinery: process wastes without biological treatment, continuous columns	2.16	783	2,090	0.31	0.62	0.23	0.134	0.37	0.14
Petroleum refinery: storm/process water without biological treatment, fixed beds[b]	0.85	—	1,311	—	—	—	0.56	—	0.25
Mixed industrial: tertiary treatment, continuous columns[c]	48.5	5,600	67,550	0.17	1.43	0.12	0.27	2.31	0.19
Petroleum refinery: powdered carbon addition to aeration basin	1.08	11	347	None[d]			0.03	2.72	0.09
Municipal: tertiary powdered activated carbon addition to aeration basin	10.0	—	—	0.08	—	—	0.02	—	—

[a] Adjusted to 1977 and 10% interest for 15 years.
[b] Intermittent operation.
[c] Excludes cost of necessary pretreatment by granular-media filtration.
[d] Manual addition of powdered activated carbon.

Toxic ions and molecules are held to the charged surfaces in various ways, by forces that range from those due to weak residual electric charges to strong chemical bonds. Often a leachate ion replaces an ion already present on the surface, thus releasing the second ion to the leachate. These processes are probably more important than solubility in the retention of toxic substances in the soil.

Biological Treatment. Biodegradation of hazardous substances such as certain hydrocarbons, pesticides, and heavy metals (cyanide, for example), has been the subject of a number of studies. Soils, particularly the surface horizon to a depth of 1–3 ft (0.3–0.9 m), contain large numbers and varieties of aerobic, facultative, and obligate anaerobic organisms which singly or together can provide an effective biological detoxification of certain hazardous agents.

Soil tests, using both lysimeters and field applications on 400 ft^2 (37 m^2) plots for periods ranging from 40 to 45 weeks, were conducted to measure the accumulation of pesticides: malathion, diazinon, carbaryl, and 2,4-D, which were added to sewage in concentrations of 0.1 mg/l. (*11*). The concentration of the pesticides was greatest at the soil's surface, but occasionally slugs of pesticides would break through for no discernible reason. Generally, however, the pesticides neither accumulated nor moved downward more than about 36 in. (0.9 m). Biological and chemical degradation was deemed to be the reason for the disappearance of the pesticides, which have half-lives under these conditions of approximately 4 weeks.

A summary of the literature produced little evidence that the pollution of ground water by chemicals was extensive or significant (*16*). The reasons cited for this were the processes of volatilization, biodegradation, and sorption active in the soils. Of these processes, biodegradation was considered the most significant.

Recent studies have affirmed the amenability of some landfill leachates to biodegradation (*17, 18*). Aerobic and anaerobic biological processes were most effective in treating leachates derived from recently constructed landfills, whereas physical-chemical processes worked best for treating leachates from stabilized landfills.

Use of biodegradation as a pretreatment device prior to shallow land burial for the detoxification of hazardous solid wastes may not be practicable. A more rational approach is to incorporate one or more "passive barriers" between the waste and the environment as part of the multiple barrier concept to prevent migration of the waste so that sufficient time for long-term biodegradation is possible. In this manner, removal of hazard from hazardous

Table 6. Effects of initial phenol concentration on decomposition rates.[a]

Initial concn.	Average VSS, mg/l.[b]	Phenol/ VSS mass Ratio	Lag time, days	decomposition rate q, day^{-1}
500	1,000	0.536	0.25	0.68
1,000	1,000	1.072	0.95	0.52
10,000	450	23.8	0.95	1.33

[a] Data of Armstrong et al. (*19*).
[b] Volatile suspended solids.

waste may occur although the actual locality of the detoxification process is within the shallow land burial site.

Use of biological countermeasures for removal of hazardous material spills has indicated that 10,000 mg phenol/l. can be decomposed (*19*). Table 6 shows the effects of initial phenol concentration on decomposition rates. In these tests, bacteria were cultured in phenol solution (500 mg/l.).

Volume Reduction (Specialized Methods)

A natural extension of separation and waste partitioning procedures is volume reduction. This process is also amenable to efficient segregation and containerization of the hazardous material. The four basic methods for achieving volume reduction are drying, incineration, compaction, and recycling. Drying is advantageous with respect to volume reduction by removal of moisture as would be the case for handling waste sludges with high toxic metals concentrations. Incineration can result in an 80–90% volume reduction and complete detoxification of the residuals. However, the waste must be amenable to incineration and also must not pose a potential air pollution problem. Compaction is closely associated with containerization and is often achieved at the same time the waste is containerized. Recycling and salvaging of the hazardous waste to maintain it in the industrial process can be effective, particularly in those plants where strict process control is maintained.

Drying and Dewatering. The dewatering of sludges containing hazardous agents follows a typical sludge handling procedure: dewatering with filter presses, vacuum filters, centrifuges, or sludge drying beds. Solid wastes with a high moisture content can be dried by using dryers or by spreading in solar drying beds. In addition to the volume and

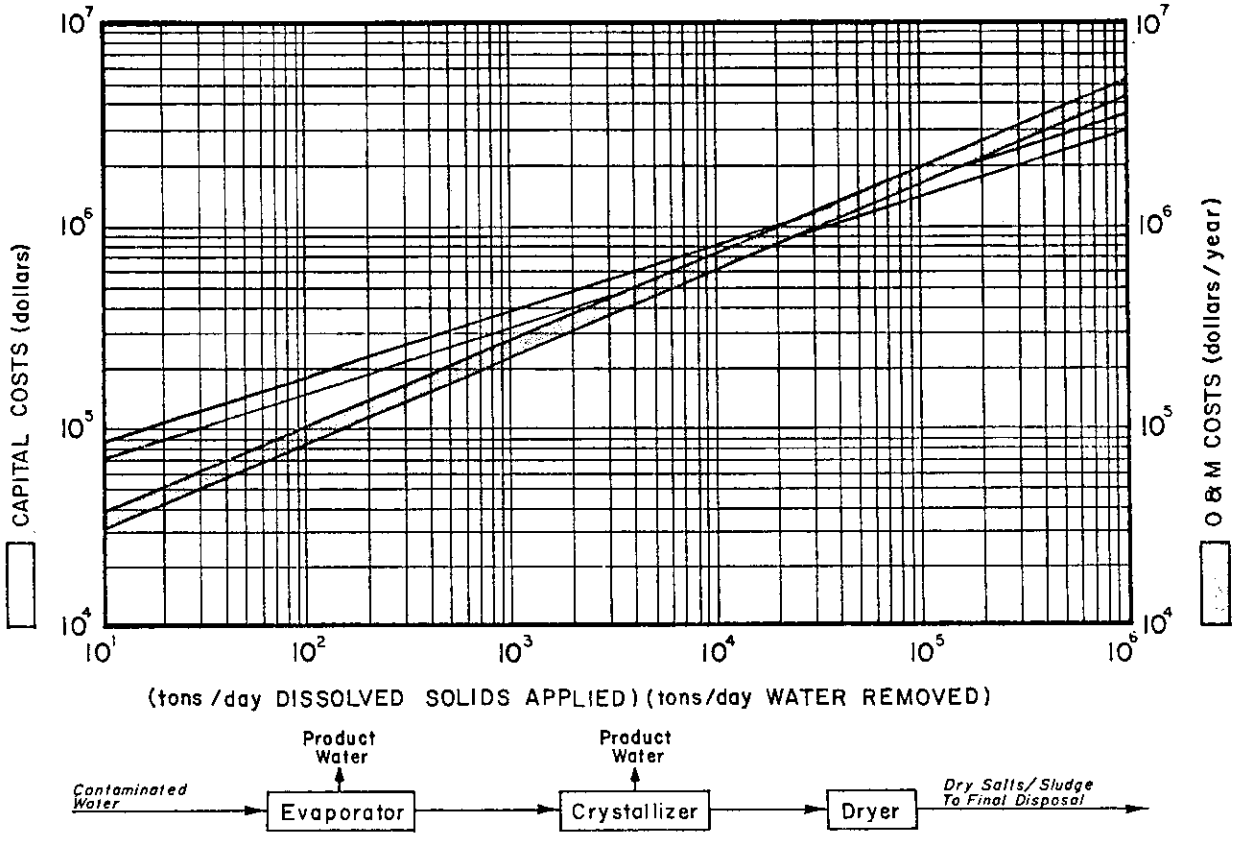

FIGURE 4. Capital and operation and maintenance costs for evaporation.

weight reduction in the wastes, an advantage is gained by removing one of the primary vectors for migration of the hazardous agents from the waste in the event of accidental release during transport; the vector being the movement of water through the hazardous waste material (*20*). The costs of evaporation and vacuum filtration are substantial (Figs. 4 and 5).

Incineration. The decision to incinerate depends on the type of hazardous solid waste, moisture content, organic fraction, heat content, economics, and the availability of land. Whenever feasible, incineration should be considered. This process significantly reduces the volume, generally will also detoxify the waste, and gives a product amenable to compaction and containerization resulting in enhanced ease of handling. Incineration processes include the stationary hearth incinerator, the multiple hearth furnace, the rotary kiln, the fluidized bed reactor, and the open pit incinerator. Each type of incinerator operates properly only within a limited range of temperatures. Generally speaking, for efficient operation, the materials burned must have a fairly uniform BTU value. This may require the blending and mixing of wastes to be burned and the addition of auxiliary fuel. Capital costs for incinerators are high, particularly for the smaller units (Fig. 6). In some cases, complete elimination of the hazardous agent may be obtained through incineration (*13*).

Compaction. Three types of equipment are suitable for compacting wastes, depending on the type and form of the hazardous solid waste. These are the compactor, the baler, and the bagger. Compactors force materials into the final storage, shipping, or disposal container. A commonly used container is the 210-l. (55-gal) drum. Volume reduction by this method is generally minimal and the primary advantage is from the perspective of handling ease. Balers compress the waste into bales, which are then wrapped, tied, or banded for storage and eventual shipping for disposal in burial grounds. Due to the nature of the waste for which this method is applicable, significant volume reduction can be realized. Baggers compress the waste into a desirable shape for handling.

Compaction and containerization are normally realized at the same time. Certain hazardous materials are more readily suitable for compaction than others. Among these are contaminated paper, cloth, rubber, plastics, wood, glass, and lightweight metal objects. Among the most difficult to handle are viscous solids or solids with a high moisture content, and corrosive, pyrophoric, and explosive wastes.

Segregation and Containerization

The next phase of residuals management involves containment for transportation and storage. This phase is accomplished during the compaction process and the compacted material may serve as a passive barrier if the physical integrity of the solid

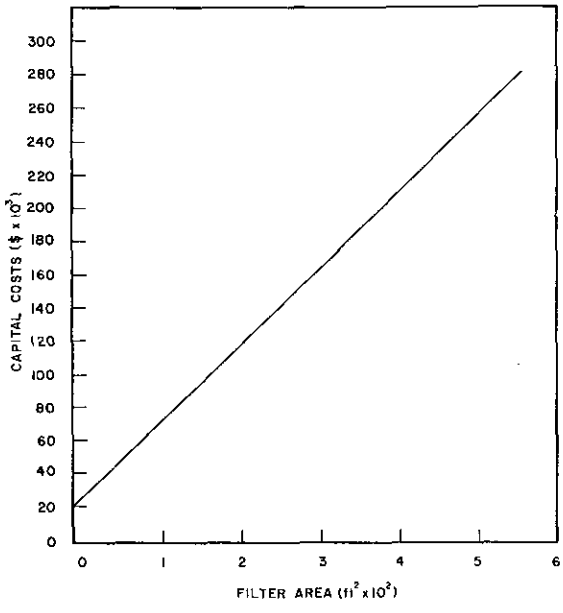

FIGURE 5. Capital cost relationship: vacuum filtration (*21*).

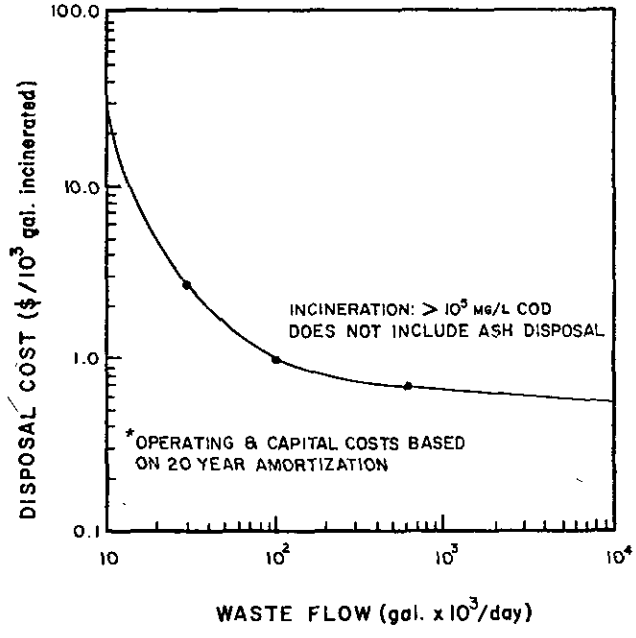

FIGURE 6. Capital cost relationship: incineration (*21*).

waste is retained. Two techniques are usually employed to achieve this component of the multiple barrier concept. These are containment and encasement. Encasement is usually combined with one or more storage methods. The burial site itself, with proper use of clays or other liner materials, can become a container. This aspect of the multiple barrier concept is more effective in reducing water movement than maintenance of physical integrity.

Containment. The initial containment of hazardous solid wastes provides temporary storage, facilitates waste transfer and transportation, improves burial operations, provides a more structurally stable burial site, and reduces the volume requirements for the burial site.

The most commonly encountered method of containment for storage and transport of hazardous wastes is the use of drums. Drummed wastes may include solids such as pesticides, tars, and hazardous sludges and liquids such as acids and solvents. Often drums are used for storage and disposal of off-grade product.

Depending on the type and form of the waste, other containers used are the previously cited wrapped, tied, or banded bales, bags, and boxes (*22*). The two common solid waste baling systems involve high-density baling and shredding followed by low-compression baling and tying. The basic differences in the two balers are that the first employs a large high-pressure baler adapted from scrap metal applications, whereas the second baler is adapted from low-density reclamation applications. Containers provide temporary storage and transport integrity.

Encasement. A method of improving the passive barrier is encasement. The use of concrete as an encasement material is widespread. Drums encased with concrete have been used for segregating hazardous wastes from the environment for a number of years. More recently, an interest in developing a technology for encasement in plastics and vitreous materials has been expressed (*23*). Various encasement materials include: polyethylene, asphalt, lime/fly ash, portland cement, plaster of Paris, metal silicate, bentonite, and vermiculite.

Encasement technology development is an area in which much active research is occurring. For example, a scheme has been proposed for agglomerating hazardous sludges in polybutadiene resin and then encapsulating the agglomerated sludge in a jacket of polyethylene (*24*).

The concept of encasement extends beyond simply enclosing containers in a material. It can also apply to the design of the burial site itself. The use of liners such as clays or asphalts in the burial site provides a further barrier against migration of the hazardous wastes.

Isolation

The concept of isolation involves segregating the hazardous wastes from the environment by burial of the wastes at remote sites and locations which do not permit the rapid dispersal of toxic materials into the biosphere. Ultimately, with respect to geologic time, the residuals of hazardous wastes will be assimilated into the environment. The intent of any ultimate disposal scheme is to provide segregation of the hazardous agents so that migration of the pollutants occurs at a rate which does not produce detrimental effects. Such design objectives can be reached through the use of passive, multiple barriers. Since the primary mode of rapid dispersal in the environment is for the pollutant to become water-borne, a passive barrier based on distance from ground and surface water is a viable component of the multiple barrier concept. Although distance to a water resource is an obvious consideration in the selection of a burial site, historically, site selection has been based on availability rather than geomorphological rationale. This oversight has led to problems in land burial operations (*25, 26*).

Criteria for isolation have been well documented (*4*). Some considerations are: active faults, high seismic risk areas, and highly permeable formations, such as karstic areas, and glacial outwash plains, should be significantly distant; the bottom of the burial site should be well above the historical high groundwater table, and flood plains, shore lands, and groundwater recharge areas should be significantly distant; the site should be distant from private wells for human and/or livestock use and from municipal water supplies, reservoirs, or wells; and location in an area of low population density and diverse fauna and flora is desirable.

Elimination of Water Drive. Another component of the multiple barrier concept is the elimination or minimization of the water drive which tends to cause migration of the hazardous agents after disposal in shallow land burial sites. These driving forces are associated with the formation and transport of leachates in the burial site. Specific factors influencing migration have been identified: infiltration rate, filtering capacity, buffering capacity, and adsorptive capacity (*27*). Leachate problems tend to become more important when precipitation exceeds evapotranspiration.

Soil parameters affecting water infiltration and runoff are: soil structure, surface tension forces which influence moisture movement, soil moisture content, soil permeability, soil mineralogy, vegeta-

tive cover, tillage effects, temperature of water and soil, entrapped air, and topography (*28–30*). An extension of this approach for containing potentially hazardous wastes has been the use of liners in the burial site (*31*). Cost estimates for various liner materials are given in Table 7.

Clays. Clays have an advantage over the other suggested liners because they have desirable buffering and adsorptive capacities that can be engineered to provide an additional barrier. The specific characteristics of clay of engineering importance are: bulk density, grain size distribution, mineral composition, exchange capacity, and resident exchangeable ions (*33, 34*). Examples of coefficients of permeability and grain size distribution, respectively, are given in Tables 8 and 9.

Nonclay Liners. Special barriers can be used to intercept and control seepage. Soil cements, asphaltic materials, and synthetic polymeric membranes are all potential barriers (*36*). The synthetic membranes are of particular significance because of their low permeability. Liner selection requires evaluation of compatibility, allowable permeability, expected lifetime, and resistance to climatic exposure.

Ion Exchange. Selected materials with active exchange sites may also be used to provide removal of objectionable ions from some industrial sludge leachates. Unfortunately, both synthetic and natural materials such as zeolites, clays, activated carbon, activated alumina, fly ash, and vermiculite are fairly specific in removing pollutants.

Residuals Disposal: A Case Study

Massive clay beds in Texas have been investigated as potential storage/disposal sites for residual wastes. The project was limited to the following tasks: (a) batch tests involving five different clays (Beaumont, Catahoula, Eagle Ford, Midway, and

Table 7. Cost estimates for various liner materials.[a]

Material	Installed cost, $/yd²	($/m²)
Polyethylene, 10–20 mils (0.25–0.51 mm)	0.90–1.44	(0.75–1.20)
PVC, 10–30 mils (0.25–0.76 mm)	1.17–2.16	(0.98–1.81)
Butyl rubber, 31–63 mls (0.79–1.60 mm)	3.25–4.00	(2.71–3.34)
Hypalon, 20–45 mils (0.51—1.14 mm)	2.28–3.06	(1.91–2.56)
EDPM, 31–63 mils (0.79–1.60 mm)	2.43–3.42	(2.03–2.86)
Chlorinated polyethylene, 20–30 mils (0.51–0.76 mm)	2.43–3.24	(2.03–2.71)
Paving asphalt, 2 in. (51 mm)	1.20–1.70	(1.00–1.42)
Paving asphalt, 4 in. (102 mm)	2.35–3.25	(1.96–2.72)
Hot sprayed asphalt, 1 gal/yd² (4.5 l./m²)	1.50–2.00	(1.25–1.67)
Asphalt sprayed on polypropylene fabric, 100 mils (2.5 mm)	1.26–1.87	(1.05–1.56)
Soil–bentonite, 9 lbs/yd² (4.9 kg/m²)	0.72	(0.60)
Soil–bentonite, 18 lb/yd² (9.8 kg/m²)	1.17	(0.98)
Soil–cement, 6 in. (152mm)	1.25	(1.05)

[a] Data of Geswein (*32*).

Table 8. Coefficients of permeability of various clays.[a]

Type column	Feed	Coefficient of permeability × 10^{-8}, cm/sec				
		Beaumont	Catahoula	Eagle Ford	Midway	Taylor
High density	Deionized water	0.13	0.32	1.6	0.21	0.73
Low density	Deionized water	3.7	8.4	12	—	—
		3.6	7.6	11	—	—
	HCl, 100 mmole/l.	—	—	14	—	—
		—	—	45	—	—
	NaOH, 100 mmole/l.	0.88	0.18	3.0	—	—
		—	—	7.2	—	—
	Phenol, 10 mmole/l.	3.5	4.4	14	—	—
		2.3	3.0	10	—	—
	$PbCl_2$, 30 mmole/l.	100	15	9.3	—	—
		110	16	9.4	—	—
	$HgCl_2$, 30 mmole/l.	15	6.7	6.3	—	—
		19	6.6	8.8	—	—

[a] Data of Sanks et al. (*35*).

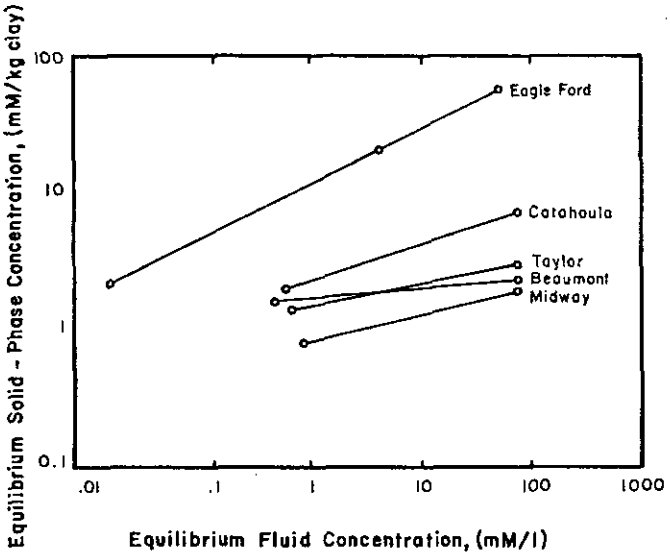

FIGURE 7. Phenol isotherms (*35*).

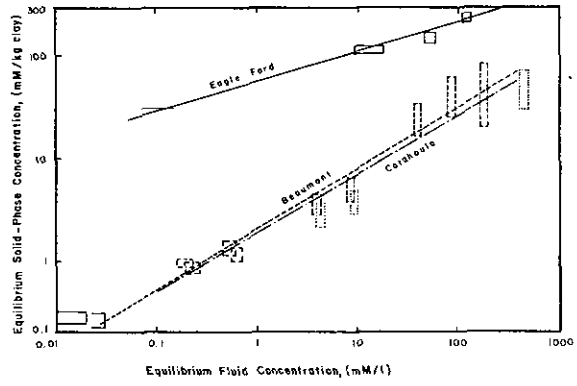

FIGURE 8. Mercury (II) isotherms (*35*).

Table 9. Grain size distribution.[a]

Material	Clay, %	Silt, %	Sand, %
Beaumont	58.3	40.5	1.2
Catahoula	38.2	54.2	7.6
Eagle Ford	46.9	41.1	12.0
Midway	55.9	42.9	1.2
Taylor	64.5	28.4	7.1
Del Rio	57.2	38.5	4.3

[a] Data of Sanks et al. (*35*).

Table 10. Cation exchange capacity (CEC).[a]

Clay	CEC, meq/100g		
	Test 1	Test 2	Average
Beaumont	52.67	53.30	53
Catahoula	55.86	57.63	56
Eagle Ford	20.76	19.18	20
Midway	59.80	59.10	59
Taylor	34.63	35.01	35
Del Rio	17.58	18.11	18

[a] Data of Sanks et al. (*35*).

Taylor) and aqueous solutions in three concentrations each of hydrochloric acid, sodium hydroxide, acetone, acetaldehyde, benzene, phenol, lead chloride, mercuric chloride, chromium chloride, and DDT (using decane as a solvent); and (b) column tests involving three selected clays (Beaumont, Catahoula, and Eagle Ford) and aqueous solutions of hydrochloric acid, sodium hydroxide, phenol, lead chloride, and mercuric chloride (*35*).

The clay content of the five specimens tested for sorption ranged from 38 to 50%, and liquid limits ranged from 54 to 85%. The predominant fraction of the clay was calcium montmorillonite, which ranged from 55 to 100%. The cation-exchange capacities ranged from 18 to 59 meq/100 g clay. The five specimens varied in their sorptive capacities. At an equilibrium fluid concentration of 10 mmole/l. (for the five clays) the following sorption, in millimoles per kilogram of clay were found: hydrogen ion, 300–9000; hydroxyl ion, 150–300; acetaldehyde, 10–40; acetone, 0.7–15; phenol, 1–40; and DDT, 5–40. Sorption of heavy metals in an equilibrium fluid concentration of 10 mmole/l. were: 8 mmole/kg for mercury in Beaumont and Catahoula clays and 100 mmole/kg for mercury in Eagle Ford clay. Lead precipitated, reducing lead concentrations in the fluid to less than 0.01 mmole/l. No clay was superior

Table 11. Capacity of clay utilized in column tests before significant breakthrough occurred.[a]

Clay type	Metal ion solution	Breakthrough criterion, C/C_o value[b]	Throughput, 1 kg clay	Amount not sorbed, mmole/kg clay	Amount sorbed, mmole/kg clay	Theoretical capacity, mmole/kg clay	Percentage of clay utilized, %
Beaumont	Lead	0.1	7.6	14	214	265	80
	Mercury	0.7	3.0	42	18	265	7
Catahoula	Lead	0.1	4.5	13.5	121.5	280	44
	Mercury	0.1	2	6	56	280	20
Eagle Ford	Lead	No breakthrough				100	Greater than 100
	Mercury	0.1	4.0	—	120	100	120

[a] Data of Sanks et al. (*35*).
[b] Ratio of concentration C at any time to initial concentration C_o.

for the sorption of all substances although Eagle Ford clay generally presented excellent characteristics (Tables 10 and 11; Figs. 7 and 8).

These results demonstrated the feasibility of using clay beds as potential storage and disposal sites (Fig. 9). In addition to the clay liner, other liners can be added to increase the number of barriers. The reconstituted clay liner may vary from several inches to several feet, depending on the waste, surrounding clays, water conditions, and other factors unique to the waste and the area. The cross section of the pit may take several forms, depending on the techniques used to open the pit, prepare the liner areas, fill the pit, and close the compartments. It is recommended that a means for monitoring leachate migration be provided.

Conclusion

Ultimately, residuals must be returned to air, land, or the oceans. The cost of disposal will be borne by the consumer, because residual wastes are generated when natural resources are processed for man's benefit.

There is a large and growing body of technical literature on waste management. Hazardous agents can be removed from wastes, although under some circumstances it is more economical to modify the manufacturing process rather than modify sections of the treatment train. The removal of hazardous agents is not simply a process that occurs at any one step in a well engineered system.

The materials and design of the disposal site itself

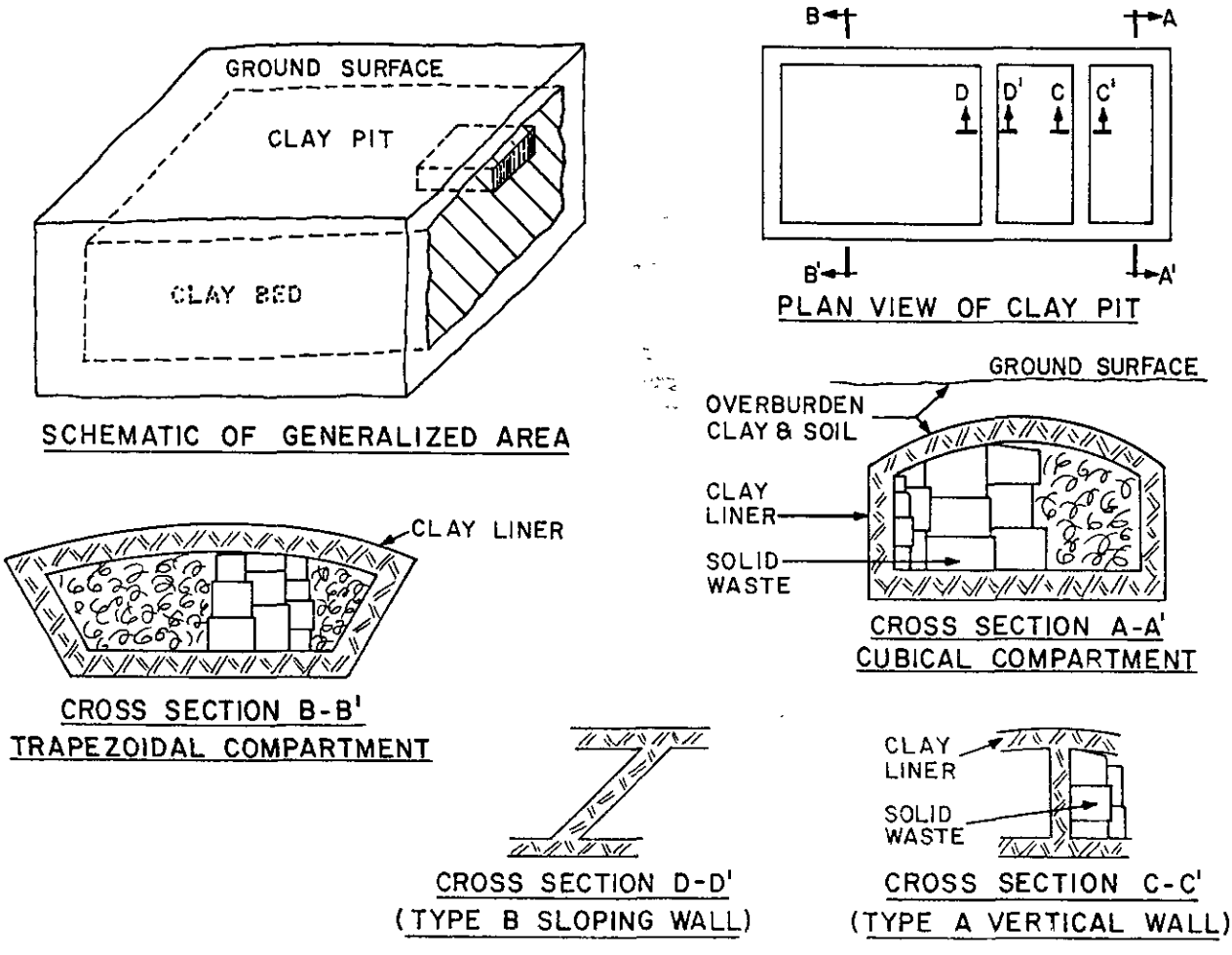

FIGURE 9. Schematic of hazardous solid waste disposal site (reconstituted clay liner or blanket only where needed) (35).

afford mechanisms for detoxifying and rendering innocuous the hazardous agents in the waste. Through the use of properly engineered treatment systems and passive but multiple barriers between residuals and the biosphere, it is possible to reduce the transport of potential pollutants to environmentally acceptable levels.

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