

CHAPTER 5

**Technologies for
Hazardous Waste Management**

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Technologies for Hazardous Waste Management

Summary Findings

Waste Reduction Alternatives

- Source segregation is the easiest and most economical method of reducing the volume of hazardous waste. This method of hazardous waste reduction has been implemented in many cases, particularly by large industrial firms. Many opportunities still exist for further application. Any change in management practices should include the encouragement of source segregation.
- Through a desire to reduce manufacturing costs by using more efficient methods, industry has implemented various process modifications. Although a manufacturing process often may be used in several plants, each facility has slightly different operating conditions and designs. Thus, a modification resulting in hazardous waste reduction may not be applicable industrywide. Also, proprietary concerns inhibit information transfer.
- Product substitutes generally have been developed to improve performance. Hazardous waste reduction has been a side-benefit, not a primary objective. In the long term, end-product substitution could reduce or eliminate some hazardous wastes. Because many different groups are affected by these substitutions, there are limitations to implementation.
- With regard to recovery and recycling approaches to waste reduction, if extensive recovery is not required prior to recycling a waste constituent, in-plant operations are relatively easy. Commercial recovery benefits are few for medium-sized generators. No investment is required, but liability remains with the generator. Commercial recovery has certain problems as a profitmaking enterprise. The operator is dependent on suppliers' waste as raw material; contamination and consistency in composition of a waste are difficult to control. Waste exchanges are

not very popular at present, since generators must assume all liability in transferring waste. Also, small firms do not generate enough waste to make it attractive for recycling.

Hazard Reduction Alternatives: Treatment and Disposal

- Many waste treatment technologies can provide permanent, immediate, and very high degrees of hazard reduction. In contrast, the long-term effectiveness of land-based disposal technologies relies on continued maintenance and integrity of engineered structures and proper operation. For wastes which are toxic, mobile, persistent, and bioaccumulative, and which are amenable to treatment, hazard reduction by treatment is generally preferable to land disposal. In general, however, costs for land disposal are comparable to, or lower than, unit costs for thermal or chemical treatment.
- For waste disposal, advanced landfill designs, surface impoundments, and injection wells are likely to perform better than their earlier counterparts. However, there is insufficient experience with these more advanced designs to predict their performance. Site- and waste-specific factors and continued maintenance of final covers and well plugs will be important. The ability to evaluate the effectiveness of these disposal technologies could be improved through better instrumentation of these facilities. Currently, their performance evaluation relies heavily on monitoring the indirect effects of their failure by, for example, detecting aquifer contamination.
- In comparing waste treatment to disposal alternatives, the degrees of permanent hazard reduction immediately achievable with treatment technologies are overwhelming attributes in comparison to land-based dispos-

al. However, comparison of these technologies at the very high destruction levels they achieve is difficult. Difficulties include: monitoring methods and detection limits, knowledge about the formation of toxic products of incomplete combustion, and diversity in performance capabilities among the different treatments.

- Chemical, physical, and biological batch-type treatment processes can be used to reduce waste generation or to recover valuable waste-stream constituents. In marked contrast to both incineration and land disposal, these processes allow checking treatment residuals before any discharge to the environment. In general, processes which offer this important added reliability are few, but waste-specific processes are emerging. Research and development efforts could encourage the timely emergence of more of this type process applicable to future hazardous wastes.

Ocean Use

- For some acids and very dilute other hazardous wastes, dumping in ocean locations may offer acceptable levels of risk for both the ocean environment and human health. However, there is generally inadequate scientific

information for decisions concerning most toxic hazardous wastes and most locations. This is a serious problem since there may be increasing interest in using the oceans as the costs of land disposal increase and if public opposition to siting new treatment facilities continues.

Uncontrolled Sites

- A major problem is that the National Contingency Plan under the Comprehensive Environmental, Response, Compensation, and Liability Act (CERCLA) does not provide specific standards, such as concentration limits for certain toxic substances, to establish the extent of cleanup. There are concerns that cleanups may not provide protection of health and environment over the long term.
- The long-term effectiveness of remedial technologies is uncertain. A history of effectiveness has not yet been accumulated. Many remedial technologies consist of waste containment approaches which require long-term operation and maintenance. In recent remedial actions, removal of wastes and contaminants, such as soil, accounted for 40 percent of the cases; such removed materials were usually land disposed.

Introduction

The purpose of this chapter is to describe the variety of technical options for hazardous waste management. The technical detail is limited to that needed for examining policy options and regulatory needs. Still, there are many technologies, and their potential roles in hazardous waste management are diverse. Thus, there are many technical aspects related to policy and regulation issues. The reader interested in the details of the technologies reviewed here is encouraged to read beyond this policy-oriented discussion.

The first group of technologies discussed are those which reduce waste volume. This distinc-

tion recognizes that where technically and economically feasible, it is better to reduce the generation of waste than to incur the costs and risks of managing hazardous waste. Waste reduction technologies include segregation of waste components, process modifications, end-product substitutions, recycling or recovery operations, and various emerging technologies. Many waste reduction technologies are closely linked to manufacturing and involve proprietary information. Therefore, there is less detailed information in this section than in others.

Much of the chapter discusses technologies that reduce the hazard from the waste gener-

ated. These are grouped as: 1) those treatments that permanently eliminate the hazardous character of the material, and 2) those disposal approaches that contain or immobilize the hazardous constituents.

There are several treatments involving high temperature that decompose materials into harmless constituents. Incineration is the obvious example, but there are several existing and emerging “destruction” technologies that are distinguished in this category. In addition to gross decomposition of the waste material, there are emerging chemical technologies which detoxify by limited molecular rearrangement and recover valuable materials for reuse. Whether by destruction or detoxification, these technologies permanently eliminate the hazard of the material.

Containment chiefly involves land disposal techniques, but chemical “pretreatment” methods for stabilization on a molecular level are rapidly emerging. Combining these methods offers added reliability, and sectors of industry appear to be adopting that approach. The dis-

ussion of containment technologies includes: 1) landfilling, 2) surface impoundments, 3) deep-well injection, and 4) chemical stabilization.

Use of the oceans is considered a technical option for some wastes. A number of regulatory and policy issues emerge concerning ocean use and are discussed.

The final section of this chapter concerns uncontrolled hazardous waste sites from which releases of hazardous materials is probable or has already occurred. Such sites are often abandoned and are no more than open dumps. The sites are addressed by CERCLA. The technical aspects of identifying, assessing, and remediating uncontrolled sites are reviewed in this section. There has been limited engineering experience with cleaning up uncontrolled sites.

Many technologies that are applicable to the same waste compete in the marketplace. The initial discussion in the section on hazard reduction treatment and disposal technologies compares the costs of comparative technologies in some detail.

Waste Reduction Alternatives

Introduction

Four methods are available to reduce the amount of waste that is generated:

1. source segregation or separation,
2. process modification,
3. end-product substitution, and
4. material recovery and recycling.

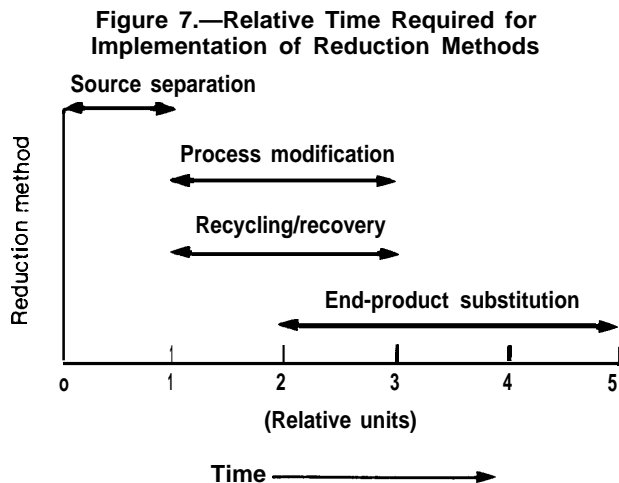
Often, more than one of these approaches is used, simultaneously or sequentially.

Reduction of the amount of waste generated at the source is not a new concept. Several industrial firms have established in-house incentive programs to accomplish this. One example is the 3P program—Pollution Prevention Pays—of the 3M Corp. Through the reduction of waste and development of new substitute products for hazardous materials, 3M has saved \$20

million over 4 years.¹ Other firms have established corporate task forces to investigate solutions to their hazardous waste management problems. One solution has been recycling and recovery of waste generated by one plant for use as a raw material at another corporate-owned facility. Such an approach not only reduces waste, but lowers operating costs.

Significant reductions in the volume of waste generated can be accomplished through source segregation, process modification, end-product substitution, or recovery and recycle. No one method or individual technology can be selected as the ultimate solution to volume reduction. As shown in figure 7, three of the methods, i.e., source segregation, process modifica-

¹M. G. Royston, *Pollution Prevention Pays* (New York: Pergamon Press, 1979).



SOURCE: Office of Technology Assessment

tions, and recovery and recycling can be implemented on a relatively short- to medium-term basis by individual generators. End-product substitution is a longer term effort. A comparison of the advantages and disadvantages of

each of the four approaches is given in table 22. Because of proprietary concerns and lack of industrywide data, the amount of waste reduction that has already occurred and the potential for further reduction is difficult to evaluate. A 1981 study by California concluded that new industrial plants will produce only half the amount of hazardous waste currently produced. Other estimates for potential waste production range from 30 to 80 percent.³ Waste reduction efforts, however, are more difficult in existing plants.

Source Segregation

Source segregation is the simplest and probably the least costly method of reduction. This approach prevents contamination of large vol-

²“Future Hazardous Waste Generation in California,” Department of Health Services, Oct. 1, 1982.

³Joanna D. Underwood, Executive Director, Inform, *The New York Times*, Dec. 27, 1982.

Table 22.—A Comparison of the Four Reduction Methods

Advantages	Disadvantages
<p>Source segregation or separation</p> <ul style="list-style-type: none"> 1) Easy to implement; usually low investment 2) Short-term solution 	<ul style="list-style-type: none"> 1) Still have some waste to manage
<p>Process modification</p> <ul style="list-style-type: none"> 1) Potentially reduce both hazard and volume 2) Moderate-term solution 3) Potential savings in production costs 	<ul style="list-style-type: none"> 1) Requires R&D effort; capital investment 2) Usually does not have industrywide impact
<p>End product substitution</p> <ul style="list-style-type: none"> 1) Potentially industrywide impact—large volume, hazard reduction 	<ul style="list-style-type: none"> 1) Relatively long-term solutions 2) Many sectors affected 3) Usually a side benefit of product improvement 4) May require change in consumer habits 5) Major investments required—need growing market
<p>Recovery/recycling</p> <ul style="list-style-type: none"> • <i>n-p/ant</i> <ul style="list-style-type: none"> 1) Moderate-term solution 2) Potential savings in manufacturing costs 3) Reduced liability compared to commercial recovery or waste exchange • <i>Commercial recovery (offsite)</i> <ul style="list-style-type: none"> 1) No capital investment required for generator 2) Economy of scale for small waste generators • <i>Waste exchange</i> <ul style="list-style-type: none"> 1) Transportation costs only 	<ul style="list-style-type: none"> 1) May require capital investment 2) May not have wide impact 1) Liability not transferred to operator 2) If privately owned, must make profit and return investment 3) Requires permitting 4) Some history of poor management 5) Must establish long-term sources of waste and markets 6) Requires uniformity in composition 1) Liability not transferred 2) Requires uniformity in composition of waste 3) Requires long-term relationships—two-party involvement

SOURCE: Office of Technology Assessment.

umes of nonhazardous waste by removal of hazardous constituents to form a concentrated hazardous waste. For example, metal-finishing rinse water is rendered nonhazardous by separation of toxic metals. The water then can be disposed through municipal/industrial sewage systems.

However, there are disincentives, particularly for small firms wishing to implement source segregation. For example, an electroplating firm may, for economic reasons, mix wastes containing cyanides and toxic metals with a waste that contains organics. The waste stream is sent to the municipal treatment system. The municipal system can degrade the organics, but the metals and cyanide accumulate in the sludge, which is disposed as a nonhazardous solid waste in a sanitary landfill. As long as the firm dilutes the cyanide and metals concentrations to acceptable limits for municipal disposal, it is in compliance with the Environmental Protection Agency's (EPA) regulations. If the firm calculates the costs of recovering the cyanide onsite, the cost may be more than the fees paid to the municipal treatment facility. Thus, there is no economic incentive for source segregation, which would yield a hazardous waste, although the public would benefit if source segregation were practiced. Alternatively, accumulation of such sludges can lead to significant levels of toxic material in sanitary landfills. Municipal treatment facilities are financed with tax dollars. In this example, the public is, in essence, subsidizing industrial waste disposal. Moreover, to carry out source segregation, a firm may have to invest in new equipment.

Process Modification

Process modifications are, in general, made on a continuous basis in existing plants to increase production efficiencies, to make product improvements, and to reduce manufacturing costs. These modifications may be relatively small changes in operational methods, such as a change in temperature, in pressure, or in raw material composition, or may involve major changes such as use of new processes or new equipment. Although process modifications

have reduced hazardous wastes, the reduction usually was not the primary goal of the modifications. However, as hazardous waste management costs increase, waste reduction will become a more important primary goal.

Three case examples were studied to analyze incentives and impacts for process modifications for hazardous waste reduction. The following factors are important:

- A typical process includes several steps. Although a change in one step may be small relative to the entire process, the combination of several changes often represents significant reductions in cost, water use, or volume of waste.
- A change in any step can be made independently and is evaluated to determine the impact on product, process efficiency, costs, labor, and raw materials.
- Generally, process modifications are plant- or process-specific, and they cannot be applied industrywide.
- A successful process change requires a detailed knowledge of the process as well as a knowledge of alternative materials and processing techniques. Successful implementation requires the cooperative efforts of material and equipment suppliers and in-house engineering staffs.

Three process changes are discussed in detail in the appendix to this chapter and are briefly summarized below:

1. Chlor-alkali industry.—Significant process developments in the chlor-alkali industry (which produces, e.g., chlorine and caustic soda) have resulted in reduction of major types of hazardous waste through modifications to the mercury electrolysis cell. The effects on waste generation are summarized in table 23. The modifications were not developed exclusively to reduce hazardous waste, but were initiated primarily to increase process efficiency and reduce production costs.
2. Vinyl chloride (plastics) production.—Several process options are available for handling waste from the production of vinyl chloride monomers (VCMs). Five al-

Table 23.—Process Modifications to the Mercury Cell

Modification	Effect on waste stream	Reason for modification
Diaphragm cell	Elimination of mercury contaminated waters	Preferred use of natural salt brines as raw material
Dimensionally stable anode	Elimination of chlorinated hydrocarbon waste	Increased efficiency
Membrane cell	Elimination of asbestos diaphragm waste	Reduce energy costs; higher quality product

SOURCE Office of Technology Assessment

ternatives are illustrated in table 24. All five have been demonstrated on a commercial scale. In most cases, the incineration options (either recycling or add-on treatment) would be selected over chlorinolysis and catalytic fluidized bed reactors. Chlorinolysis has limited application because of the lack of available markets for the end products. If further refinements could be made to the catalytic process, such as higher concentration of hydrogen chloride (HCl) in the gas stream which would allow it to be used with all oxychlorination plants, its use could be expanded.

3. Metal-finishing industry .-Several modifications in metal cleaning and plating processes have enabled the metal-finishing industry to eliminate requirements for on-site owned and operated wastewater treatment facilities. By changing these processes to eliminate formation of hazardous

sludge, the effluent can be discharged directly to a municipal wastewater treatment facility, saving several million dollars in capital investment.

End-Product Substitution

End-product substitution is the replacement of hazardous waste-intensive products (i.e., industrial products the manufacture of which involves significant hazardous waste) by a new product, the manufacture of which would eliminate or reduce the generation of hazardous waste. Such waste may arise from the ultimate disposal of the product (e.g., asbestos products) or during the manufacturing process (e.g., cadmium plating).

Table 25 illustrates six examples of end-product substitution, each representing a different type of problem. General problems include the following:

Table 24.—Advantages and Disadvantages of Process Options for Reduction of Waste Streams for VCM Manufacture

Treatment option	Type	Advantages	Disadvantages
High-efficiency incineration of vent gas only	Add-on treatment	1. Relatively simple operation 2. Relatively low capital investment	1. Second process required to handle liquid waste stream
High-efficiency incineration without HCl recovery	Add-on treatment	1. Relatively simple operation 2. Relatively low capital investment	1. Loss of HCl
High-efficiency incineration with HCl recovery	Recycling	1. Heat recovery 2. Recover both gaseous and liquid components 3. High reliability	1. Exit gas requires scrubbing 2. Requires thorough operator training 3. Auxiliary fuel requirements
Chlorinolysis	Modification of process	1. Carbon tetrachloride generated	1. High temperatures and pressures required 2. High capital investment costs 3. Weakening market for carbon tetrachloride
Catalytic fluidized bed reactor	Recycling	1. Low temperature 2. Direct recycle of exit gas (no treatment required)	1. Limited to oxychlorination plants

SOURCE Office of Technology Assessment,

Table 25.—End-Product Substitutes for Reduction of Hazardous Waste

Product	Use	Ratio of waste: ^a original product	Available substitute	Ratio of waste: ^a substitute product
Asbestos	Pipe	1.09	Iron Clay PVC	0.1 phenols, cyanides, 0.05 fluorides 0.04 VCM manufacture + 1.0 PVC pipe
	Friction products (brake linings)	1.0+ manufacturing waste	Glass fiber Steel wool Mineral wools Carbon fiber Sintered metals Cement	0
	Insulation	1.0+ manufacturing	Glass fiber Cellulose fiber	0.2
PCBs	Electrical transformers	1.0	Oil-filled transformers Open-air-cooled transformers	0 0
Cadmium	Electroplating	0.29	Zinc electroplating	0.06
Creosote treated wood	Piling		Concrete, steel	0.0 (reduced hazard)
Chlorofluorocarbons	Industrial solvents	70/81 =0.9	Methyl chloroform; methylene chloride	0.9 (reduced hazard)
DDT	Pesticide	1.0+ manufacturing waste	Other chemical pesticides	(reduced hazard) 1.0+ manufacturing waste

^aQuantity of hazardous waste generated/unit of product

SOURCE Office of Technology Assessment

- Not all of the available substitutes avoid the production of hazardous waste. For example, in replacing asbestos pipe, the use of iron as a substitute in pipe manufacturing generates waste with phenols and cyanides; and also, during the manufacture of polyvinyl chloride (PVC) pipe, a hazardous vinyl chloride monomer is emitted.⁴
- Substitution may not be possible in all situations. For example, although a substantial reduction in quantity of hazardous waste generated is achieved by using clay pipes, clay is not always a satisfactory replacement for asbestos.⁵

Generally, development of substitutes is motivated by some advantage, either to a user, (e.g., in improved reliability, lower cost, or easier operation), or to the manufacturer (e.g., reduced production costs). A change in consumer behavior also may cause product changes.

⁴Sterling-Hobe Corp., *Alternatives for Reducing Hazardous Waste Generation Using End-Product Substitution*, prepared for Materials Program, OTA, 1982.

⁵Ibid.

For example, increased use of microwave ovens has increased the demand for paper and Styrofoam packaging to replace aluminum. Most end-product substitutions aimed at reduced generation of hazardous waste, however, do not have such advantages. The only benefit may be reduction of potential adverse effects on human health or the environment. Unless the greater risks and costs of hazardous waste management are fully internalized by waste generators, other incentives may be needed to accomplish end-product substitution.

In addition to the approach in chapter 3, option III, end-product substitution may be encouraged by:

1. regulations,
2. limitation of raw materials,
3. tax incentives,
4. Federal procurement practices, and
5. consumer education.

Regulations have been used to prohibit specific compounds. For example, bans on certain pesticides such as dichlorodiphenyltrichloro-

ethane (DDT) have resulted in development and use of other chemicals. Legislative prohibition of specific chemicals, such as polychlorinated biphenyls (PCBs), is another option.

Limiting the supply of raw materials required for manufacture is another method of encouraging end-product substitution. For example, limiting either the importation or domestic mining of asbestos might encourage substitution of asbestos products. A model for this method is the marketing-order system of the U.S. Department of Agriculture, used to permit the cultivation of only specified quantities of selected crops. Using similar strategies, a raw material like asbestos could be controlled by selling shares of a specified quantity of the market permitted to be mined or imported.

Tax incentives are another means to force end-product substitution. Excise taxes on products operate as disincentives to consume and have been implemented in the past (e.g., taxes on alcohol, cigarettes and gasoline). This type of taxation might be incorporated to encourage product substitution. The design and acceptance of a workable, easily monitored tax system, however, might be difficult to develop.

Federal procurement practices and product specifications can have significant influence on industrial markets. Changes in military procurement were proposed in 1975 to allow for substitution of cadmium-plating by other materials. A change in product specifications to permit this substitution would affect not only the quantity of cadmium required for military use, but also might impact nonmilitary applications.

A public more aware of the hazard associated with production of specific products might be inclined to shift buying habits away from them.

Larger Economic Contexts. -If a substitution requires a complete shift in industrial markets (e.g., if a product manufactured with asbestos is replaced by one made with cement), the impact may be large—both manufacturers and suppliers may be affected. In addition, users will be impacted according to the relative merits of the products. Other sectors potentially af-

ected by end-product substitution include importers of raw materials, exporters of the original product, and related equipment manufacturers.

Generally, a product substitution offers a cost advantage over the original product, which counters market development expenditures. Potential savings can be achieved by the introduction of product substitutes-e. g., increased demand may require increased production, thus reducing the cost per unit. Incentives or the removal of disincentives, however, maybe necessary to increase product demand by a sufficient margin to give the substitute a more competitive marketplace position,

A significant factor in the introduction of a substitute product is the stage of growth for existing markets. For example, if the market for asbestos brake lining is declining or growing at a very slow rate, or if large capital investments are required for development of a substitute lining, introduction of a substitute may not be economically practical. The availability of raw materials also affects the desirability of substitutes. If the original product is dependent on limited supplies of raw materials, substitutes will be accepted more rapidly.

Recovery and Recycling

Recovery of hazardous materials from process effluent followed by recycling provides an excellent method of reducing the volume of hazardous waste. These are not new industrial practices. Recovery and recycling often are used together, but technically the terms are different. Recovery involves the separation of a substance from a mixture. Recycling is the use of such a material recovered from a process effluent. Several components may be recovered from a process effluent and can be recycled or discarded. For example, a waste composed of several organic materials might be processed by solvent distillation to recover halogenated organic solvents for recycling; the discarded residue of mixed organics might be burned for process heat.

Materials are amenable to recovery and recycling if they are easily separated from process effluent because of physical and/or chemical differences. For example, inorganic salts can be concentrated from aqueous streams by evaporation. Mixtures of organic liquids can be separated by distillation. Solids can be separated from aqueous solutions through filtration. Further examples of waste streams that are easily adaptable to recovery and recycling are listed in table 26.

Recovery and recycling operations can be divided into three categories:

1. In-plant recycling is performed by the waste (or potential waste) generator, and is defined as recovery and recycling of raw materials, process streams, or byproducts for the purpose of prevention or elimination of hazardous waste. (Energy recovery without materials recovery is not included in this discussion of in-plant recycling, but is discussed later in this chapter as a treatment of wastes.) If several products are produced at one plant by various processes, materials from the effluents of one process may become raw materials for another through in-plant recycling. An example is the recovery of relatively dilute sulfuric acid, which is then used to neutralize an alkaline waste. In-plant recycling offers several benefits to the manufacturer, including savings in raw materials, energy requirements, and disposal or treatment costs. In addition, by reducing or eliminating the amount of waste generated, the plant owner may be exempted from some or all RCRA (Resource Conservation and Recovery Act) regulations,

2. Commercial (offsite) recovery can be used for those wastes combined from several processes or produced in relatively small quantities by several manufacturers. Commercial recovery means that an agent other than the generator of the waste is handling collection and recovery. These recovery systems may be owned and operated by, or simply serve, several waste generators, thereby offering an advantage of economy of scale. In most cases commercial recovery systems are owned and operated by independent companies, and are particularly important for small waste generators. In commercial recovery, responsibility for the waste and compliance with regulations and manifest systems remains that of the generator until recovery and recycling is completed.
3. Material exchanges (often referred to as "waste" exchanges) are a means to allow raw materials users to identify waste generators producing a material that could be used. Waste exchanges are listing mechanisms only and do not include collection, handling, or processing. Although benefits occur by elimination of disposal and treatment costs for a waste as well as receipt of cash value for a waste, responsibility for meeting purchaser specifications remains with the generator, *

Standard technologies developed that can be adapted for recovery of raw materials or by-products may be grouped in three general cate-

*For a discussion of the problems being encountered with using waste exchanges for hazardous waste see "Industrial Waste Exchange: A Mechanism for Saving Energy and Money," Argonne National Laboratory, July 1982.

Table 26.—Commercially Applied Recovery Technologies

Generic waste	Typical source of effluent	Recovery technologies
Solids in aqueous suspension	Salt/soda ash liming operations	Filtration
Heavy metals	Metal hydroxides from metal-plating waste; sludge from steel-pickling operations	Electrolysis
Organic liquids	Petrochemicals/mixed alcohol	Distillation
Inorganic aqueous solution	Concentration of inorganic salts/acids	Evaporation
Separate phase solids, grease/oil	Tannery waste/petroleum waste	Sedimentation/skimming
Chrome salt solutions	Chromium-plating solutions/tanning solutions	Reduction
Metals; phosphate sulfates	Steel-pickling operations	Precipitation

SOURCE: Office of Technology Assessment

gories. Physical separation includes gravity settling, filtration, flotation, flocculation, and centrifugation. These operations take advantage of differences in particle size and density. Component separation technologies distinguish constituents by differences in electrical charge, boiling point, or miscibility. Examples include ion exchange, reverse osmosis, electrolysis, adsorption, evaporation, distillation, and solvent extraction. Chemical transformation requires chemical reactions to remove specific chemical constituents. Examples include precipitation, electrodialysis, and oxidation-reduction reactions. These technologies are reviewed in table 27.

A typical recovery and recycling system usually uses several technologies in series. Therefore, what may appear as a complex process actually is a combination of simple operations. For example, recycling steel-pickling liquors may involve precipitation, gravity settling, and flotation. Precipitation transforms a component of high volatility to an insoluble substance that is more easily separated by gravity settling, a coarse separation technique, and flotation, a finishing separation method. Integration of process equipment can introduce some complexity. The auxiliary handling equipment (e.g., piping, pumps, controls, and monitoring devices that are required to provide continuous treatment from one phase to another) can be extensive. A detailed description of the recycling and recovery of pickling liquors from the steel industry is provided in the appendix at the end of this chapter.

Recovery and recycling technologies applied to waste vary in their stages of development. Physical separation techniques are the most commonly used and least expensive. The separation efficiency of these techniques is not as high as more complex systems, and therefore the type of waste to which it is applied is limited. Complex component separations (e.g., reverse osmosis) are being investigated for application to hazardous waste. These generally are expensive operations and have not been implemented commercially for hazardous waste reduction. Chemical transformation methods are also expensive. Precipitation and thermal oxi-

dation, however, appear to have current commercial application in hazardous waste management.

Table 28 illustrates some technologies currently being investigated for application to waste recovery and recycle. An expanded discussion of emerging new technologies, specifically in phase separation is provided in the following section of this chapter.

Economic Factors

These factors include:

1. research and development required prior to implementation of a technology;
2. capital investment required for new raw material, or additional equipment; i.e., recovery and recycle equipment, control equipment, and additional instrumentation;
3. energy requirements and the potential for energy recovery;
4. improvements in process efficiency;
5. market potential for recycled material, either in-house or commercially, and anticipated revenues;
6. management costs for hazardous waste before use of recovery and recycle technology;
7. waste management cost increases, resulting from recovery/recycling, i.e., additional manpower, insurance needs, and potential liability; and
8. the value of improved public relations of a firm.

Because of the number of processing steps involved, recovery and recycling can be more expensive than treatment and disposal methods. Earned revenue for recovered materials, however, may counter the cost of recovery.

Many market and economic uncertainties must be considered in an evaluation of proposed technology changes. For example, if deregulation of oil and natural gas results in an increase in energy costs, additional energy requirements, and/or credits earned for energy recovery from a process could be affected. The uncertainty of continued availability of a nec-

Table 27.—Description of Technologies Currently Used for Recovery of Materials

Technology/description	stage of development	Economics	Types of waste streams	Separation efficiency	Industrial applications
Physical separation:					
Gravity settling:					
Tanks, ponds provide hold-up time allowing solids to settle; grease skimmed to overflow to another vessel	Commonly used in wastewater treatment	Relatively inexpensive; dependent on particle size and settling rate	Slurrries with separate phase solids, such as metal hydroxide	Limited to solids (large particles) that settle quickly (less than 2 hours)	industrial wastewater treatment first step
Filtration:					
Collection devices such as screens, cloth, or other; liquid passes and solids are retained on porous media	Commonly used	Labor intensive: relatively inexpensive; energy required for pumping	Aqueous solutions with finely divided solids; gelatinous sludge	Good for relatively large particles	Tannery water
Flotation:					
Air bubbled through liquid to collect finely divided solids that rise to the surface with the bubbles	Commercial application	Relatively inexpensive	Aqueous solutions with finely divided solids	Good for finely divided solids	Refinery (oil/water mixtures); paper waste; mineral industry
Flocculation:					
Agent added to aggregate solids together which are easily settled	Commercial practice	Relatively inexpensive	Aqueous solutions with finely divided solids	Good for finely divided solids	Refinery; paper waste; mine industry
Centrifugation:					
Spinning of liquids and centrifugal force causes separation by different densities	Practiced commercially for small-scale systems	Competitive with filtration	Liquid/liquid or liquid/solid separation, i.e., oil/water; resins; pigments from lacquers	Fairly high ^(90/70)	Paints
Component separation					
Distillation:					
Successfully boiling off of materials at different temperatures (based on different boiling points)	Commercial practice	Energy intensive	Organic liquids	Very high separations achievable (99 + % concentrations) of several components	Solvent separations; chemical and petroleum industry
Evaporation:					
Solvent recovery by boiling off the solvent	Commercial practice in many industries	Energy intensive	Organic/inorganic aqueous streams; slurries, sludges, i.e., caustic soda	Very high separations of single, evaporated component achievable	Rinse waters from metal-plating waste
ion exchange:					
Waste stream passed through resin bed, ionic materials selectively removed by resins similar to resin adsorption. Ionic exchange materials must be regenerated	Not common for HW	Relatively high costs	Heavy metals aqueous solutions; cyanide removed	Fairly high	Metal-plating solutions
Ultrafiltration:					
Separation of molecules by size using membrane	Some commercial application	Relatively high	Heavy metal aqueous solutions	Fairly high	Metal-coating applications
Reverse osmosis:					
Separation of dissolved materials from liquid through a membrane	Not common: growing number of applications as secondary treatment process such as metal-plating pharmaceuticals	Relatively high	Heavy metals; organics, inorganic aqueous solutions	Good for concentrations less than 300 ppm	Not used Industrially

Table 27.—Description of Technologies Currently Used for Recovery of Materials—Continued

Technology/description	Stage of development	Economics	Types of waste streams	Separation efficiency	Industrial applications
Electrolysis: Separation of positively/negatively charged materials by application of electric current	Commercial technology; not applied to recovery of hazardous materials	Dependent on concentrations	Heavy metals; ions from aqueous solutions; copper recovery	Good	Metal plating
Carbon/resin absorption: Dissolved materials selectively absorbed in carbon or resins. Adsorbents must be regenerated	Proven for thermal regeneration of carbon; less practical for recovery of adsorbate	Relatively costly thermal regeneration; energy intensive	Organics/inorganics from aqueous solutions with low concentrations, i.e., phenols	Good, overall effectiveness dependent on regeneration method	Phenolics
Solvent extraction: Solvent used to selectively dissolve solid or extract liquid from waste	Commonly used in industrial processing	Relatively high costs for solvent	Organic liquids, phenols, acids	Fairly high loss of solvent may contribute to hazardous waste problem	Recovery of dyes
Chemical transformation: Precipitation: Chemical reaction causes formation of solids which settle	Common	Relatively high costs	Lime slurries	Good	Metal-plating wastewater treatment
Electrodialysis: Separation based on differential rates of diffusion through membranes. Electrical current applied to enhance ionic movement	Commercial technology, not commercial for hazardous material recovery	Moderately expensive	Separation/concentration of ions from aqueous streams; application to chromium recovery	Fairly high	Separation of acids and metallic solutions
Chlorinolysis: Pyrolysis in atmosphere of excess chlorine	Commercially used in West Germany	Insufficient U.S. market for carbon tetrachloride	Chlorocarbon waste	Good	Carbon tetrachloride manufacturing
Reduction: Oxidative state of chemical changed through chemical reaction	Commercially applied to chromium; may need additional treatment	Inexpensive	Metals, mercury in dilute streams	Good	Chrome-plating solutions and tanning operations
Chemical dechlorination: Reagents selectively attack carbon-chlorine bonds	Common	Moderately expensive	PCB-contaminated oils	High	Transformer oils
Thermal oxidation: Thermal conversion of components	Extensively practiced	Relatively high	Chlorinated organic liquids; silver	Fairly high	Recovery of sulfur, HCl

*Good implies 50 to 80 percent efficiency, fairly high implies 80 percent, and very high implies 90 percent

SOURCE: Office of Technology Assessment.

Table 28.—Recovery/Recycling Technologies Being Developed

Technology	Development needs	Potential application
Ion exchange	Commercial process for other applications (desalinization), applications to metal recovery under development. Not economic at present due to investment requirements	Chromium recovery; metal plating waste
Adsorption	R&D on new resins and regeneration methods	Organic liquids with or without metal contamination; pesticides
Electrolysis	Cathode/anode, material development for membranes	Metallic/ionic solution
Extract ion	Reduction in loss of acid or solvent in process	Extraction of metals with acids
Reverse osmosis	Membrane materials, operating conditions optimized, demonstration of process	Salt solutions
Evaporation	Efficiency improvement/ demonstration of process	Fluorides from aluminum smelting operation
Reduction	Efficient collection techniques	Mercury
Chemical dehalogenation	Equipment development for applications to halogenated waste other than PCB oils	Halogenated organics

SOURCE: Office of Technology Assessment

essary raw material could influence a decision for recovery of materials from waste streams. Uncertainties in interest rates may discourage investment and could thus increase a required rate-of-return projected for a new project. Changes in allowable rates of capital equipment depreciation also may affect costs significantly.

In addition, changes in RCRA regulations for alternative management options (e.g., landfilling, ocean dumping, and deep-well injection) affect disposal costs. Stricter regulations or prohibitions of certain disposal practices for particular wastes could increase the attractiveness of recycling and recovery operations. However, if hazardous wastes are stored for longer than 90 days, current regulations require permits for that facility. If large quantities of a waste must accumulate (for economic reasons) prior to recycling or recovery, the permit requirement may discourage onsite recycling.

Previously, recovery and recycling was considered as an in-plant operation only; i.e., material was recovered and recycled within one plant. Currently, larger corporations are beginning to evaluate recovery opportunities on a

broader scale. Recycling within the corporate framework is gaining greater attention as a cost reduction tool with an added benefit of reducing public health risks.

Emerging Technologies for Waste Reduction

Although the effects are more difficult to predict, some technological developments have potential for the reduction of hazardous waste. For example, developments in the electronics industry have provided instrumentation and control systems that have greater accuracy than was possible just a few years ago. These systems provide more precise control of process variables, which can result in higher efficiency and fewer system upsets, and a reduction in hazardous waste. The application and improvements of instrumentation and control systems vary with each process. Thus, as new plants are constructed and fitted with new technologies, smaller quantities of hazardous waste will be generated. The technologies that are discussed in this section have a direct impact on the volume and hazard level of waste currently generated through one or more of the reduction methods discussed earlier.

Segregation Technology .—New developments in segregation technology can increase recovery and recycling of hazardous waste. Notably, membrane segregation techniques have substantially improved. Membrane separation has been used to achieve filtration, concentration, and purification. However, large-scale applications, such as those required in pollution control have been inhibited by two factors: 1) replacement costs associated with membrane use and 2) technical difficulties inherent in producing large uniform surface areas of uniform quality. Because of the inherent advantages of membrane separation over more conventional separation techniques like distillation or evaporation, further development of membrane separation for large-scale commercial applications is attractive. These advantages include lower energy requirements resulting in reduced operating costs and a simpler, more compact system that generally leads to reduced capital costs. Commercial applications exist for all but coupled transport designs, which are still at the laboratory stage. All of these illustrated systems have possible application for reduction of hazardous waste. However, microfiltration, ultrafiltration, reverse osmosis, and electrodialysis processes have more immediate application. Dialysis has been used on only a small scale; the high flow systems generally typical of hazardous waste treatments make its use impractical. Gas separations by membranes do not have immediate application to hazardous waste use. The development of new materials for both membranes and supporting fabrics and the use of new layering techniques (e. g., composite membranes) have led to improved permeability and selectivity, higher fluxes, better stability, and a reduced need for prefiltering and staged separations.

Improved reliability is the most important factor in advancement of membrane separations technology. New types of membranes have demonstrated improved performance. Thin-film composites that can be used in reverse osmosis, coupled transport, and electrolytic membranes have direct application to the recovery and reduction of hazardous materials from a processing stream.

The major cost in a membrane separation system is the engineering and development work required to apply the system to a particular process. Equipment costs are secondary; membranes generally account for only 10 percent of system costs. However, membranes must be replaced periodically and sales of replacement membranes are important to membrane production firms. Currently the largest profit items are for high-volume flow situations (e.g., water purification) or for high-value product applications (e. g., pharmaceutical productions). Over 20 companies cover the membrane market; the largest company is Millipore with 1980 total sales of \$255 million.

The predicted market growth rate for membrane segregations is healthy, generally 10 to 20 percent annually of the present membrane market (\$600 million to \$950 million). Chlor-alkali membrane electrodialysis cells for the production of chlorine and sodium hydroxide lead the projected application areas in hazardous waste with growth rates of 25 to 40 percent of the present market (\$10 million to \$15 million). The recovery of chromic acid from electroplating solutions by coupled transport also has direct application for the reduction of hazardous waste. Other uses include ultrafiltration of electrocoat-painting process waste and waste water recovery by reverse osmosis. The use of membrane segregation systems in pretreatment of hazardous waste probably is the largest application for the near future.

Biotchnology.-Conventional biological treatments have been used in industrial waste treatment systems for many years (see tables 29 and 30). Recent advances in the understanding of biological processes have led to the development of new biological tools, increasing the opportunities for biotechnology applications in many areas, including the treatment of dilute hazardous waste. The potential impacts of these advancements on waste treatment techniques, process modifications, and end-product substitutes are discussed here.

Biotechnology has direct application to waste treatment systems to degrade and/or detoxify

Table 29.—Conventional Biological Treatment Methods

Treatment method	Aerobic (A) anaerobic (N)	Waste applications	Limitations
Activated sludge	A	Aliphatics, aromatics, petrochemicals, steel making, pulp and paper industries	Volatilization of toxics; sludge disposal and stabilization required
Aerated lagoons	A	Soluble organics, pulp and paper, petrochemicals	Low efficiency due to anaerobic zones; seasonal variations; requires sludge disposal
Trickling filters	A	Suspended solids, soluble organics	Sludge disposal required
Biocontactors	A	Soluble organics	Used as secondary treatment
Packed bed reactors	A	Vitrification and soluble organics	Used as secondary treatment
Stabilization ponds	A&N	Concentrated organic waste	Inefficient; long retention times, not applicable to aromatics; sludge removal and disposal required
Anaerobic digestion	N	Nonaromatic hydrocarbons; high-solids; methane generation	Long retention times required; inefficient on aromatics
Land farming/spreading	A	Petrochemicals, refinery waste, sludge	Leaching and runoff occur; seasonal fluctuations; requires long retention times
Composting	A	Sludges	Volatilization of gases, leaching, runoff occur; long retention time; disposal of residuals

Aerobic—requires presence of oxygen for cell growth
 Anaerobic—requires absence of oxygen for cell growth

SOURCE Office of Technology Assessment

Table 30.—Industries With Experience in Applying Biotechnology to Waste Management

Industry	Effluent stream	Major contaminants
Steel	Coke-oven gas scrubbing operation	NH ₃ , sulfides, cyanides, phenols
Petroleum refining Organic chemical manufacture	Primary distillation process Intermediate organic chemicals and byproducts	Sludges containing hydrocarbons Phenols, halogenated hydrocarbons, polymers, tars, cyanide, sulfated hydrocarbons, ammonium compounds
Pharmaceutical manufacture	Recovery and purification solvent streams	Alcohols, ketones, benzene, xylene, toluene, organic residues
Pulp and paper	Washing operations	Phenols, organic sulfur compounds, oils, lignins, cellulose
Textile	Wash waters, deep discharges	Dyes, surfactants, solvents

SOURCE Office of Technology Assessment

chemicals. Development of new microbial strains can be used to improve:

1. degradation of recalcitrant compounds,
2. tolerance of severe or frequently changing operating conditions,
3. multicomponent destruction,
4. rates of degradation, and

5. ability to concentrate nondegradable constituents.

Compounds thought to be recalcitrant, (e.g., toluene, benzene, and halogenated compounds) have been shown to be biodegradable by isolated strains. Strain improvement in these species through genetic manipulations has led

to improved degradation rates. Opportunities exist for applications of this technology in remedial situations—i.e., cleanup at spills or abandoned sites.⁶⁷ The improvement of conventional biological systems through the development of specific microbial strains (“superbugs”) capable of degrading multiple compounds has been proposed. However, this approach faces engineering difficulties, and development of collections of organisms working together might be preferable.

Development of biological pretreatment systems for waste streams has some potential for those wastes that contain one or two recalcitrant compounds. A pretreatment system designed to remove a specific toxic compound could reduce the shock effects on a conventional treatment process. In some cases, a pretreatment system may be used with other nonbiological treatment methods (i.e., incineration) to remove toxic compounds that may not be handled in the primary treatment system or to make them more readily treated by the primary system. In other cases, pretreatment might render a waste nonhazardous altogether.

One area of research in advanced plant genetics is in the use of plants to accumulate metals and toxic compounds from contaminated soils. Current research is direct to four areas. The first involves use of plants to decrease the metal content of contaminated soils, through increased rates of metal uptake. Plants then could be used to decontaminate soils through concentration of compounds in the plant fiber. The plants then would be harvested and disposed. The second area of development focuses on direct metal uptake in nonedible portions of the plant. For example, the development of a grain crop like wheat that could accumulate metal from soil in the nonusable parts of the plant would allow commercial use of contaminated land. A third area of research is

G. T. Thibault and N. W. Elliott, “Biological Detoxification of Hazardous Organic Chemical Spills,” in *Control of Hazardous Material Spills*, Conference Proceedings (Nashville, Term.: Vanderbilt University, 1980), pp. 398402.

G. C. Walton and D. Dobbs, “Biodegradation of Hazardous Materials in Spill Situations,” in *Control of Hazardous Material Spills Conference Proceedings* [Nashville, Term.: Vanderbilt University, 1980], pp. 2345.

directed toward development of crops that can tolerate the presence of metal without incorporating these toxic elements in plant tissue. Finally, research is being conducted concerning the use of plants in a manner similar to microorganisms to degrade high concentrations of hazardous constituents.

Changes in process design incorporating advances in biological treatment systems may result in less hazardous waste. The development of organisms capable of degrading specific recalcitrant materials may encourage source separation, treatment, and recycling of process streams that are now mixed with other waste streams and disposed. The replacement of chemical synthesis processes with biological processes may result in the reduction of hazardous waste. Two methods of increasing the rate of chemical reactions are through higher temperatures and catalysts. One type of catalyst is biological products (enzymes) that inherently require milder, less toxic conditions than do other catalytic materials.

Historically, many biological processes (fermentations) have been replaced by chemical synthesis. Genetic engineering offers opportunities to improve biological process through reduced side reactions, higher product concentrations, and more direct routes; thus, genetic engineering offers a means of partially reversing this trend. The development of new process approaches would require new reactor designs to take advantage of higher biological reaction rates and concentrations.

Biotechnology also could lead to substitution of a less or nonhazardous material for a hazardous material, particularly in the agricultural field. One of the primary thrusts of plant genetics is the development of disease-resistant plants, thus reducing the need for commercial products such as fungicides. Genetic engineering to introduce nitrogen-fixation capabilities within plants could reduce the use of chemical fertilizers and potentially reduce hazardous waste generated in the manufacture of those chemicals. However, two problems must be resolved before large-scale applications: 1) the genetic engineering involved in nitrogen fixa-

tion is complex and not readily achieved, and z) the overall energy balance of internal nitrogen-fixation may reduce growth rates and crop yield.

Major Concerns for Biotechnology.—Although genetic engineering has some promising applications in the treatment of hazardous waste streams, several issues need to be addressed prior to widespread commercialization of the technology:⁸

- The factors for scale-up from laboratory tests to industrial applications have not been completely developed. Limited field tests have shown degradation rates in the field may be much slower than laboratory rates where pure cultures are tested in pure compounds.
- Basic biochemical degradation mechanisms are not well understood. The potential exists for the formation of other hazardous compounds through small environmental changes or system upsets and, without this basic understanding, chemical pathways cannot be anticipated.
- The potential exists for release of hazardous compounds into the environment through incomplete degradation or system failure.
- There is a possibility of adverse effects resulting from the release of “engineered” organisms into the environment.

The potential benefits of applied genetics to hazardous waste probably outweigh these factors. Although these factors must be addressed, they should motivate rather than overshadow research in this area.

Chemical Dechlorination With Resource Recovery.—In the late 1970's private efforts were undertaken to find a reagent that would selectively attack the carbon-chlorine bond under mild conditions, and thus chemically strip chlorine from PCB-type chemicals forming a salt and an inert sludge. Goodyear Tire & Rubber Co.

made public its method, Sunohio and Acurex Inc. have developed proprietary reagents, modified the process, and commercialized their processes with mobile units. These processes reduce the concentration of PCB in transformer oil, which may be 50 to 5,000 parts per million (ppm) to less than 2 ppm. The Sunohio PCBX process is used for direct recycling of the transformer oil back into transformers, while the oil from the Acurex process is used as a clean fuel in boilers.⁹

Although, the development of these processes was initially aimed at PCB-laden oils of moderate concentration (50 to 500 ppm), their chemistry is generic in that it attacks the carbon-halogen bonds under mild conditions. Thus, they are potentially applicable to pesticides and other halogenated organic wastes as well as wastes with higher concentrations of PCBs. The PCBX process has been applied to pesticides and other halogenated waste with detoxification observed, but without published numerical results or further developments.¹⁰ Acurex claims it has commercially treated oil with a PCB concentration of 7,000 ppm. In tests performed by Battelle Columbus Laboratories for Acurex, its process reduced dioxin concentration in transformer oil from 380 parts per trillion (ppt) to 40 ± 20 ppt. Acurex and the Energy Power Research Institute have tested the effectiveness of the process in the laboratory on capacitors which contain 100 percent PCB (40 to 50 percent chlorine, by weight). The next step is construction of a mobile commercial-scale facility which would shred, batch process, and test the capacitor material.¹¹

The Sunohio (first to have a chemical dechlorination process approved by EPA) has five units in operation. Acurex has four mobile units in operation at this time and at least two other companies currently market similar chemical PCB destruction services. Acurex,

⁸S. p. Pirages, L. M. Curran, and J. S. Hirschhorn, “Biotechnology in Hazardous Waste Management: Major Issues,” paper presented at *The Impact of Applied Genetics on Pollution Control* symposium sponsored by the University of Notre Dame and Hooker Chemical Co., South Bend, Ind., May 24-26, 1982.

⁹*Alternatives to the Land Disposal of Hazardous Wastes*, Governor's Office of Appropriate Technology, California, 1981.

¹⁰Oscar Norman, developer of the PCBX process, personal communication, January 1983.

¹¹Leo Weitzman, Acurex Corp., personal communication, January 1983.

Sunohio, and licensees have been selling their PCB services for over a year. Acurex and The Franklin Institute plan to commercialize their processes for spill sites involving halogenated organics.¹²

¹²Charles Rogers, Office of Research and Development, Industrial and Environmental Research Laboratory (IERL), Environmental Protection Agency, Cincinnati, Ohio, personal communication, January 1983.

As an alternative to incineration, these chemical processes offer the advantages of no air emissions, no products of incomplete combustion, reduced transportation risks, and the recycling of a valuable material or the recovery of its fuel value. Further, as with many chemical processes, there is the opportunity to directly check the degree of destruction before any product is discharged or used.

Hazard Reduction Alternatives: Treatment and Disposal

Introduction

The previous section discussed technologies to reduce the volume of waste generated. This section analyzes technologies that reduce the hazard of waste. These include treatment and disposal technologies. These two groupings of technologies contrast distinctly in that it is preferable to permanently reduce risks to human health and the environment by waste treatments that destroy or permanently reduce the hazardous character of the material, than to rely on long-term containment in land-based disposal structures.

In the United States, as much as 80 percent (by volume) of the hazardous waste generated is land disposed (see ch. 4). Of these wastes, a significant portion could be treated rather than land disposed for greater hazard reduction. In California, for example, wastes which are toxic, mobile, persistent and bioaccumulative comprise about 29 percent of the hazardous waste disposed of offsite.^{13 14}

Following a brief summary comparison, this section reviews over 15 treatment technologies. Many of these eliminate the hazardous character of the waste. Technologies in the next group discussed are disposal alternatives. Their effectiveness relies on containing the waste to prevent, or to minimize, releases of waste and

human and environmental exposure to waste. In this category, the major techniques are landfills, surface impoundments, and underground injection wells.

This discussion begins with a comparison of the treatment and disposal technologies and ends with a cost comparison. These discussions focus on the competitive aspects of the numerous hazard reduction technologies. However, choosing among these technical alternatives involves consideration of many factors, some of which are neither strictly technical or economic. Choices by waste generators and facility operators also depend on Federal and State regulatory programs already in place, those planned for the future, and on perceptions by firms and individuals of existing regulatory burdens may exist for a specific waste, technology, and location.

Summary Comparison

For the purpose of an overview, qualitative comparisons among technologies can be made. Based on principle considerations relevant across all technologies, the diverse range of hazard reduction technologies can be compared as presented in table 31. The table summarizes the important aspects of the above issues for each generic grouping of technologies included. Individual technologies are considered in more detail in the following discussions on treatment and disposal technologies. For simplicity, the technologies are grouped generically, and only a limited number

¹³California Department of Health Services, "Initial Statement of Reasons for Proposed Regulations (R-32-82)," Aug. 18, 1982, p. 23.

¹⁴California Department of Health Services, "Current Hazardous Waste Generation," Aug. 31, 1982, p. 6.

Table 31 .—Comparison of Some Hazard Reduction Technologies

	Disposal		Incineration and other thermal destruction	Treatment	Chemical stabilization
	Landfills and Impoundments	Injection wells		Emerging high-temperature decomposition*	
Effectiveness How well it contains or destroys hazardous characteristics	Low for volatiles, questionable for liquids based on lab and field tests	High, based on theory, but limited field data available	High, based on field tests, except little data on specific constituents	Very high, commercial scale tests	High for many metals, based on lab tests
Reliability issues:	Siting, construction, and operation Uncertainties long-term integrity of cells and cover, liner life less than life of toxic waste	Site history and geology, well depth, construction and operation	Long experience with design Monitoring uncertainties with respect to high degree of DRE, surrogate measures, PICs, incinerability	Limited experience Mobile units, onsite treatment avoids hauling risks Operational simplicity	Some inorganics still soluble Uncertain leachate test, surrogate for weathering
Environmental media most affected	Surface and ground water	Surface and ground water	Air	Air	None likely
Least compatible waste:	Liner reactive, highly toxic, mobile, persistent, and bioaccumulative	Reactive, corrosive, highly toxic, mobile, and persistent	Highly toxic and refractory organics, high heavy metals concentration	Possibly none	Organics
Costs Low, Mod, High	L-M	L	M-H (Coincin = L)	M-H	M
Resource recovery potential	None	None	Energy and some acids	Energy and some metals	Possible building material

*Molten high-temperature fluid wall, and plasma arc treatments

^bWaste for which this method may be less effective for reducing exposure, relative to other technologies Waste listed do not necessarily denote common usage

SOURCE Office of Technology Assessment

of groups are compared, The principal considerations used for comparison are the following:

- **Effectiveness.**—This does not refer to the intended end result of human health and environmental protection, but to the capability of a technology to meet its specific technical objective. For example, the effectiveness of chemical dechlorination is determined by how completely chlorine is removed. In contrast, the effectiveness of landfills is determined by the extent to which containment or isolation is achieved.
- **Reliability .**—This is the consistency over time with which a technology’s objective is met, Evaluation of reliability requires consideration of available data based on theory, laboratory-scale studies, and commercial experience.

A prominent factor affecting the relative reliability of a technology is the adequacy of substitute performance measures. Verification that a process is performing as designed is not always possible and, when possible, verification to a high level of confidence may require days or weeks to complete and may not be useful for timely adjustments. In some cases, key process variables can be used as substitute measures for the effectiveness of the technology. Substitute measures are used either be-

cause they provide faster and/or cheaper performance information, A disadvantage of surrogate measures is that there may not be reliable correlation between the surrogate measurement and the nature of any releases to the environment.

The reliability of a technology should also be judged on the degree of process and discharge control available. This refers to the ability to: 1) maintain proper operating conditions for the process, and 2) correct undesirable releases. Process control requires that information about performance be fed back to correct the process. Control systems vary categorically with respect to two important time variables:

1. the length of time required for information to be fed back into the system (e.g., time for surrogate sampling and analysis, plus time for corrective adjustments to have the desired effect); and
2. the length of time for release of damaging amounts of insufficiently treated materials in the event of a treatment upset.

In the case of landfills, once ground water monitoring has detected a leak, damaging discharges could have already occurred.

If detection systems are embedded in the liner, then detection of a system failure is quicker and more reliable, and it offers more opportunity for correction. Landfilling and incineration are examples where these time factors are important. In contrast, batch treatment processes, as discussed in the preceding section on "Waste Reduction," offer the distinct opportunity to contain and check any release, and retreat it if needed, so that actual releases of hazardous constituents are prevented. Other chemical and biological treatments are flow-through processes, with different rates of flow-through. These treatments vary in their opportunity for discharge correction. Generally, processes used in waste segregation and recycling offer this kind of reliability.

- Environmental media most affected.—This refers to the environmental media contaminated in the event that the technology fails.
- Least compatible waste.—Some technologies are more effective than others in preventing releases of hazardous constituents when applied to particular types of waste.
- Costs.—Costs vary more widely among generic groups of technologies than within these groups. Table 31 presents generalized relative costs among these groups. The final section of this chapter gives some unit management cost details.
- **Resource recovery potential.**—Treatments that detoxify and recover materials for recycling are discussed under "Waste Reduction." However, some materials, as well as energy, can be recovered with some of the technologies reviewed in this section. To the extent that materials and fuels are recovered and used, the generation of other hazardous wastes maybe reduced. Potential releases of hazardous constituents from recovery and recycling operations must also be considered,

Treatment Technologies

In this section, treatment technologies refers to those techniques which decompose or break

down the hazardous wastes into nonhazardous constituents. * Most of these treatments use high temperatures to decompose waste. Some of the promising emerging technologies cause decomposition by high-energy radiation and/or electron bombardment. There are several important attributes of high-temperature destruction technologies which make them attractive for hazardous waste management:

- the hazard reduction achieved is permanent;
- they are broadly applicable to waste mixes; most organics, for example, may be converted into nonhazardous combustion products; and
- the volume of waste that must ultimately be land disposed is greatly reduced,

In addition, with some of these treatments, there is a possibility of recovering energy and/or materials.** However, potential recovery of energy and materials is not the primary focus of this discussion.

Incineration is the predominant treatment technology used to decompose waste. The term "incineration" has been given a specific meaning in Federal regulations, where it denotes a particular subclass of thermal treatments, and draft Federal regulations may give specific meaning to the additional terms "industrial boiler" and "industrial furnace." Although the Federal definitions affect the manner in which a facility is regulated, unless specifically noted,

• Treatments can also be used to segregate specific waste constituents, or to mitigate their characteristics of ignitability, corrosiveness, or reactivity. Most of these are referred to as "industrial unit processes," and their use is usually embedded in larger treatment schemes. A lengthy listing will not be reproduced here. Many were described in the preceding section on "Waste Reduction Technologies." The interested reader is also referred to any industrial unit operations manual. Another source is "Chemical, Physical, Biological (CPB) Treatment of Hazardous Wastes," Edward J. Martin, Timothy Oppelt, and Benjamin Smith, Office of Solid Waste, U.S. Environmental Protection Agency, presented at the Fifth United States-Japan Governmental Conference of Solid Waste Management, Tokyo, Japan, Sept. 28, 1982.

•*For example, the Chemical Manufacturers Association claims that a significant portion of the hydrochloric acid produced in the United States and some sulfuric acid come from incineration of chlorinated organics through wet-scrubbing of the stack gases. (CMA, personal communication, December 1982.) Also, there is clear potential for metals recovery with the emerging high-temperature technologies.

“combustion” or “incineration” are used in this report to refer to the generic processes of interest, and do not necessarily mean specific facility designs or regulatory categories.

Applicable Wastes

Liquid wastes are generally more easily incinerated than sludge or waste in granular form, because they can be injected easily into the combustion chamber in a manner which enhances mixing and turbulence. Wastes with heterogeneous physical characteristics and containerized or drummed wastes are difficult to feed into a combustion chamber. The rotary kiln is designed for sludge-like, granular and some containerized waste. Recently, a new firm has emerged (Continental Fibre Drum) which manufactures combustible fiber drums for waste containers. These fiber drums of organic waste can be incinerated in specially designed rotary kilns.

Elemental metals, of course, cannot be degraded. Waste which contain excessive levels of volatile metals may not be suitable for incineration. Under the high-temperature conditions in an incinerator, some metals are volatilized or carried out on particulate. Oxides of metals can generally be collected electrostatically. However, some volatilized forms cannot be electrically charged, resisting electrostatic collection. These include metallic mercury, arsenic, antimony, and cadmium, and very small particles.¹⁵ (Particles having insufficient surface area also can't be adequately charged and collected,) Wet second-stage electrostatic precipitators are designed for removing these forms of volatilized metals, but they are expensive and not in widespread use. High-pressure drop-emission controllers have also been effective, but their use is declining.

Technical Issues

There are approximately 350 liquid injection and rotary kiln incinerators currently in service for hazardous waste destruction.¹⁸ Most

¹⁵Frank Whitmore, Versar, inc., persona} communication, August 1982.

¹⁶Gene Crumpler, Office of Solid Waste, Hazardous and Industrial Waste Division, Environmental Protection Agency, personal communication, January 1983.

of these facilities may eventually be permitted as RCRA hazardous waste incinerators. A far greater, although unknown, number of facilities may be combusting hazardous waste principally in order to recover their heating value. Under current regulations, these facilities would not be permitted as hazardous waste incinerators.” Under future regulations they may become subject to performance standards similar to those in effect for incinerators, be prohibited from burning certain types of ignitable hazardous waste, or be subject to some intermediate level of regulation.

To regulate incinerators, EPA has decided to use performance standards rather than specification of design standards. The current regulations specify three performance standards for hazardous waste incineration.¹⁸ These standards are described below:

1. A 99.99 percent destruction and removal efficiency (DRE) standard for each principal organic hazardous constituent (POHC) designated in the waste feed. (This is the most difficult part of the standard to meet.) The DRE is calculated by the following mass balance formula:

$$\text{DRE} = (1 - \text{Wout}/\text{Win}) \times 100 \text{ percent,}$$
 where:

$$\text{Win} = \text{the mass feed rate of 1 POHC in the waste stream going into the incinerator, and}$$

$$\text{Wout} = \text{the mass-emission rate of the same POHC in the exhaust prior to release to the atmosphere.}$$
2. Incinerators that emit more than 4 lb of hydrogen chloride per hour must achieve a removal efficiency of at least 99 percent. (All commercial scrubbers tested by EPA have met this performance requirement.)
3. Incinerators cannot emit more than 180 milligrams (mg) of particulate matter per dry standard cubic meter of stack gas. This standard is intended to control the emissions of metals carried out in the exhaust gas on particulate matter. (Recent tests indicate that this standard may be more difficult to achieve than was earlier thought.¹⁹)

¹⁸Ibid.

¹⁹40 CFR, sec. 264.343.

²⁰Wrumpler, op. cit.

There are instances in which the incinerator performance standards do not fully apply. First, the regulations do not apply to facilities that burn waste primarily for its fuel value. To date, energy recovery of the heat value of waste streams qualifies for the regulatory exemption.²⁰ Second, facilities burning waste that are considered hazardous because of characteristics of ignitability, corrosiveness, and reactivity are eligible for exemptions from the performance standards. Of the three, the exemption for energy recovery applies to a greater volume of hazardous waste. Finally, incinerators operating at sea are not governed by RCRA but rather by the Marine Protection, Research, and Sanctuaries Act of 1972. Regulations under this act do not require scrubbing of the incinerator exhaust gas. In the future, EPA may require that incinerator ships operating in close proximity to each other scrub their exhaust gases.

With regard to combustion processes, the most important design characteristics are the “three Ts:”

1. maintenance of adequate temperatures within the chamber,
2. adequate turbulence (mixing) of waste feed and fuel with oxygen to assure even and complete combustion, and
3. adequate residence times in the high-temperature zones to allow volatilization of the waste materials and reaction to completion of these gases.

Finally, the DRE capability of these technologies generally varies widely depending on the waste type to which it is applied, Chlorine or other halogens in the waste tend to extinguish combustion; so, in general, these wastes tend to be more difficult to destroy. An important related misconception is that the more toxic compounds are the more difficult they are to burn. Toxic dioxins and PCBs are popular examples of highly halogenated wastes which are both highly toxic and difficult to destroy, but these should not imply a rule. Discussion of waste “incinerability” is included below.

²⁰40 CFR, sec. 261.2 (c)(2).

Waste treatments with reliable high-destruction efficiencies offer attractive alternatives to land disposal for mobile, toxic, persistent, and bioaccumulative wastes. However, these treatment technologies are not free of technical issues. The first three issues noted below relate directly to **policy** and regulation, and the remaining three issues summarize sources of technical uncertainty with respect to the very small concentrations of remaining substances. Improvements in policy and regulatory control should recognize these technical issues:

- **Significant sources of toxic combustion products, emitted to the air, are not being controlled with the same rigor as are RCRA incinerators.** These include emissions from facilities inside the property boundaries of refineries and other chemical processing plant sites. In addition, “boilers” can receive and burn any ignitable hazardous waste which has beneficial fuel value (see discussion on “Boilers”). Draft regulations governing boilers are currently being developed under RCRA and very limited reporting requirements are brand new. Under the Clean Air Act, there is only very limited implementation governing the remaining facilities. Standards have been set for only four substances, and apply to only a small class of facilities.
- There are some problems with the technology-based DRE performance standards. EPA uses the technology-based performance standard for practicality, and for its technology-forcing potential. However, the performance standard overly simplifies the environmental comparisons among alternatives.

Complete knowledge about the transport, fate, and toxic effects of each waste compound from each facility is unobtainable. Thus, some simplified regulatory tool is needed. However, the most important and known factors should be included in regulatory decisions. Notably, these could include: the toxicity of the waste, the load to the facility (the waste feed concentra-

tion and size of the facility), and population potentially affected. Future regulations, however, could endeavor to shape the manner in which competing technologies are chosen in a more environmentally meaningful way (see ch. 6),

Finally, the 99.99 percent DRE may be viewed as a “forcing” standard with respect to some high-temperature technologies, but emerging high-temperature technologies (notably plasma arc) may offer much greater and more reliable DREs. Rather than forcing, it may discourage the wide use of more capable technologies,

- Strengthening regulations with respect to the technical uncertainties below will require deliberate research efforts in addition to anticipated permitting tests. Test data for wastes that are difficult to burn are lacking. The current incinerator performance standard is based on EPA surveys from the mid-1970’s which involved easier to burn wastes, higher fuel to waste feed ratios than in current use, and smaller than commercial-scale reactors, EPA is currently testing or observing test burns for many of the technologies described, using compounds found to be representative of very difficult to burn toxic waste. Most of these data are still being evaluated; few results have become available. In the next few years, a great deal of test burn data will be generated regarding existing facilities and given wastes. In addition, the cost of test burn is often \$20,000 to \$50,000. These costs burden both EPA research and private industry. Such data will help permit writers, but these data will have limited use in resolving many of the technical uncertainties described below.
- Implementation of the current performance standards relies on industrywide use of monitoring technology operating at the limits of its capability. In DRE analyses, the fourth nine is often referred to as guesswork; standardized stack gas sampling protocols for organic hazardous constituents are still being developed. This is particularly true with respect to organics carried on particulate matter and to the

more volatile compounds. Methods for concentrating the exhaust gas in order to obtain the sample especially for volatile compounds are still evolving. The newness of these tests suggests there may be a wide variety in the precision capabilities among the laboratories which analyze DRE test results.

- The measurements currently used in daily monitoring of performance cannot reliably represent DRE at the 99.99 percent level. For recordkeeping and enforcement, air and waste feed rates along with gas temperature are used as indirect measures for DRE. For facilities already equipped with carbon monoxide meters (and for all Phase II regulated incinerators), carbon monoxide concentration in the stack gas is also included. Also, waste/fuel mix and waste/fuel ratio can have a great effect on DRE. Thus, these ratios are noted in the permits. However, it is difficult to specify acceptable ranges of mixes based on test burn information. The idea behind the specifications is that as long as actual values of these parameters remain within prescribed limits during operation, the desired DRE is being achieved. These measures are chosen not only because they are easily and routinely monitored, but also because there is a theoretical basis for using them to indicate combustion efficiency. However, all these measures are only indirectly related to the compounds of concern. For example, carbon monoxide is a very stable and easily monitored product of incomplete combustion (PIC). Thus, it is often used as a sensitive indicator for combustion efficiency in energy applications. However, its relationship to other combustion products and to remaining concentrations of POHCs is very indirect and uncertain,

Most experts agree that the development of a way to accurately measure DRE concurrently with treatment process, would eliminate much of the technical uncertainties surrounding incineration. To this end, EPA is studying devices which monitor total organic carbon, and the National

Bureau of Standards (NBS) is studying various combinations of available monitoring techniques.²¹ It is not likely that a single technique can be developed in the near term to monitor the whole range of compounds of concern, but the development of a combination of devices to do the job holds promise. However, these techniques will still have problems. This will include: cost; some reliance on correlations to surrogate measures; and, in the case of the NBS approach, the possible introduction of corrosive tracer compounds.

- There is sharp disagreement in the scientific and regulatory community about the use of waste "incinerability." This concept is a regulatory creation, not a physical attribute of any material. The idea behind incinerability is that as long as the least incinerable waste (i.e., the most difficult to burn waste) is destroyed to the required extent, all other waste would be destroyed to an even greater extent. Thus, waste "incinerability," in addition to waste concentration, is used to select a limited number of waste constituents for monitoring in a test burn. Problems with this approach result largely from lack of basic information about measures for incinerability. This presents uncertainty in the selection of those POHCs to be monitored in the waste feed and stack gas. Heat combustion is the informational surrogate currently used because it is readily determined. However, this measure relates poorly to waste incinerability. Chlorine and other halogens in the waste tend to extinguish combustion, but simple halogen content give poor indication of incinerability. Autoignition temperature is closely related to incinerability, but for most hazardous compounds, it has not been measured. Better predictors of incinerability could be developed. One scheme, proposed by NBS, would use a combination of factors, but it needs to be tested.
- There is a lack of basic understanding **about how stable toxic PICs** are formed.

²¹W. Schaub, National Bureau of Standards, personal communication, January 1983.

Some compounds, known to be very difficult to incinerate, also occur as PICs from combusting mixtures of compounds thought to be more easily burned. Our ability to monitor these compounds has only recently made such observations possible, and there are many high-temperature kinetic reactions not fully understood. Unless specifically analyzed, a selected PIC would go undetected. While additional testing of individual combustion facilities will demonstrate specific DRE capabilities, these observations are not likely to improve our fundamental understanding of PIC formation. In particular, with the cost of test burns with POHC monitoring so high, some more basic research on PIC formation would be appropriate. Current EPA research and development, however, is focused in support of near-term permitting activities.

Review of Selected High-Temperature Treatment Technologies

There are a variety of treatment technologies involving high temperatures which have, or will likely have, important roles in hazardous waste management. Most of these technologies involve combustion, but some are more accurately described as destruction by infrared or ultraviolet radiation.

Discussion below focuses on the distinguishing principles, the reliability and effectiveness, and the current and projected use of these technologies. Unless otherwise noted, DRE values were measured in accordance with EPA testing procedures. Table 32 summarizes the advantages, disadvantages, and status of these technologies.

1. Liquid injection incineration.—With liquid injection, freely flowing wastes are atomized by passage through a carefully designed nozzle (see fig. 8). It is important that the droplets are small enough to allow the waste to completely vaporize and go through all the subsequent stages of combustion while they reside in the high-temperature zones of the incinerator. Residence times in such incinerators are short, so nozzles especially, as well as other

Table 32.—Comparison of Thermal Treatment Technologies for Hazard Reduction

Advantages of design features	Disadvantages of design features	Status for hazardous waste treatment
Currently available incinerator designs:		
Liquid injection Incineration		
Can be designed to burn a wide range of pumpable waste. Often used in conjunction with other Incinerator systems as a secondary afterburner for combustion of volatilized constituents Hot refractory minimizes cool boundary layer at walls. HCl recovery possible.	Limited to destruction of pumpable waste (viscosity of less than 10,000 SS). Usually designed to burn specific waste streams. Smaller units sometimes have problems with clogging of injection nozzle.	Estimated that 219 liquid injection incinerators are in service, making this the most widely used incinerator design.
Rotary kilns:		
Can accommodate great variety of waste feeds ³ solids, sludges, liquids, some bulk waste contained in fiber drums Rotation of combustion chamber enhances mixing of waste by exposing fresh surfaces for oxidation.	Rotary kilns are expensive. Economy of scale means regional locations, thus, waste must be hauled, increasing spill risks.	Estimated that 42 rotary kilns are in service under interim status. Rotary kiln design is often centerpiece of integrated commercial treatment facilities. First noninterim RCRA permit for a rotary kiln incinerator (IT Corp.) is currently under review.
Cement kilns:		
Attractive for destruction of harder-to-burn waste, due to very high residence times, good mixing, and high temperatures Alkaline environment neutralizes chlorine	Burning of chlorinated waste limited by operating requirements, and appears to increase particulate generation. Could require retrofitting of pollution control equipment and of instrumentation for monitoring to bring existing facilities to comparable level. Ash may be hazardous residual.	Cement kilns are currently in use for waste destruction, but exact number is unknown. National kiln capacity is estimated at 41.5 million tonnes/yr. Currently mostly nonhalogenated solvents are burned.
Boilers (usually a liquid Injection design)⁴		
Energy value recovery, fuel conservation Availability on sites of waste generators reduces spill risks during hauling	Cool gas layer at walls result from heat removal This constrains design to high-efficiency combustion within the flame zone, Nozzle maintenance and waste feed stability can be critical. Where HCl is recovered, high temperatures must be avoided. (High temperatures are good for DRE.) Metal parts corrode where halogenated waste are burned.	Boilers are currently used for waste disposal. Number of boiler facilities is unknown, quantity of wastes combusted has been roughly estimated at between 17.3 to 20 million tonnes/yr.
Applications of currently available designs:		
Multiple hearth		
Passage of waste onto progressively hotter hearths can provide for long residence times for sludges Design provides good fuel efficiency. Able to handle wide variety of sludges	Tiered hearths usually have some relatively cold spots which inhibit even and complete combustion. Opportunity for some gas to short circuit and escape without adequate residence time. Not suitable for waste streams which produce fusible ash when combusted Units have high maintenance requirements due to moving parts in high-temperature zone.	Technology is available; widely used for coal and municipal waste combustion.
Fluidized-bed incinerators:		
Turbulence of bed enhances uniform heat transfer and combustion of waste. Mass of bed is large relative to the mass of injected waste.	Limited capacity in service. Large economy of scale	Estimated that nine fluidized-bed incinerators are in service. Catalytic bed may be developed.
At-sea incineration: shipboard (usually liquid injection incinerator):		
Minimum scrubbing of exhaust gases required by regulations on assumption that ocean water provides sufficient neutralization and dilution. This could provide economic advantages over land-based incineration methods Also, incineration occurs away from human populations Shipboard incinerators have greater combustion rates, e.g., 10 tonnes/hr.	Not suitable for waste that are shock sensitive, capable of spontaneous combustion, or chemically or thermally unstable, due to the extra handling and hazard of shipboard environment. Potential for accidental release of waste held in storage (capacities vary from between 4,000 to 8,000 tonnes).	Limited burns of organochlorine and PCB were conducted at sea in mid-1970. PCB test burns conducted by Chemical Waste Management, Inc., in January 1982 are under review by EPA. New ships under construction by At Sea Incineration, Inc.
At-sea incineration: oil drilling platform-based:		
Same as above, except relative stability of platform reduces some of the complexity in designing to accommodate rolling motion of the ship.	Requires development of storage facilities. Potential for accidental release of waste held in storage.	Proposal for platform incinerator currently under review by EPA.

Table 32.—Comparison of Thermal Treatment Technologies for Hazard Reduction—Continued

Advantages of design features	Disadvantages of design features	Status for hazardous waste treatment
<p>Pyrolysis: Air pollution control needs minimum: air-starved combustion avoids volatilization of any inorganic compounds. These and heavy metals go into insoluble solid char. Potentially high capacity.</p>	<p>Greater potential for PIC formation. For some wastes produce a tar which is hard to dispose of. Potentially high fuel maintenance cost. Waste-specific designs only.</p>	<p>Commercially available but in limited use.</p>
<p>Emerging thermal treatment technologies:</p>		
<p>Molten salt: Molten salts act as catalysts and efficient heat transfer medium. Self-sustaining for some wastes. Reduces energy use and reduces maintenance costs. Units are compact; potentially portable. Minimal air pollution control needs; some combustion products, e.g., ash and acidic gases are retained in the melt.</p>	<p>Commercial-scale applications face potential problems with regeneration or disposal of ash-contaminated salt. Not suitable for high ash wastes. Chamber corrosion can be a problem. Avoiding reaction vessel corrosion may imply tradeoff with DRE.</p>	<p>Technology has been successful at pilot plant scale, and is commercially available.</p>
<p>High-temperature fluid wall: Waste is efficiently destroyed as it passes through cylinder and is exposed to radiant heat temperatures of about 4,000° F. Cylinder is electrically heated; heat is transferred to waste through inert gas blanket, which protects cylinder wall. Mobile units possible.</p>	<p>To date, core diameters (3", 6", and 12") and cylinder length (72 limit throughput capacity. Scale-up may be difficult due to thermal stress on core. Potentially high costs for electrical heating.</p>	<p>Other applications tested; e.g., coal gasification, pyrolysis of metal-bearing refuse and hexachlorobenzene. Test burns on toxic gases in December 1962.</p>
<p>Plasma arc: Very high energy radiation (at 50,000° F) breaks chemical bonds directly, without series of chemical reactions. Extreme DREs possible, with no or little chance of PICs, Simple operation, very low energy costs, mobile units planned.</p>	<p>Limited throughput. High use of NaOH for scrubbers.</p>	<p>Limited U.S. testing, but commercialization in July 1963 expected. No scale-up needed.</p>
<p>Wet oxidation: Applicable to aqueous waste too dilute for incineration and too toxic for biological treatment. Lower temperatures required, and energy released by some wastes can produce self-sustaining reaction. No air emissions.</p>	<p>Not applicable to highly chlorinated organics, and some wastes need further treatment.</p>	<p>Commercially used as pretreatment to biological wastewater treatment plant. Bench-scale studies with catalyst for nonchlorinated organics.</p>
<p>Super critical water: Applicable to chlorinated aqueous waste which are too dilute to incinerate. Takes advantage of excellent solvent properties of water above critical point for organic compounds. injected oxygen decomposes smaller organic molecules to CO₂ and water. No air emissions.</p>	<p>Probable high economy of scale. Energy needs may increase on scale-up.</p>	<p>Bench-scale success (99.99% DRE) for DDT, PCBs, and hexachlorobenzene.</p>

SOURCE: Off Ice of Technology Assessment, compiled from references 12 through 29.

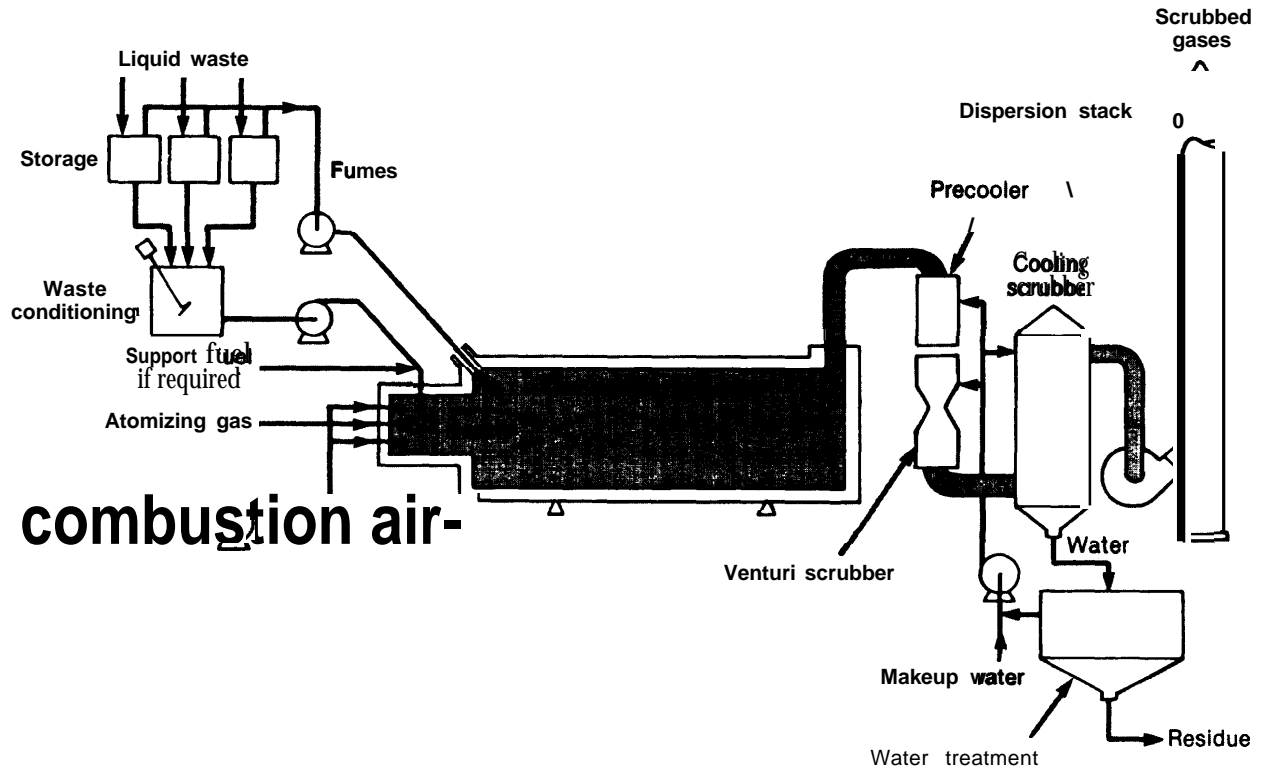
features, must be designed for specified waste stream characteristics such as viscosity. Certain waste must be preheated. Nonclogging nozzles are available, but all nozzles must be carefully maintained. One of the chief costs is maintenance of refractory walls. Incinerator design is a complex, but advanced field. Many distinguishing design features are currently proprietary; especially nozzle designs and refractory composition.

Injection incinerator designs, especially nozzle design, tend to be waste-specific. However, individual designs exist for the destruction of

many different liquid waste mixes: motor and industrial oils, emulsions, solvents, lacquers, and organic chemicals of all kinds including relatively hard-to-destroy pesticides and chemical warfare agents.

Liquid injection incinerators, together with rotary kilns (see below) form the current basis of the hazardous waste incineration industry. These technologies have been used for the purpose of destroying industrial waste for many years. In the mid-1970's EPA testing and data reviews of these facilities provided the basis for the current interim performance standard

Figure 8.— Injection Liquid Incineration



SOURCE D A Hitchcock, "Solid Waste Disposal Incineration," *Chemical Engineering*, May 21, 1979

of 99.99 percent DRE for incineration of hazardous materials.

EPA has recently begun testing incinerators to better understand the DRE capabilities for the most difficult-to-burn waste. Analysis is not yet complete, but preliminary indications both confirm the 99.99 percent capabilities, and underscore the sensitivities of individual incinerators to operational and waste feed variables.²²

2. Rotary kilns.—These can handle a wider physical variety of burnable waste feeds—solids and sludge, as well as free liquids and gases. A rotating cylinder tumbles and uncovers the waste, assuring uniform heat transfer. The cyl-

inders range in size from about 3 ft in diameter by about 8 or 10 ft long, up to 15 or 20 ft in diameter by about 30 ft long. Rotary kilns operate between temperature extremes of approximately 1,500° and 3,000° F, depending on location measured along the kiln. They range in capacity from 1 to 8 tons of waste per hour.²³

The primary advantage of rotary kilns is their ability to burn waste in any physical form and with a variety of feed mechanisms. Many large companies that use chemicals (such as Dow Chemical Co., 3M Corp., and Eastman Kodak) incinerate onsite with their own rotary kilns. For flexibility, this is often in combination with injection incinerators. Similarly, large waste management service firms (EnSCO and Rollins Environmental Services) operate large rotary kilns as part of their integrated treatment cen-

²²Timothy Oppelt, and various other personal communications, Environmental Protection Agency, Office of Research and Development, IERL, Cincinnati, Ohio, December 1982 and January 1983.

²³Ibid.

ters. Others are in commercial operation throughout the United States and Europe.²⁴

3. Cement kilns.—These are a special type of rotary kiln. Liquid organic waste are cofired with the base fuel in the kiln flame. The very thorough mixing and very long residence times make possible more complete combustion of even difficult to burn organic waste. Temperatures in the kiln range between 2,600° and 3,000° F (1,400° and 1,650° C). Also, the alkaline environment in the kiln neutralizes all of the hydrochloric acid produced from the burning of chlorinated waste. Most ash and nonvolatile heavy metals are incorporated into the clinker (product of the kiln) and eventually into the cement product. Heavy metals incorporated into the clinker may present either real or perceived risks (toxicological and structural), but little is known about such concerns.²⁵ A portion (perhaps 10 percent) of the ash and metals carry over into the kiln dust that is collected in the system's air-pollution control system. Some of this material is recycled to the kiln, the balance is generally landfilled.^{26 27}

Five controlled test burns for chlorinated waste have been documented in wet process cement kilns in Canada, Sweden, Norway, and most recently, the United States. The foreign results have tended to confirm the theoretical predictions—that 99.99 percent or better can be achieved for chlorinated hydrocarbons. However, these studies lack strong documentation of control protocols. In the Swedish results, representative concentrations of very difficult to burn waste were destroyed beyond the limits of monitoring technology, indicating bet-

ter than 99.99 percent destruction.²⁸ The California Air Resources Board recently recommended the use of cement kilns to destroy PCB waste.²⁹ EPA has recently completed a carefully controlled test on the most difficult to burn waste at the San Juan Cement Co. in Duabolo, Puerto Rico. The results of this test are still being evaluated.

Some hazardous wastes are currently being burned in cement kilns under the energy recovery exclusion, but, these have been generally nonhalogenated solvents or waste oils, rather than the most toxic and/or difficult to burn compounds, for which they may be well suited. Since 1979 the General Portland Co. of Paulding, Ohio, has been burning 12,500 tons per year of nonhalogenated waste solvents as a supplemental fuel.

There is theoretically no limit on the fuel-to-waste-feed ratio; as long as the waste mix has sufficient heating value, a kiln could be fired solely on waste feed. Idled kilns could be used as hazardous waste facilities. Local public concerns, notably over spills during hauling, have presented the major obstacle to such incinerator use, but commercial interest apparently is still strong. So much will depend on how new regulations affect land disposal use.

4. Boilers.—Ignitable waste with sufficient heating value are coincinerated with a primary fuel in some types of boilers. The boiler converts as much as possible of the heat of combustion of the fuel mix into energy used for producing steam. Different types of boilers have been designed to burn different types of fuels. Boilers burn lump coal, pulverized coal, No. 2 oil, No. 6 oil, and natural gas.³¹ The predom-

²⁴Technologies for the Treatment and Destruction of Organic

Wastes as Alternatives to Land Disposal, State of California, Air Resources Board, August 1982.

²⁵Myron W. Black, "Impact of Use of Waste Fuels Upon Cement Manufacturing," paper presented at the First International Conference on Industrial and Hazardous Wastes, Toronto, Ontario, Canada, October 1982.

²⁶Douglas L. Hazelwood and Francis J. Smith, et al., "Assessment of Waste Fuel Use in Cement Kilns," prepared by A. T. Kearney and the Portland Cement Association for the Office of Research and Development, EPA, contract No. 68-03-2586, March 1981.

²⁷Alternatives to the Land Disposal of Hazardous Wastes, op. cit.

²⁸Robert Olexsey, "Alternative Thermal Destruction Processes for Hazardous Wastes," Environmental Protection Agency, Office of Research and Development, May 1982.

²⁹An Air Resources Board Policy Regarding incineration as an Acceptable Technology for PCB Disposal," State of California, Air Resources Board, December 1981.

³⁰Myron W. Black, "Problems in Siting of Hazardous Waste Disposal Facilities—The Peerless Experience," paper presented at a conference on Control of Hazardous Material Spills, 1978.

³¹Environmental Protection Agency, Office of Research and Development, "Technical Overview of the Concept of Disposing of Hazardous Waste in Industrial Boilers," contract No. 68-3-2567. October 1981.

inant application to hazardous waste involves boilers of the kind that would normally burn No. 2 fuel oil.

These boilers are similar to liquid injection incinerators, but there are important differences with respect to the high destruction efficiencies desirable for hazardous waste: 1) they have purposefully cooled walls, and 2) at least some of the walls and other parts exposed to the combustion products are often metallic instead of refractory. The reason that the walls of the boiler must be cooled is to make use of the heating energy from the product gas. In the combustion chamber, this results in a relatively cool area (a thermal boundary layer) through which combustion products might pass.

The metallic surfaces avoid some expensive refractory maintenance but the bare metal surfaces are susceptible to corrosion where halogenated organic waste are burned. For this reason industrial boiler owners, concerned for the life of their equipment, probably limit their use of such waste. However, there is a growing industrial trend toward recovery of hydrochloric acid from the stack gas. * 32 Acid recovery requires that stack gas temperatures greater than 1,200 C be avoided, since this condition shifts the chemical equilibrium toward free chlorine. For hazardous waste destruction, however, higher temperatures are better.

For these reasons, efficient boilers must be designed so that hydrocarbon destruction occurs mostly in the flame zone with very little reaction occurring after the flame zone. As is the case with incinerators, boiler design is well advanced, and many designs are proprietary. High fuel efficiency designs may recirculate the flame envelope back into itself to enhance the formation of the series of reactions necessary for complete combustion. Other designs may involve staged injections with varying waste-to-fuel ratios .33

● Currently a significant amount, perhaps over ✓ percent of the U.S. hydrochloric acid, is produced from stack gas scrubbers. Half of this is from boilers and half from incinerators.

32James Karl, Dow Chemical Co., personal communication, January 1983.
33Elmer Monroe, Du Pont Chemical Co., personal communication, December 1982.

Evaluating the actual hazardous waste destruction capabilities of various boilers has only just begun by EPA. Only three tests were complete at the time of this report; seven more are planned. Tests to date have been conducted primarily with nonhalogenated, high heating value solvents and other nonhalogenated materials. These tests have demonstrated DREs generally in the 99.9 percent area. Subsequent testing will be directed toward waste that are considered to be more difficult to destroy than those tested up to this point.³⁴ Testing at cooperating boiler facilities is expected to confirm that boilers of a wide variety of sizes and types can achieve hazardous waste destruction efficiencies comparable to those achieved by incineration for some common waste fuels. Industry cooperation will be needed, though, for field testing of those difficult-to-burn and the more toxic wastes marginally useful as fuels.

Actual waste destruction achieved through coincineration probably has more to do with how and why the boiler is operated, and with knowledge of the waste feed contents, than with the type and size of boiler. Destruction by combustion for toxic organic compounds requires very complete, efficient combustion. Thus, in a boiler, the objective of getting usable heat out of the fuel mix is similar to that of achieving high destruction of toxic organic waste. However, the marginal benefits of achieving incremental degrees of destruction may be valued differently by different users. For example, it may cost less at very large boilers (e.g., those at utilities and large industrial facilities) to save fuel costs through increased combustion efficiency than at smaller boilers. Thus, utility boilers are probably designed and operated for stringent fuel efficiency by an economic motivation that may parallel the rigorous incinerator performance standard in its effect for DREs. Although there would be an economic advantage for these facilities to burn waste fuels, many would not be able to find reliable and sufficient supplies. On the other hand, the objective with many industrial boilers is to **deliver an optimal** amount of heat

34Olexsey, op. cit.

over time. Thus, achieving 100-percent combustion efficiency is not desirable if it takes 2 days to achieve this goal, Incinerators have as their direct goal the destruction of the fuel compound which is not so in boilers.

Excluding the very largest utility and industrial boilers, there are about 40,000 large (10 million to 250 million Btu/hr) industrial boilers and about 800,000 small- to medium-sized institutional, commercial, and industrial boilers nationwide.³⁵ It is expected that most of the industrial boilers having firing capacities less than 10 million Btu/hr may not readily lend themselves to coincineration. so

Finally, there are about 14 million residential, single-home boilers which could burn hazardous waste.³⁷ These small boilers could have adverse health effects on small, localized areas. In addition, any fuels blended with organics and illegally burned, in apartment houses or institutional boilers, for example, should be expected to reduce the lives of these boilers through corrosion.

To assess the role that boilers currently play in hazardous waste management nationwide, it is necessary to know what compounds are being burned, in which facilities, and with what DREs. Without reporting requirements for coincineration, information is seriously lacking. Currently, boilers may be burning twice the volume of ignitable hazardous waste that is being incinerated. Except for those from petroleum refining, all were discharged to the environment until environmental, handling, or increasing primary fuel costs encouraged their use as a fuel.³⁸ Of the entire spectrum of burnable waste, those having the highest Btu content are attracted to boilers. This may have economic effects on regulated incineration, because some hazardous waste incinerators

could also benefit from the fuel value of the same waste used as auxiliary fuel in boilers.

5. Multiple hearth incinerators.—These use a vertical incinerator cylinder with multiple horizontal cross-sectional floors or levels where waste cascades from the top floor to the next and so on, steadily moving downward as the wastes are burned. These units are used primarily for incineration of sludges, particularly those from municipal sewage sludge treatment and, to a much lesser extent, certain specialized industrial sludges of generally a low-hazard nature. They are used almost exclusively at industrial plants incinerating their sludges on their own plant site for the latter cases.³⁹ Such incinerators are not well suited for most hazardous waste for two reasons: they exhibit relatively cold spots, and the waste is introduced relatively close to the top of the unit. Because hot exhaust gases also exit from the top, there is the potential for certain volatile waste components to short-circuit or “U-turn” near the top of the incinerator and exit to the atmosphere without spending an adequate time in the hot zone to be destroyed. This may be improved by having a separate afterburner chamber, but this option does not appear to have become accepted in the hazardous waste field.⁴⁰

At least one brief test of a typical multiple hearth furnace was conducted in the early 1970's, in which the sewage was “seeded” with a small quantity of pesticide material. Although the pesticide was not detected in the exhaust, the researchers became aware of the short-circuiting and residence-time problems and did not pursue the application of multiple hearths to hazardous wastes any.

6. Fluidized bed combusters.—This is a relatively new and advanced combustor design being applied in many areas. It achieves rapid and thorough heat transfer to the injected fuel and waste, and combustion occurs rapidly. Air forced up through a perforated plate, maintains

³⁵M. Turgeon, Office of Solid Waste, Industrial and Hazardous Waste Division, EPA, personal communication, January 1983.

Olexey, op. cit.

³⁷C.C. Shih and A.M. Takata, TRW, Inc., “Emissions Assessment of Conventional Stational Combustion Systems: Summary Report” prepared for the Office of Research and Development, EPA, September 1981.

³⁸EPA “Technical Overview of the Concept of Disposing of Hazardous Wastes in Industrial Boilers,” op. cit.

³⁹Alternatives to the *Land Disposal of Hazardous Wastes*, op. cit.

⁴⁰Oppelt, op. cit.

a turbulent motion in a bed of very hot inert granules. The granules provide for direct conduction-type heat transfer to the injected waste. These units are compact in design and simple to operate relative to incinerators. Another advantage is that the bed itself acts as a scrubber for certain gases and particulate. Its role in hazardous waste may be limited to small and specialized cases due to difficulties in handling of ash and residuals, low throughput capacity and limited range of applicable waste feeds.⁴¹

There are presently only about zoo such combusters in the United States, used chiefly for municipal and similar sludges. About nine are used for hazardous waste.⁴² Existing fluidized bed combusters are sparsely distributed and relatively small. Future applications of fluidized bed technology to hazardous waste is likely to occur at new facilities built specifically for this purpose rather than at existing municipal facilities.

Recent EPA testing at the Union Chemical Co., Union, Me., is still being evaluated. Early test results are mixed with regard to 99.99 percent destruction.⁴³ The simplicity of this technology and its ease of operation seem to indicate high reliability for achieving those levels of destruction and wastes for which it will prove to be applicable. A catalytic, lower temperature fluidized bed technology is being developed which may have lower energy costs, and may be more applicable to hazardous waste destruction.⁴⁴ However, incompatibilities between catalysts proposed on various hazardous waste may present problems to overcome.

7. Incineration at sea.—This is simply incinerator technology used at sea, but without stack gas scrubbers. (The buffering capacity of the sea and sea air is the reason for the lack of a

scrubber requirement.) Free from the need to attach scrubbers, marine incinerator designers can maximize combustion efficiency in ways that land-based incinerators cannot.⁴⁵ Incinerators based on oil drilling platforms would further be freed from accommodating rolling ship motion.

Various EPA monitoring of test commercial burns of PCBs and government burns of herbicide Agent Orange and mixed organochlorines in the mid and late 1970's confirmed the 99.99 + percent destruction capability for liquid injection incineration used at sea.⁴⁶ Current technology exists only for liquids. Rotary kilns could be adapted to ships and more readily to oil drilling platforms.

There exists considerable controversy about the test burns recently conducted for PCBs destruction onboard the M.T. Volcanus. Data results are not yet available. Major concerns are whether the land and marine alternatives represent the same environmental risk and if the performance standards are evenly applied. EPA's view is that they represent roughly the same risk.⁴⁷ Regarding the performance standards, it should be recognized that the scrubbing the exhaust gas of land-based incinerators may be providing the fourth nine in their DRE performance. Thus, an at-sea DRE of 99.9 percent may be more similar to the land-based DRE of 99.99 percent than it may appear. The contribution of scrubbers to DRE values are not well known.

Additional concerns about incineration at sea include: stack gas monitoring, which is difficult enough on land and perhaps more soon a ship at sea, and the risk of accidents near shore or at sea. The ecological effects of a spill of Agent Orange on phytoplankton productivity could be substantial.⁴⁸ Storage facilities necessary for drilling platform-based incinera-

⁴¹Alternatives to the Land Disposal of Hazardous Wastes, op. cit.

⁴²Proctor and Red fern, Ltd., and Weston Designers Consultants, "Generic Process Technologies Studies" (Ontario, Canada: Ontario Waste Management Corp., System Development Project, August 1982).

⁴³J. Miliken, Environmental Protection Agency, personal communication, November 1982.

⁴⁴R. Kuhl, Energy Inc., Idaho Falls, Idaho, personal communication, January 1983.

⁴⁵K. Kamlet, National Wildlife Federation, *mean Dumping of Industrial Wastes*, B. H. Ketchum, et al. (ed.) (New York: Plenum Publishing Corp., 1981).

⁴⁶D. Oberacker, Office of Research and Development, IERL, Environmental Protection Agency, Cincinnati, Ohio, personal communication, December 1982.

⁴⁷Ibid.

⁴⁸Kamlet, op. cit.

tion may involve still higher spill risks. Public opposition to hazardous waste sites applies also to storage of waste at ports.

Other High Temperature Industrial Processes

Other types of applicable combustion processes including metallurgical furnaces, brick and lime kilns, and glass furnaces, are examples of existing industrial technologies which might be investigated as potential hazardous waste destruction alternatives.⁴⁹ There is no reporting of such uses that may be occurring, and no DRE data have been collected. The beneficial use exclusion may apply to many of such practices.⁵⁰ However, objectives of such processes are not necessarily complementary or supportive of high DRE. The technical potential for hazardous waste destruction and need for regulation of such practice needs investigation.

Emerging Thermal Destruction Technologies

Undue importance should not be placed on the distinction between current and emerging technologies. The intent is merely to distinguish between technologies currently "on the shelf" and those less commercially developed for hazardous waste applications.

Pyrolysis. -This occurs in an oxygen deficit atmosphere, generally at temperatures from 1,000° to 1,700°F. Pyrolysis facilities consist of two stages: a pyrolyzing chamber, and a fume incinerator. The latter is needed to combust the volatilized organics and carbon monoxide produced from the preceding air-starved combustion. The fume incinerator operates at 1,800° to 3,000°F. The pyrolytic air-starved combustion avoids volatilization of any inorganic components and provides that inorganics, including any heavy metals, are formed into an insoluble easily handled solid char residue. Thus, air pollution control needs are minimized.⁵¹

⁴⁹PEDCO Environmental Services, Inc., "Feasibility of Destroying Hazardous Wastes in High Temperature Industrial Processes," for the Office of Research and Development, IERL, EPA, Cincinnati, Ohio, May 1982.

⁵⁰40 CFR, sec. 261 (c)(2).

⁵¹Alternatives to the *Land Disposal of Hazardous Wastes*, op. cit.

Pyrolysis has been used by the Federal Government to destroy chemical warfare agents and kepone-laden sludge and by the private sector to dispose of rubber scrap, pharmaceutical bio-sludge, and organic chlorine sludges. Most recently, pilot plant test burns on chlorinated solvents from a metal-cleaning plant have been destroyed with 99.99 percent destruction.⁵²

Broader application would await much more equipment development and testing. Among the potential problems with pyrolysis are:

- Greater potential for toxic and refractory PICs formation than with combustion in air. The reducing atmosphere produces larger amounts of these compounds, and they may pass through the off-gas afterburner.
- Production of an aqueous tar that maybe difficult to dispose in either a landfill or an incinerator.
- Substantial quantities of auxiliary fuel may be required to sustain temperature in the afterburner.⁵³

Commercially, high throughput (up to 6,500 lb/hr) and required air pollution control requirements may be key future benefits. However, maintenance costs due to moving parts, and the need for well-trained operators may be relatively high.⁵⁴

Molten Salt Reactors.-These achieve rapid heating and thorough mixing of the waste in a fluid heat-conducting medium. Liquid, solid, or gaseous wastes are fed into a molten bath of salts (sodium carbonate or calcium carbonate). Solids must be sized to 1/4- or 1/8-inch pieces in order to be fed into the bed. The bed must be initially preheated to 1,500° to 1,800° F. Provided that the waste feed has a heating value of at least 4,000 Btu/lb, the heat from combustion maintains the bed temperature, and the combustion reactions occur with near completion in the bed instead of beyond it. The sodium carbonate in the bed affects neutraliza-

⁵²Oppelt, op. cit.

⁵³ibid.

⁵⁴Technologies of the Treatment and Destruction of Organic Wastes as Alternatives to Land Disposal, op. cit.

tion of hydrogen chloride and scrubbing of the product gases. Thus, the bed is responsible for decomposition of the waste, removal of the waste residual, and some off-gas scrubbing. A bag house for particulate completes air pollution control and the removal system.⁵⁵ (See fig. 9.)

In EPA tests, a pilot scale unit (200 lb/hr) destroyed hexachlorobenzene with DRE's exceeding 6 to 8-9's (99.9999-percent to 99.999999-percent destruction and removal) and chlordane with DREs exceeding 6 to 7-9's.⁵⁶ Rockwell International also claims 99.999-percent destruction efficiencies* from private tests on malathion and trichloroethane.

Reactor vessel corrosion has impeded development of molten salt destruction (MSD). Ves-

⁵⁶Ibid.

⁵⁶S. Y. Yosim, et al., Energy Systems Group, Rockwell International, "Molten Salt Destruction of PCB and Chlordane," EPA contract No. 68-03-3014, Task 21, final draft, January 1983.

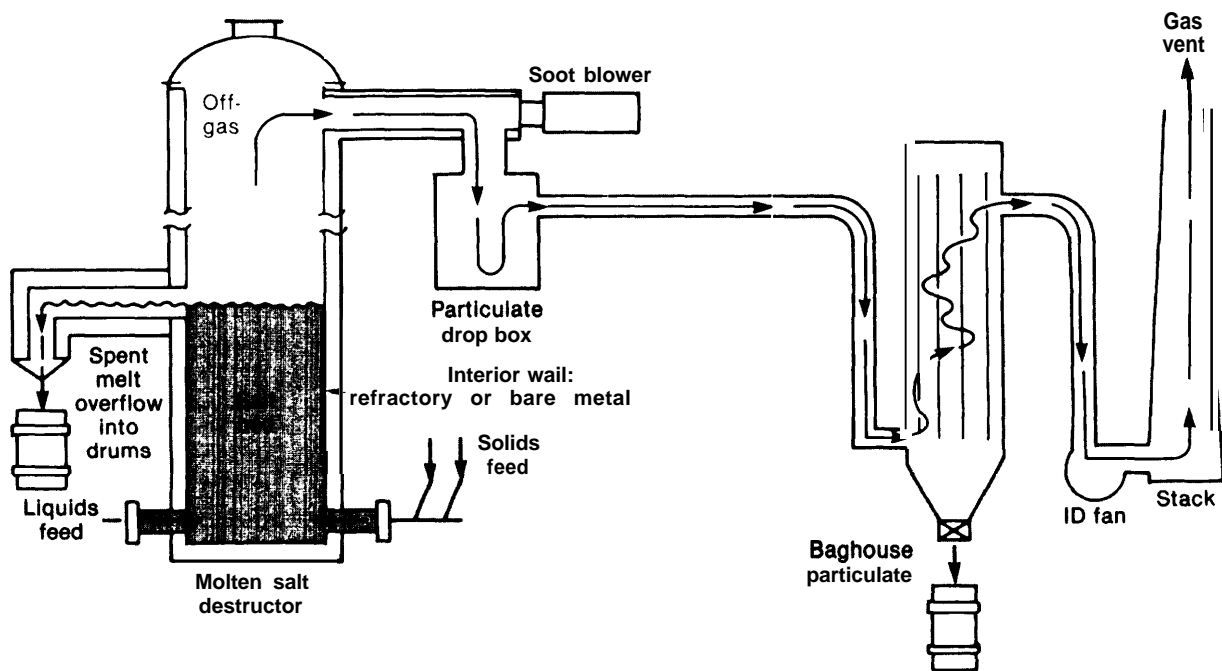
* Not DRE; small amounts removed in bed salts and baghouse treatment were not measured.

sel corrosion is accelerated by temperature, reducing conditions (less than sufficient oxygen), and the presence of sulfur. Traditionally, MSD reaction vessels have been refractory lined, presenting operational and maintenance costs similar to those of conventional incinerators. Rockwell International offers an MSD system with a proprietary steel alloy reactor vessel. This vessel is warranted for 1 year if the system is operated within specified ranges of temperature, excess air, and melt sulfur content.⁵⁷

Ash as well as metal, phosphorous, halogen, and arsenic salts build up in the bed and must be removed. In the case of highly chlorinated waste (50 percent or more) the rate at which salt must be removed approaches the rate of waste feed. Both the salt replacement (or regeneration) and residual disposal determine economic viability for a given application. In pro-

⁵⁷J. Johanson, Rockwell International, Inc., personal communication, January 1983.

Figure 9.—Molten Salt Destruction: Process Diagram



SOURCE Adapted from S. Y. Yosim, et al., Energy Systems Group, Rockwell International, "Molten Salt Destruction of HCB and Chlordane," EPA contract No. 68-03-3014, Task 21, final draft, January 1983

posed commercial ventures, sodium chloride residue would be landfilled and calcium chloride would be sold as road salt or injected deep well.⁵⁸

The process is intended to compete with rotary kilns and may find application for a broad market of wastes that are too dilute to incinerate economically. However, water in the waste feed, as with any incineration technology, uses up energy in evaporation. Due to the extremely high DREs demonstrated in pilot scale tests, the process is expected to be very attractive for destroying the highly toxic organic mixtures and chemical warfare agents, which currently present serious disposal problems. Rockwell International is in final negotiations with two commercial ventures in California and Canada. Commercial-scale units offered are 225 and 2,000 lb/hour.⁵⁹

High Temperature Fluid-Wall Reactors.—In these reactors, energy is transferred to the waste by radiation (rather than by conduction and convection as in the above processes). A porous central cylinder is protected from thermal or chemical destruction by a layer of inert gas. The gas is transparent to radiation, and the cylinder is heated by radiation from surrounding electrodes to 3,000° to 4,000° F. The refractory cylinder reradiates this energy internally to the passing waste.⁶⁰ The important result is very rapid and thorough heating of the waste stream for complete combustion or generation. The speed of the heating presents little opportunity for the formation of intermediate products for incomplete combustion that present concerns in conventional incineration processes. Also, process control is good since the radiation is directly driven by electricity.

A bench-scale reactor (¼ lb/min) has destroyed PCBs in contaminated soil (1 percent by weight) with 99.9999 percent DRE.⁶¹ In addition, the Thagard Research Corp., which conducted the tests, claims that it has privately

burned hexachlorobenzene with 99.9999 percent DRE in a 10 ton per day unit.⁶² A commercial-scale unit (20 to 50 tons per day) is operated as a production unit by a licensee in Texas, which has agreed to allow Thagard to continue hazardous waste destruction demonstration burns there.⁶³ In December 1982, California and EPA conducted demonstration burns of some gases that are difficult to destroy thermally—1,1,1-trichloroethane, carbon tetrachloride, dimethyl chloride, Freon 12®, and hexachlorobenzene. Results are currently being assessed.

Further scaleup may be needed to provide commercial throughput, and this will involve larger ceramic cores. The effects of thermal stresses on the life of the cores present the major untested concern for scale up.

Near-term commercialization of the Thagard reactor is planned. During 1983, a Miami investment firm is expected to underwrite the development of a mobile reactor, reducing breakdown and setup time from several weeks to only a few days. This will facilitate the collection of test burn performance at potential applications sites.⁶⁴ Also, Southern California Edison Inc. is considering the process for future destruction of PCB-laden soil and for stabilization of a variety of its heavy metal-bearing liquid waste. The utility is also interested in selling byproducts of carbon black from the process.⁶⁵

In addition to its potential mobility resulting from its compact design the only air pollution control need for the fluid wall reactor may be a bag house to control particulate. The process is not expected to be economically competitive with conventional incineration, but will be applicable especially to contaminated soils and silts.

Plasma-Arc Reactors.—These use very high energy free electrons to break bonds between molecules. A plasma is an ionized gas (an elec-

⁵⁸Ibid.
⁵⁹Ibid.

⁶⁰*Technologies for the Treatment and Destruction of Organic Wastes as Alternatives to Land Disposal*, OP. cit.

⁶¹E. Matovitch, Thagard Research Corp., personal communication, January 1983.

⁶²Ibid.
⁶³Ibid.
⁶⁴Ibid.

⁶⁵E. Faeder, Southern California Edison Power CO., personal communication, January 1983.

trically conductive gas consisting of charged and neutral particles). Temperatures in the plasma are in excess of 50,000°F—any gaseous organic compounds exposed to plasma are almost instantly destroyed. Plasma arc, when applied to waste disposal, can be considered to be an energy conversion and transfer device. The electrical energy input is transformed into a plasma. As the activated components of the plasma decay, their energy is transferred to waste materials exposed to the plasma. The wastes are then atomized, ionized, and finally destroyed as they interact with the decaying plasma species. There is less opportunity for the formation of toxic PICs. Most of the destruction occurs without progression of reactions which could form them.⁶⁶

Private tests conducted for the Canadian Government have demonstrated 99.9999999 percent (i.e., 9-9's) destruction on pure transformer fluid (58 percent chlorine by weight).⁶⁷ Depending on the waste, the gas produced has a significant fuel value.⁶⁸ A high degree of process control and operational simplicity are additional advantages. For halogenated waste (a major market target), the gases would have to be scrubbed but the scrubbers needed are very small.

The process is in the public domain and nearing commercialization. The developer plans to market mostly small, self-contained, mobile units. Costs are intended to be competitive with incineration.⁶⁹ The first commercial application is planned to be in operation in July 1983.

Wet Oxidation.—Proven in commercial application, wet oxidation processes can destroy reliably nonhalogenated organic waste (e. g., cyanides, phenols, mercaptans, and nonhalogenated pesticides). The oxidation reactions are fundamentally the same as in combustion but occur in liquid state. Since it is not necessary

to add large quantities of air as in incineration, potentially contaminated gas emissions are avoided. The reactions take place at temperatures of 430° to 660° F (and pressures of 1,000 to 2,000 psi). For many applicable waste feeds, the oxidation reaction resulting produces enough heat to sustain the process, or even to produce low pressure steam as an energy by-product. The oxidation reactions typically achieve 80 percent complete decomposition to carbon dioxide and water, and partial decomposition to low molecular weight organic acids of the remaining waste feed.⁷⁰ Currently, the process remains commercially applicable to aqueous organic waste streams which are too dilute for incineration, yet too toxic for biological treatment,

Still in development are catalytic modifications to the wet oxidation process, aimed at the more stable highly chlorinated organics. Bench-scale tests conducted by I. T. Envirosience have demonstrated that a bromide-nitrate catalyst promotes completeness of oxidation. Should this process achieve destructions similar to those of incineration, its lack of air emissions, and the ease of using performance monitoring would be advantageous.⁷¹

Super Critical Water.—At temperatures and pressures greater than 374° C and 218 atm, water becomes an excellent solvent for organic compounds and can break large organic molecules down into molecules of low molecular weight.⁷² In a system patented by Modar, Inc., injected oxygen completely oxidizes the lower molecular weight molecules to carbon dioxide and water. DDT, PCBs and hexachlorobenzene have been destroyed with efficiencies exceeding 99.99 percent in bench-scale testing.⁷³ Costs are expected to be highly dependent on scale.⁷⁴ If high-destruction efficiency is maintained

⁶⁶C. C. Lee, Office of Research and Development, IERL, Environmental Protection Agency, personal communication, January 1983.

⁶⁷Plasma Research Inc., unpublished test results, January 1983.

⁶⁸*Alternatives to the Land Disposal of Hazardous Wastes*, op. cit.

⁶⁹W.T. Barton, Plasma Research Inc., personal communication, January 1983.

⁷⁰OP. Shaefer, Zimpro, Inc., personal communication, November 1982.

⁷¹Oppelt, op. cit.

⁷²M. Modell, "Destruction of Hazardous Waste Using Supercritical Water," paper delivered at the 8th Annual Research Symposium on Land Disposal, Incineration, and Treatment of Hazardous Wastes (Fort Mitchell, Ky.: Environmental Protection Agency, Mar, 8, 1982).

⁷³Ibid.

⁷⁴*Alternatives to the Land Disposal of Hazardous Wastes*, op. cit.

through scaleup, this could be an attractive alternative to incineration.

Biological Treatment

Conventional biological treatments use naturally occurring organisms to degrade or remove hazardous constituents. In contrast, biotechnology uses bacteria which have been selected from nature, acclimated to particular substrates, and mutated through methods such as exposure to ultraviolet light for fixation of the adapted characteristics. Many toxic substances cannot be degraded biologically, although they may be effectively removed from a waste stream this way. Types of conventional biological techniques, waste stream applications, and their limitations are listed in table 29. These techniques have found widespread use for treatment of municipal and industrial wastes to prevent the formation of odorous gases, to destroy infectious micro-organisms, to remove nutrients for aquatic flora, and to remove or destroy some toxic compounds. Several biological techniques may be used as a series of steps to treat a waste, including ending with landfarming (also called land spreading or land treatment). The latter refers to the deposit of a waste, or some sludge or residue from a treatment, onto land or injected some small distance beneath the surface. Naturally occurring organisms in the soil degrade the waste, usually organic, and periodic plowing may be necessary to ensure adequate oxygen levels for degradation.

The physical, chemical, or biological processes that can be used to eliminate or reduce the hazardous attributes of wastes exist in as many forms as those processes used to manufacture the original material. All of these treatments produce waste residuals; usually a liquid and a solid waste. The hazardous characteristics of these waste residuals must be evaluated in terms of the objective desired for their final disposition or recovery. Without such an objective it is difficult to evaluate the benefit, either economic or environmental, of applying the treatment process. These treatments can result in merely changing the form or location of the waste. For example, concentrating organics

from a dilute waste stream does not necessarily provide any benefit in terms of increased protection of health. If this separation and concentration treatment allows the waste constituent to be recovered or, alternatively, makes a destruction technology viable, the treatment has been beneficial.

Residuals from hazardous waste treatments are discharged to surface waters, to publicly owned wastewater treatment works (POTWs) or are sent to landfills or land treatment disposal. To the extent that the treatments considered below can reduce the toxic characteristics of wastes through destructive or degradative reactions, they are similar in their effect to thermal destruction technologies. To the extent that they are able to mitigate specific hazard characteristics, they render the wastes nonhazardous. And, to the extent that they reduce the mobility of the waste, they reduce the interaction of land-disposed wastes with the environment.

Many references exist describing unit physical, chemical, and biological processes and how they may be combined. This discussion will not attempt to duplicate any such descriptive listings. Table 30 lists the established applications. Selection of one or several processes depends on such factors as waste feed concentration, desired output concentration, the effects of other components in the feed, throughput capacity, costs, and specific treatment objectives.

Landfills

Landfilling is the burial of waste in excavated trenches or cells. The waste may be in bulk form or containerized. In the early 1970's, landfills specifically designed to contain industrial waste were constructed. * Experience with the operation and construction of these more advanced landfills has been an evolutionary process, and is ongoing.

Over time, fractions of the waste can be released from the landfill, either as leachate or

● In 1972, Chemtrol announced the opening of the reportedly first landfill designed to securely contain hazardous industrial waste.

as volatilized gases. The objective of landfilling design is to reduce the frequency of occurrence of releases so that the rate of release does not impair water or air resources. * Liquids are able to leak through compacted clays or synthetic lining materials. Reducing the potential for migration of toxic constituents from a landfill requires minimizing the production of liquids and controlling the movement of those that inevitably form.

Liquids can enter a landfill in several ways:

- by disposal of free liquid waste,
- by evolution from sludges and semisolids,
- from precipitation infiltrating through the cover into the landfill cell, and
- from lateral movement of ground water infiltrating through the sides or the bottom of the cell.

No one disputes the presence of liquids in a landfill; the objective of good landfill design is to control their movement. Flow of liquids through soil and solid waste occurs in response to gravity and soil moisture conditions. When the moisture content within a landfill exceeds field capacity, liquids move under saturated flow, and percolate to the bottom. Liquid movement under saturated conditions is determined by the hydraulic force driving the liquid, and the hydraulic conductivity of the liner material. Hydraulic force can result in discharge through a liner,

Landfills can be designed to reduce migration, but there is no standard design. Advanced designs would have at least the following features: a bottom liner, a leachate collection and recovery system, and a final top cover.

Figure 10 depicts a landfill with these engineered features. Taken together, these features are intended to make it physically easier for water to run off the surface cover instead of infiltrating it and to collect leachate through

the drainage layer instead of permeating the liner. Beds constructed of graded sizes of gravel and sand are sometimes used as intermediate drainage layers to speed internal dewatering.

Applicable Wastes

Virtually any waste can be physically buried in a landfill; however, landfills are least effective at controlling the migration of waste constituents which are volatile and soluble. Landfilled wastes that are toxic, persistent, soluble, and volatile are most likely to present a risk of human exposure. Federal regulations outline pretreatment requirements for wastes which are ignitable, reactive, and/or corrosive* but do not address characteristics of persistence, toxicity, volatility, or volubility.

Current Use and Evaluation.—It is estimated that 270 landfills are currently in use for hazardous waste disposal. (See ch. 4 for discussion of facility data.) These facilities are among those which may apply for RCRA authorization as hazardous waste disposal facilities.

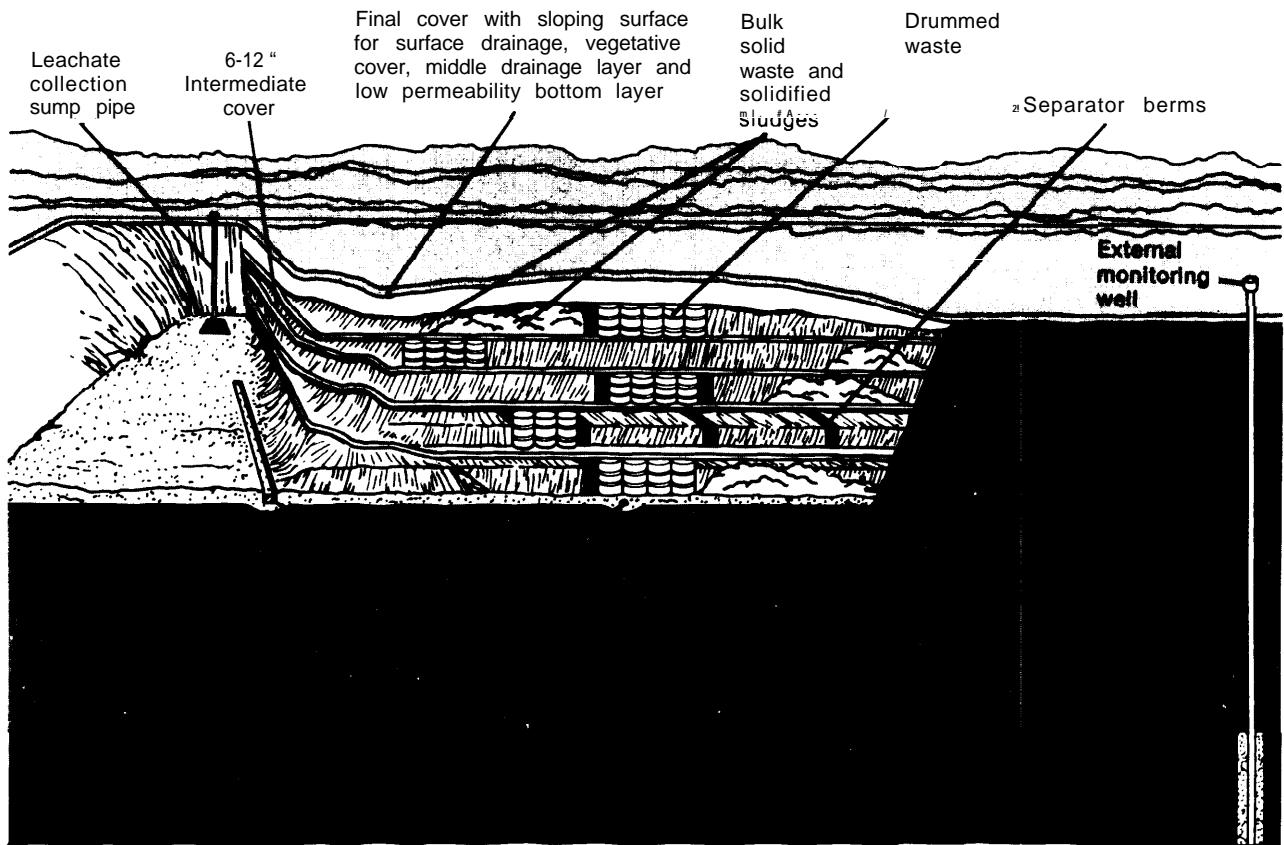
Existing landfills are constructed and operated with varying degrees of sophistication. Numerical information on the distribution of landfills that incorporate particular control features is not available. It is likely, however, that many existing facilities do not have any sort of constructed bottom liner nor any leachate or gas collection systems.⁷⁵ Often, existing facilities were sited with little regard to local hydrogeology. The degree of sophistication of existing landfill facilities ranges from those that have minimal control features and accept virtually any waste, to those which combine a favorable site location with waste pretreatment or a restrictive waste policy, engineered control features, leak detection, and ground water monitoring programs. Landfills also vary in capacity. Most are small (burying less than

*Criteria for determining "impairment" of ground water are currently defined by a statistically significant increase over background levels, or exceeding established limits. See discussion on ground water monitoring requirements, ch. 7. No criteria currently exist for impairment of air resources; research is underway to determine the magnitude and potential severity of gaseous emissions.

⁷⁵More detail on regulatory requirements are discussed in the subsequent section titled "Technical Regulatory Issues," see also ch. 7.

⁷⁵Environmental Protection Agency, *Final EIS, Subtitle C, Resource Conservation and Recovery Act of 1976*, app. D, SW-189c. 1980.

Figure 10.—Generalized Depiction of a Hazardous Waste Landfill Meeting Minimum Federal Design Criteria



NOTE: This is not a prescriptive or exact depiction of a landfill design, or is it necessarily representative of all hazardous waste landfills. Alternative designs are allowed. See also figure 12 for detail on single and double liner design.

SOURCE: Office of Technology Assessment, adapted from Draft RCRA Guidance Document, Landfill Design, Liner Systems and Final Cover, July 1982, and USEPA Draft SW-867, SW-869, SW-870, Municipal Environmental Research Laboratory, Cincinnati, Ohio, September 1980.

16,500 tons per facility in 1981).⁷⁶ Smaller landfills may tend to use less sophisticated control measures.

Long-term landfill performance is determined by:

- the **reliability** of the leachate collection system and the longevity of liner(s), and top cover;
- the hydrogeological characteristics of the site;
- the characteristics of the waste prior to disposal; and
- daily operations at the site—e.g., the liquids management strategy at the site, the

testing practiced by the operator, and the level of quality control over site operations.

Engineered Control Features

A landfill has three primary engineered control features: a bottom liner(s), a leachate collection system, and a cover. The bottom liner(s) retard the migration of liquids and leachate from the landfill cells. Bottom liners are constructed of compacted clay, a clay and soil mixture, or synthetic material—often synthetic membranes. Leachate is collected through a series of pipes buried in a drainage bed placed above the bottom liner. A mechanical pump raises the leachate through standpipes to the surface. The final cover reduces infiltration of precipitation into the closed landfill. Intermedi-

⁷⁶Westat, Part A Universe Telephone Verification Contract No. 68-01-6322, Nov. 11, 1982.

ate covers can be applied for the same purpose during operation of the landfill. Table 33 summarizes function and failure mechanisms for each of these components.

1. Bottom liners.—The function of a liner placed beneath a landfill is to retard the migration of leachate from the landfill so that it can be collected and removed. For synthetic liners, retarding migration is dependent on their characteristic low permeability and compatibility with a wide spectrum of wastes. For some compacted clay liners, migration of leachate is retarded both by their low permeability and by the capacity of clays to decrease the concentration of certain waste constituents in the leachate through a variety of chemical reactions—e.g., precipitation, filtration, adsorption,

or exchange of charged chemical species with the clay particles.”

All liners exhibit some measure of hydraulic conductivity; that is, they allow passage of liquid under hydraulic pressure. * Based on laboratory and field testing, typical ranges of conductivity are approximately 10^{-11} to 10^{-14} m/see for synthetic membranes, and 10^6 to

“See for example, M. Lewis, “Attenuation of Polybrominated Biphenyls and Hexachlorobenzene by Earth Materials” (Washington, D. C.: Environmental Protection Agency, No. 600/S2-81-191, December 1981); and L. Page, A. A. Elsewi, and J. P. Martin, “Capacity of Soils for Hazardous Inorganic Substances” (Riverside, Calif.: University of California, August 1977).

*For low permeability synthetics, the rate of fluid passage is difficult to measure because it is so close to passage in the vapor phase, Synthetics are tested under pressure, and their permeability is back-calculated.

Table 33.— Engineered Components of Landfills: Their Function and Potential Causes of Failure

Function	Potential causes of failure
<p>COVER</p> <p>To prevent infiltration of precipitation into landfill cells. The cover is constructed with low permeability synthetic and/or clay material and with graded slopes to enhance the diversion of water.</p>	<ul style="list-style-type: none"> • After maintenance ends, cap integrity can be threatened by desiccation, deep rooted vegetation, animals, and human activity. • Wet/dry and freeze/thaw cycles, causing cracking and increased infiltration. • Erosion; causing exposure of cover material to sunlight, which can cause polymeric liners to shrink, break, or become brittle. • Differential settling of the cover, caused by shifting, settling, or release of the landfill contents over time. Settling can cause cracking or localized depressions in the cover, allowing ponding and increased infiltration.
<p>Leachate collection and recovery system:</p> <p>To reduce hydrostatic pressure on the bottom liner, and reduce the potential for flow of leachate through the liner.</p> <p>Leachate is collected from the bottom of the landfill cells or trenches through a series of connected drainage pipes buried within a permeable drainage layer. The collection leachate is raised to the surface by a mechanical pump.</p>	<ul style="list-style-type: none"> • Clogging of drainage layers or collection pipes. • Crushing of collection pipes due to weight of overlying waste • Pump failures.
<p>Bottom liner</p> <p>To reduce the rate of leachate migration to the subsoil.</p>	<ul style="list-style-type: none"> • Faulty installation, damage during or after installation. • Deformation and creep of the liner on the sloping walls of the landfill. • Differential settling, most likely to where landfill is poorly sited or subgrade is faulty. • Structural failure of the liner in response to hydrostatic pressure. • Degradation of liner material resulting from high strength chemical leachate or microbial action. • Swelling of polymeric liners, resulting in loss of strength and puncture resistance. • Chemical extraction of plasticizers from polymer liners.

10^{-11} m/sec for clay liners.⁷⁸ The units of measure for hydraulic conductivity involve a thickness component. Thus, although an intact synthetic material has a very low conductivity, they are very thin. * In comparison, clay liners often range in thickness from several feet to several yards.

All liner materials are subject to breaches in their physical integrity. With the exception of obvious chemical incompatibilities that can rapidly deteriorate a liner, these failures can be a more important factor in increasing the rate at which liquids can migrate than the inherent conductivity of the liner. Two major sources of structural failure for all liners are incorrect installation and damage during or shortly after installation.

Proper installation of any liner requires considerable technical expertise. For clay liners, the moisture content of the clay prior to compaction and the method of compaction are critical factors. For example, varying the water content in a clay prior to compaction can result in differences of two orders of magnitude in the permeability of the clay.⁷⁹ For synthetic liners, proper welding of the seams joining the panels of the liner and avoiding damage to the dimensional stability of the membrane fabric are critical. Damage to liner fabric stability can occur while stretching synthetic liners over the large areas involved in landfills. For example, a single large panel of synthetic material may cover 20,000 ft² feet and weigh 10,000 lb.

Preparation of the soil under the liner is critical to the performance of all liners. Proper preparation is necessary to prevent local deformational stresses. Clay liners are likely to respond to deformational stress by shearing. Depending on the characteristics of the synthetic

material used, they may respond by stretching or tearing. In the past, liners were often installed by contracting firms which had minimal technical expertise and little motivation to be assiduous in their installation practices. More recently, manufacturers of synthetic liners and designers of clay liners are combining the sale of their products with actual installation, in order to maximize performance of their product and protect business.⁸⁰ Certification of proper liner installation is not currently required by EPA, but it is required by several states.⁸¹

Liners are also subject to damage after installation. One source of damage is vehicular traffic at the site—e.g., the heavy equipment used to spread sand and gravel directly on top of the liner to place the drainage layer for collection of leachate. Synthetic liners are vulnerable to localized tears and punctures. Clay liners can also be damaged after installation—e.g., slumping of the clay can occur on side slopes.⁸² Once a liner has been covered by the drainage layer, it is impossible to visually inspect it for damage.

Chemical reactions between liner and leachate can significantly increase liner permeability.^{83 84 85} For example, organic or inorganic acids may solubilize certain minerals within clays and a variety of organic liquids dissolve the monomers within PVC lines.

Laboratory tests can identify obvious chemical incompatibilities between a liner material and an expected leachate, and can also project general wear characteristics. (Table 5A-1 in app. 5A summarizes the findings of such tests.)

⁷⁸ED. J. Folkes, Fifth Canadian Geotechnical Colloquium, "Control of Contaminant Migration by the Use of Liners," National Research Council of Canada, April 1982.

* Synthetic membranes are produced in thicknesses ranging from 0.5 millimeters (20 roils) to 2.5 millimeter (100 roils). J. P. Giroud and J. S. Goldstein, "Geomembrane Liner Design," Waste Age, September 1982.

⁷⁹David E. Daniel, "problems in Predicting the permeability of Compacted Clay Liners," Symposium on Uranium Mill Tailings Management, Colorado State University, Geothermal Engineering Program, Ft. Collins, Colo., October 1981.

⁸⁰R. Kresic, Midwest Accounts Manager for Schlegel Lining Technology, Inc., Ohio, personal communication, November 1982.

⁸¹D. Lennett, Environmental Defense Fund, personal communication, December 1982.

⁸²Environmental Protection Agency, *Lining of Waste Impoundment and Disposal Facilities*, SW-870, ch. 4 "Failure Mechanisms," September 1980.

⁸³*Ibid.*

⁸⁴H. E. Haxo, "Interaction of Selected Liner Materials With Various Hazardous Wastes" (Cincinnati, Ohio: Environmental Protection Agency (NTIS No. 600/9410-010)).

⁸⁵D. Anderson, "Does Landfill Leachate Make Clay Liners More Permeable?" *Civil Engineering—ASCE*, September 1982, pp. 66-69.

However, laboratory data cannot directly predict performance under actual field conditions. Laboratory tests are conducted on only a small sample of the liner material; this presents problems for estimating field permeability of clays. Calculations of liner permeability based on field measurements demonstrate that laboratory estimates are frequently too low. Development of improved field techniques are underway.^{86 87} Also, laboratory tests cannot account for possible damage in the physical integrity of the liner material resulting from installation, operation, and long-term wear in the potentially harsh service environment of a landfill. This may compound problems in projecting the service life of synthetic liners.*

Further, testing for chemical compatibility requires prediction of expected leachate characteristics over time. This is difficult for landfills accepting a variety of waste types. Some landfill facilities segregate waste into cells to make leachate prediction simpler and more reliable.

2. Leachate collection system.—Leachate collection systems are a series of perforated drainage pipes buried at the lowest points within a landfill. These pipes are designed to collect liquids which flow under the influence of gravity to the low points. Once the collected liquids reach a predetermined level, they are pumped to the surface.⁸⁸ Overall, the system operates much like a sump pump in a household. Liquids that are recovered are tested for their hazardous characteristics. If the liquids are determined to be hazardous (under the RCRA criteria for hazardous waste), they are

⁸⁶D. E. Daniel, "Predicting Hydraulic Conductivity of Clay Liners" (Austin, Tex.: University of Texas, Department of Civil Engineering, 1982).

⁸⁷R. E. O'Son and D. E. Daniel, "Field and Laboratory Measurement of the Permeability of Saturated and Partially Saturated Fine Grained Soils" (Austin, Tex.: University of Texas, Department of Civil Engineering, June 1979).

•For example, manufacturers of synthetic lining material warranty their product for a specified time period [e. g., 10 to 30 years) against material defects in compounds and workmanship which would affect performance. However, the warranty can be voided if the liner material shall have been exposed to harmful chemicals, abused by machinery, equipment or persons, or if installation is inadequate.

⁸⁸K. Malinowski, CECOS International, New York, personal communication, August 1982.

treated and discharged or redispersed in the landfill.⁸⁹

The levels of leachate within a landfill will change with time in response to infiltration, pumping, and recharge rates. High leachate levels must be reduced by pumping in order to reduce hydraulic pressure on the bottom liner.⁹⁰ In general, doubling the height of the ponded liquid doubles the force driving the leachate through the liner.⁹¹ Information from commercial landfill facilities show that liquids levels can reach over 10 ft. If the system is working properly, the leachate can easily be pumped out.⁹² Conversely, pumping can be hampered by technical difficulties such as the inability of the cover to prevent further infiltration. In such cases, reducing leachate levels can take months to years.⁹³

After land filling operations end, leachate is required to be pumped out during the post-closure period "until leachate is no longer detected."⁹⁴ Failures in the collection system which impede leachate flow to the pump might be misinterpreted as the end of leachate generation. Some failures, such as poor leachate transmission through the filter beds or collapse of the drainage pipes, are both difficult to detect and to repair.

3. Cover.—After operations at the landfill have ceased, the final cover is installed. The function of the final cover is to reduce the infiltration of water and to provide a physical barrier over the waste. To do this, it must remain structurally sound over time. Covers can be constructed of layers of synthetic membranes, clays, and soil. Leachate standpipes pierce the cover in order to project into the landfill cells. Soil is placed over the cover, and vegetation is established to stabilize the soil.

⁸⁹Environmental Protection Agency, *Management of Hazardous Leachate*, SW-871, September 1980.

⁹⁰EPA, op. cit., SW-870, 1980, sec. 5.6.

⁹¹D. Daniel, personal communication, October 1982.

⁹²B. Simonsen, Vice president, IT Corp., and P. Vardy, Vice President of Waste Management, Inc., personal communication, December 1982.

⁹³P. N. Skinner, "Performance Difficulties of 'Secure' Landfills in Chemical Waste and Available Mitigation Measures," American Society of Chemical Engineers, October 1980.

⁹⁴47 FR 32,366, July 26, 1982.

Covers are subject to a number of failure mechanisms (see table 33). Some of these, such as erosion or piercing of the cover by plant roots, can be reduced through proper and continued maintenance and repair of the site. * However, if maintenance ends, the integrity of the cover will be threatened by ubiquitous weathering processes, such as desiccation, erosion, and freeze/thaw cycles. Deep-rooted vegetation, burrowing animals, and human activity can also cause damage. Depending on the site location and pretreatment of the waste, the risk of leachate migration caused by infiltration through the cover may be reduced before the facility operator's maintenance responsibility ends. These factors are critical, since the cover is the primary line of defense against waste migration after the post-closure period.

Other potential sources of cover damage cannot be prevented by simple maintenance. Foremost among these are subsidence damage and deterioration of synthetic membranes over time. Subsidence refers to the settling of the waste and the cover; subsidence damage has been identified by EPA as one of the most critical factors resulting in poor landfill performance.⁹⁵ Figure 11 depicts a cover designed with a gently sloping crown to facilitate runoff, and examples of cover failure. Ideally, the crown should be designed and constructed to compensate for estimated long-term subsidence. However, there are several factors which make this difficult.⁹⁶

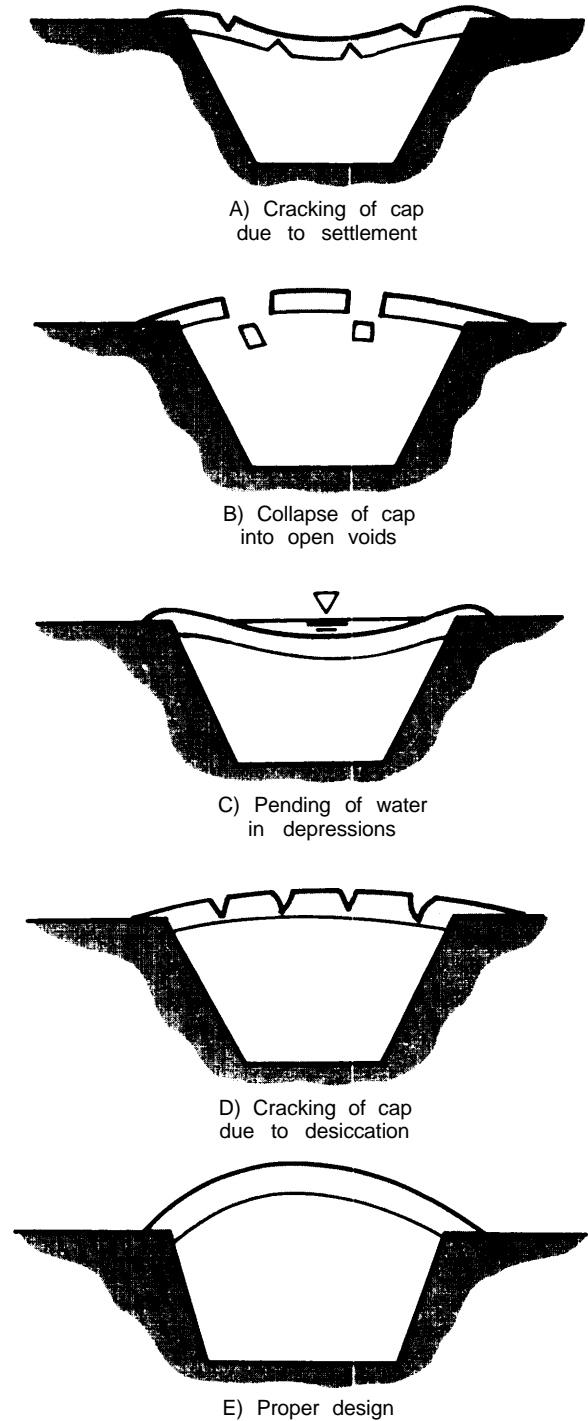
Comparatively uniform subsidence might be expected to occur for landfills containing one form of waste (i.e., a monofill). Many landfills, however, contain a variety of wastes, both containerized and in bulk. Bulk liquids and sludges

● Under current regulations, the landfill operator is required to maintain the site for 30 years after closure. If the facility operator has met the requirements for monitoring and closure, the Post-Closure Liability Fund established under CERCLA can be used to pay the costs of monitoring, care, and maintenance of the site thereafter, and if funds are available. See ch. 7; also Public Law 98-510, sec. 107(k)(1).

⁹⁵G. Dietrich, former Director of EPA's Office of Solid Waste, in testimony at the Mar. 11, 1982 public hearing on containerized liquids in landfills.

⁹⁶Skinner, op. cit., pp. 17, 20-23.

Figure 11.—Potential Failure Mechanisms for Covers



SOURCE. "Shallow Land Burial of Low-Level Radioactive Waste, David Daniel, AM, ASCE Journal of Geotechnical Engineering Division, January 1983.

provide little internal structural support. Vaporization may also be a problem. Containers do provide short-term support, but they deteriorate, often within a few years. The rate of container deterioration is difficult to predict; it depends on site- and waste-specific factors. It may not be possible to compact a mixed waste landfill sufficiently, e.g., compaction comparable to preparation of a building foundation. Further, the internal structure of the landfill cells is constructed of compacted support walls, which retain their original height while the wastes within settle. Cracking around the perimeter of the cover has resulted.” Finally, the extraction of collected leachate produces void spaces and exacerbates settling.

Some of these subsidence concerns are being addressed by landfill operators. For example, some commercial facilities place drummed waste on its side, a position providing less structural support, in order to hasten the collapse and settling of the buried drums.⁹⁸ This reduces future subsidence by enhancing the structural stability of the landfill prior to installing the final cover. Other facilities prohibit burial of liquids and emphasize treatment to enhance structural stability. *Q

Correction of Failure Mechanisms.—The failure mechanisms described can enhance the migration of waste constituents. The ability to correct potential failures is critical to landfill performance.

Detection of excessive contamination from leachate migration, either through a leak-detection system or external ground water monitoring, requires corrective action. Repairing the source of the leak is generally not possible. Liner repair requires: 1) locating the source of the leak, and 2) exhuming the waste. The first is difficult, although remote sensing techniques

⁷P. Varty, Vice President, Waste Management Inc., personal communication, January 1983.

⁹⁸For example, Waste Management Inc. and SCA Chemical Waste Services, Inc.

w]. Greco, Divisional Vice President, Government and Industry Affairs, Browning-Ferris Industries, personal communication, June 1982.

to locate leak sources are being developed.¹⁰⁰ Exhuming the waste is costly and potentially dangerous. Alternatively, pumping leachate can reduce the volume of leachate available for migration. Generally, leachate is removed by pumping from the collection system above the liner. OTA found little information on leak detection systems designed as secondary leachate removal systems, although this seems a promising area for future engineering design.

If infiltration through the cover is determined to be the cause of migration, the cover can be repaired (subsequent repairs may be necessary). The more complex and sophisticated the design of the cover, the more difficult and costly it is to repair. Cover repair may require carefully peeling back each protective layer until each is found to be sound. Cover repair generally requires partial reconstruction of gas collection and cover drainage systems, recompaction of soil layers, and revegetation of the surface soil. These procedures generally require work done by hand. Depending on the geographic location of the landfill, repair operations can be precluded during wet weather; the same conditions that exacerbate further damage.¹⁰¹ Ultimately corrective actions at landfills may rely primarily on mitigating the effects (e.g., cleansing ground water, diverting contaminated plumes) of the failure rather than correcting the cause of the failure.

Hydrological Characteristics of the Site

Site hydrology encompasses the properties, distribution, and circulation of water on the land surface, in the soil and underlying rocks, and in the atmosphere. Hydrological information includes data on the interrelated effects of geological and climatic characteristics on the properties and circulation of water. Over geologic time, these processes have shaped the

100 A comparison of these techniques has been prepared by Wailer, Muriel Jennings, and J. L. Davis, “Assessment of Technologies To Detect Landfill Liner Failures,” in proceedings of the Eighth Annual Research Symposium, EPA 600/9-82-002, March 1982.

¹⁰¹ Skinner, op. cit.

environment within which the landfill must operate.

There are two key site characteristics critical to the design and operation of landfills: general climatic characteristics that determine the amount of leachate generated and the characteristics of the underlying geology that determine the potential for liquids to migrate and the consequent risk of migration from the site. The potential for leachate generation and migration can vary markedly depending on the characteristics of the site. An engineered landfill sited over many feet of native low-permeability clays, resting on unfractured bedrock, and in an area where evaporation historically exceeds precipitation is less likely to impair ground water. In contrast, an engineered landfill relying solely on a synthetic liner, sited on unconsolidated dredged fill material, overlying fractured bedrock, and in an area where precipitation historically exceeds evaporation, is more likely to result in migration of excess leachate.

EPA has established criteria for siting low-level radioactive waste landfills, which state that "locations for radioactive waste disposal should be chosen so as to avoid adverse environmental and human health impacts and wherever practicable to enhance isolation over time."¹⁰² Current interim final regulations for hazardous waste disposal have only incentives (in terms of reduced monitoring requirements) for landfills sited in areas with exceptionally protective natural hydrology. No outright restrictions exist for sites with poor hydrological features.¹⁰³

Characteristics of the Waste Prior to Disposal

A wide variety of wastes are currently landfilled. Certain waste characteristics and disposal methods make waste containment difficult. For example, landfilling bulk liquid waste plays an important role in site destabilization. One researcher notes that disposal of waste liquid has "changed little in the last 30 years."¹⁰⁴

¹⁰²R. Abrams, "Comments to U.S. Environmental Protection Agency Regarding Proposed Amendments to 40 CFR 265: Special Requirements for Liquid Waste," 1982.

¹⁰³FR vol. 47, July 26, 1982.

¹⁰⁴Anderson, op. cit.

A variety of treatments can be used to improve the structural stability and reduce the mobility of landfilled waste. These techniques convert waste into a solid with greater structural integrity. Stabilized or solidified waste are less likely to leach from a land disposal site than are untreated waste—even though the physical and chemical characteristics of the constituents of the waste may not be changed by the process. Stabilization/solidification usually involves the addition of materials that ensure that the hazardous constituents are maintained in their least soluble form.

Stabilization/solidification processes can be categorized as follows:^{105 106}

- **Cement-based process.**—The wastes are stirred in water and mixed directly with cement. The suspended particles are incorporated into the hardened concrete.
- **Pozzolanic process.**—The wastes are mixed with fine-grained siliceous (pozzolanic) material and water to produce a concrete-like solid. The most common materials used are fly ash, ground blast-furnace slag, and cement-kiln dust.
- **Thermoplastic techniques.**—The waste is dried, heated, and dispersed through a heated plastic structure. The mixture is then cooled to solidify the mass.
- **Organic polymer techniques.**—The wastes are mixed with a pre-polymer in a batch process with a catalyst. Mixing is terminated before a polymer is formed and the spongy resin-mixture is transferred to a waste receptacle. Solid particles are trapped in this spongy mass.
- **Surface encapsulation.**—The wastes are pressed or bonded together and enclosed in a coating or jacket of inert material.

The type of waste most amenable to stabilization, solidification, and encapsulation techniques are inorganic materials in aqueous solutions or suspensions that contain appreciable amounts of metals or inorganic salts (e.g., metal-finishing waste). Metal ions in these res-

¹⁰⁵state of California, op. cit.

¹⁰⁶Martin, Oppelt, and Smith, "Chemical, Physical, Biological Treatment of Hazardous Wastes," September 1982.

idues are held as relatively insoluble ions in a crystalline lattice.

Waste containing more than 10 to 20 percent organic substances are generally not good candidates for this treatment method. Their diverse properties interfere with the physical and chemical processes that are important in binding the waste materials together. Some solidifying reagents may never harden if the waste contains inhibiting materials. Silicate and cement reactions can be slowed by organics or by certain metals. Organic polymers can be broken down by solvents, strong oxidizers, strong acids, or by exposure to sunlight.

Solidification pretreatment provides extra environmental protection in land disposal of treatable residues. For specific wastes, certain chemical stabilization treatments so thoroughly immobilize toxic constituents in EPA approved tests that they have been tentatively removed from hazardous waste regulation.¹⁰⁷ Usually, however, some metal cations remain somewhat mobile. In addition, there are considerable objections to EPA's leaching test as a stimulation of landfill conditions.

Some of the stabilization processes result in products that have compression strengths similar to cement or concrete. The durability of stabilized waste to wet/dry and freeze/thaw cycles, however, has generally not been good. Stabilization/solidification processes generally improve the physical handling characteristics of the waste, enhance structural integrity of the landfill, and eliminate the "free-liquid" status of the waste. Mixing waste with various absorbents can also remove the free-liquid status, but generally leaves the toxic constituents more soluble and mobile than the chemical stabilization methods.

Current Landfill Practice

Many improvements in landfill operation have occurred since passage of RCRA. Furthermore, waste handlers, landfill designers, and liner manufacturers are taking steps to ensure their specific facility, product, or service con-

¹⁰⁷F. Kelley, Stablex Corp., and H. Busby, Chemfix Corp., personal communication, November 1982.

tribution is used to its best effect. Examples of such actions are:

1. some facilities emphasize land burial of waste treatment residuals which are generally less toxic and mobile, than untreated waste;
2. some facility owners and/or operators have sought out especially protective hydrological settings for construction of landfills;
3. some facilities segregate wastes with similar characteristics. This facilitates leachate prediction and testing for liner comparability;
4. several waste handlers have established a strict prohibition against burial of liquids, in bulk or in containers;
5. some manufacturers of synthetic lining materials provide compatibility testing and installation with the sale of their product sale;
6. some firms are researching methods to incorporate the natural attenuation capacity of clays in their liner designs. That is, they attempt to correlate expected leachate characteristics to the attenuative capacity of the clay so that the leachate that eventually passes through meets specific water quality criteria; and
7. some landfill design firms are prospectively designing land-fills to make corrective actions easier—e. g., to facilitate installation of a grout curtain to reduce lateral migration of ground water of contaminated leachate plumes.

Evaluation of Current Landfill Performance

Releases should be minimized, but there are substantial differences in philosophy about what this "minimization goal" means. The EPA narrative performance standard for landfills, states that landfill liners should prevent migration of leachate for the operating life of the fill (i.e., the landfill system should be 100 percent effective in its control of leachate) and that migration should be minimized thereafter.¹⁰⁸ This criteria fails to recognize that,

¹⁰⁸FR vol. 47, July 26, 1982, p. 32314.

because of the potential failures discussed, complete prevention of migration even during the operating life is probably unattainable. In fact, RCRA standards for ground water quality recognize that complete prevention may not be necessary. These standards for contaminant levels in ground water will be the criteria against which landfill performance will be judged. Critics argue that evidence of contamination is a poor criterion because it may not be detected, could be widespread before it is detected, and aquifer cleanup is expensive and may be unachievable (see also "Technical Regulatory Issues").

The first generation of landfills designed specifically for disposal of hazardous waste are now in the ground.¹⁰⁹ Quantitative data on their current effectiveness is limited. Data provided by a study of four landfills in New Jersey, which had leak-detection systems installed, showed they began collecting between 45 to 75 gal/day within months of their construction.¹¹⁰ Although controversial, this study concluded that the collection of liquids was due to failure of the primary liners. No landfills have been closed long enough to test the effectiveness of long-term maintenance or corrective actions. There is little quantitative evidence on which to project landfill performance, especially over the long term.

Future evaluations of landfill performance will depend on monitoring. The external ground-water monitoring currently required may not be sufficient (see ch. 7). In comparison to external monitoring, however, leak-detection systems embedded within a double liner may provide more reliable information on potential resource degradation and human exposure.

By examining how landfills work, their failure mechanisms, and available corrective measures, OTA'S review of landfill performance resulted in two principle findings: 1) uncertainty remains about the performance ca-

pabilities of each of the control features of a landfill, and 2) greater use should be made of waste treatments which increase waste stability as well as reduce long-term mobility of waste constituents.

EPA is conducting additional analyses of failures that have occurred at existing sites.¹¹¹ Such analyses invariably indicate that poor performance can be attributed to poor operating practice, design, or maintenance. Operation of any facility will always be subject to error or misjudgment; this underscores the importance of site and waste characteristics, the necessity of designing for both reliable indicators of potential failure, and corrective action capability. There is room to improve in both of these areas.

The performance standards and minimum design requirements for new landfills are based on the experience gained in recent years. However, as noted frequently in the preamble to EPA's land disposal regulations, there is limited experience and operating data for landfills (or closed surface impoundments). This lack of information hampers the development of performance design guidance.¹¹² Laboratory and field testing of liners and covers is underway. Little is being done to monitor actual facility performance; yet it is unlikely that our current experience is adequate to anticipate all future difficulties. Without better information on actual facility performance, it will be difficult to evaluate landfills constructed according to minimum design requirements, or to evaluate alternative landfill designs. There are technical methods available to improve our information base.

In-situ instrumentation for systematically gathering data on the following performance indices has been suggested:¹¹³

1. leachate accumulation at sites other than manholes;

¹¹¹William L. Murphy Rohrer, Senior Environmental Scientist, Pope-Reid Associates, Inc., personal communication, January 1983.

¹¹²Comments to EPA regarding proposed rules, "Docket 3004, Permitting Standards for Land Disposal Facilities," prepared by the New York State Attorney General, Robert Abrams, Nov. 9, 1982.

¹¹³Ibid., p. 4.

¹⁰⁹A. L. Kruger, "Alternatives to Landfilling Wastes" (Princeton, N. J.: Princeton University, Department of Chemical Engineering, Ph.D. Thesis, February 1982).

¹¹⁰Peter Montague, "Hazardous Waste Landfills: Some Lessons From New Jersey, Civil *Engineering-ASCE*, September 1982, pp. 53-56, and more detailed unpublished draft.

2. stress/strain characteristics of synthetic membranes;
3. settlement of individual lifts inside the cells;
4. leachate delivery to leachate collection system;
5. differential and areal settlement of the cap;
6. seasonal moisture contents of the cap;
7. erosion rates of cap soils;
8. actual cap infiltration rates;
9. three-dimensional chemical conditions inside the cells, especially in the vicinity of the liner face;
10. gas evolution rates in particular cells; and
11. contaminant transport phenomena in soil liner.

Technical Regulatory Issues

The current regulatory framework will affect the future use, operation, and design of landfills. Liability requirements may encourage certain industry sectors to employ alternative treatment technology or waste reduction activities. If implemented, requirements to demonstrate financial responsibility for future corrective action may be an even greater incentive (see also ch. 7).

Current regulations will require upgrading the design of new facilities to include the use of liners, guidelines for waste pretreatment, leachate collection systems, and covers. Existing portions of facilities are broadly exempted from retrofitting that do not have the minimal control features of a liner or collection system.

The current regulations will influence the construction and operation of landfills. Key regulatory points with likely impacts on future use of landfills are:

- a preference for the use of artificial liners;
- minimal restrictions on the waste allowed to be landfilled; and
- minimal restrictions on the siting of landfills.

Influence on Liner Selection.—The current regulations state that liner materials for new hazardous waste landfills should not allow migra-

tion of leachate into the liner during the operating life of the facility. This could favor the selection of synthetic membrane liners, since they can absorb de minimis quantities of leachate.¹¹⁴ This preference tends to isolate the capability of a liner from the rest of the engineered landfill system, its environmental setting, and the persistence and toxicity of the waste it contains.

Furthermore, this preference could inhibit the comparative evaluation of clay and synthetic liners, and overlooks uncertainties about the long-term limitations of any liner material. **A more farsighted approach might require the use of both a synthetic and a compacted clay liner.** The synthetic liner would be used to collect the more concentrated leachate likely to be produced during the operating life of the facility. This would protect the clay liner from the concentrated leachate constituents which can increase the permeability of the clay liner, thus enhancing the long-term integrity of the clay liner backup.¹¹⁵

Restrictions on Waste Being Landfilled.—In July 1982, detailed rules were issued defining wastes allowable for landfilling. Treatments are required to mitigate waste characteristics of ignitability, reactivity, and corrosiveness. Incompatible wastes cannot be placed in the same landfill cell. These requirements should greatly reduce the hazards of fires, explosions, and generation of toxic fumes. There are no restrictions against landfilling highly toxic, persistent waste and no treatments are required to mitigate a waste constituent's toxicity or mobility.¹¹⁶ Containerized liquids cannot be landfilled unless the liquids are rendered not free flowing. Many treatments that can modify the free liquid form do not immobilize toxic constituents. The regulations allow the disposal of free waste liquids into landfills with synthetic liners and leachate collection systems.

Siting Restriction.—The current regulations contain only minimal siting restrictions. For

¹¹⁴FR 47, No. 143, 32314, July 26, 1982.

¹¹⁵David Anderson, geotechnical consultant with K. W. Brown & Associates, College Station, Texas, personal communication, January 1983.

¹¹⁶FR 32,366, July 26, 1982.

example, they suggest that new landfills should not be sited within a 100-year flood plain, but that if they are, they should be designed to withstand such a flood.¹¹⁷ Many believe that restrictions should be imposed on sites based on proximity to natural features such as major supplies of ground water used for drinking, designated sole-source aquifers, aquifer recharge areas, sink holes, and wetlands.¹¹⁸ Such site characteristics are not addressed by the regulations.

Technology Forcing.—Although EPA is promoting the use of some technologies in their most advanced form, less reliable landfilling designs are allowed. Incinerator performance standards have been set close to the limits of their known technical capabilities. Meeting these requirements for routine incineration at many existing facilities will require improvements in engineering design and operation of the facility. However, owners and operators of many existing landfills have already instituted voluntary or State-mandated operating, design stand-

¹¹⁷Ibid., pp. 32, 290.

¹¹⁸David Burmaster, "Review of Land Disposal Regulations," paper submitted to OTA Materials Program, November 1982.

ards, and monitoring programs more demanding than Federal requirements, including the use of a double liner.¹¹⁹

For landfilling, the regulations establish the minimum design requirements for landfill liner system and methods for leachate monitoring—i.e., one bottom liner* and external monitoring via ground-water wells for detecting and assessing the effect of leachate migration (see fig. 12). The reliability of this design is inferior to a double liner with a leak-detection system. There is an incentive to promote the use of this more advanced design, through granting an initial waiver of the ground-water monitoring program,

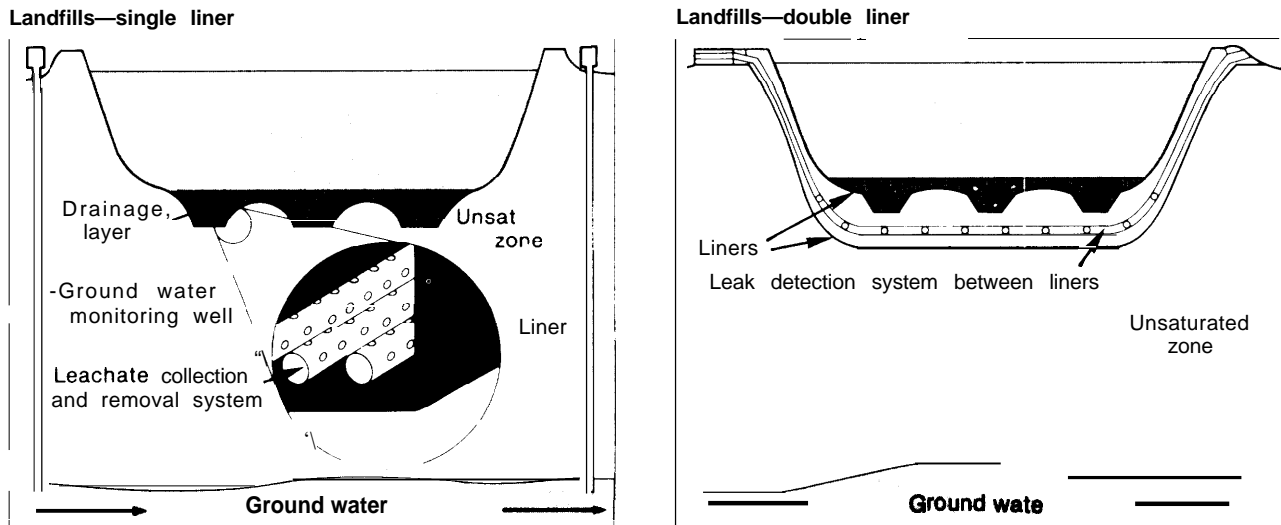
Surface Impoundments

Surface impoundments are depressions in the ground used to store, treat, or dispose of a variety of industrial wastes. They have a variety of names: lagoons, treatment basins, pits,

¹¹⁹Burmaster, op. Cit.

*As discussed above, the single liner is likely to be a membrane liner.

Figure 12.—Schematic of Single and Double Synthetic Liner Design



This is the new minimum requirement for newly constructed landfills: a single liner (probably a synthetic membrane), a leachate collection system, and ground water monitoring wells.

SOURCE: Civil Engineering—ASCE, January 1983

If two synthetic liners and a leak-detection system are used as shown above, no ground water monitoring is initially required under the new regulations.

and ponds.¹²⁰ These depressions can be natural, man-made, lined, or unlined. They can be several feet in diameter or hundreds of acres in size.

Applicability

The majority of wastes put into surface impoundments come from four industrial groups: paper and allied products, petroleum and coal products, primary metals, and chemicals and allied products.¹²¹ These wastes are generally impounded as bulk liquids or sludges.

Surface impoundments are used either to treat or store industrial wastes. For treatment, surface impoundments are widely used for dewatering sludges, neutralizing and separating waste constituents, and biodegrading waste waters. Storage simply refers to temporary holding. Although estimates of capacity vary, national estimates indicate that there are approximately 1,100 surface impoundments used for hazardous waste, covering a total area of close to 29 million yd² [see ch. 4).

Evaluation

Surface impoundments have allowed release of hazardous waste constituents through catastrophic failure, leachate migration, and volatilization of organics. Impoundments are more subject to catastrophic failure than landfills because they tend to contain more bulk liquid. Evidence of surface- and ground-water contamination resulting from impoundments is well documented.¹²² This has occurred from sudden releases; e.g., by overtopping the sides, dike failures, or rupture of the liner due to inadequate subgrade preparation, or sinkhole formation.^{123 124} In addition, slow leakage can contaminate soil and ground water. This is

especially true for unlined impoundments. Investigations at some unlined "evaporation ponds" have shown that seepage accounted for more of the reduction in volume than did evaporation.¹²⁵ In general, these release pathways are addressed by Federal regulations (see also "Technical Regulatory Issues").

There is an expected rate of leakage even through intact liners. Some liquids are chemically aggressive to liners, increasing the rate of movement through the liner. Leakage occurs in much the same manner described in the previous section for landfills. The rate of leakage generally depends on the same factors (see discussion of liners in the "Landfill" section). For impoundments, one primary difference is that there is always a hydraulic gradient acting on the liner. An additional concern is how long the wastes are held in the impoundment before their hazardous characteristics have been mitigated,

Some organic liquids currently being held in impoundments are volatile. Volatilization for many organic chemicals can occur at normal atmospheric temperatures and pressures. This has recently led to investigations of the potential magnitude and severity of organic air emissions.

There is little field data to indicate the magnitude of air emissions from surface impoundments. Most of the information available is from mathematical models that estimate an emissions rate from the many factors influencing volatilization. These include the concentration of organics in the waste, their vapor pressures and solubilities, environmental factors such as air and water temperature, wind velocity, and the surface area of the impoundment,^{126 127}

¹²⁰D. W. Miller (ed.), *Waste Disposal Effects on Ground Water* (Berkeley, Calif.: Premier Press, 1980), p. 108.

¹²¹*Ibid.*, pp. 111-129.

¹²²See for example, *Final Environmental Impact Statement for Subtitle C, RCRA, 1976*, pt. 1, app. J.

¹²³William L. Murphy Rohrer, Senior Environmental Scientist, Pope-Reid Associates, Inc., personal communication concerning ongoing EPA research on failure mechanisms at land-based disposal facilities, January 1983.

¹²⁴J. P. Giroud and J. S. Goldstein, "Geomembrane Liner Design," *Waste Age*, September 1982.

¹²⁵*Surface Impoundments and Their Effects on Ground Water Quality in the United States—A Preliminary Survey*, [J. S. EPA, Office of Drinking Water, **570/9-78-004**, June 1978.

¹²⁶L. J. Thibodeaux, et al., "Chemical Volatilization Mechanisms From Surface Impoundments in the Absence of Wind," *Land Disposal of Hazardous Waste*, proceedings of the 8th Annual Research Symposium, EPA 600/9-82-002, March 1982.

¹²⁷Thomas T. Shen, "Estimation of organic Compound Emissions From Waste Lagoons," *Journal of Air Pollution Control Association*, vol. 32, No. 1,

Many of the models were designed to represent other environmental transport phenomenon, e.g., evaporation from oceans or lake basins, and have been adapted for application to organic emissions. Consequently, estimates of emissions derived from these models must be viewed with caution. Nonetheless, the models estimate a significant rate of emissions. For example, emissions from a 1/4-acre impoundment, "holding 100 mg/l benzene and 100 mg/l chloroform, are estimated to be almost 45 lb/hr of benzene and 39 lb/hr of chloroform. 128 This rate of emissions would decline but continue until a covering was installed. Further model development work, including validation sampling, is underway.¹²⁹

Technical Regulatory Issues

The effectiveness of the interim final regulations lies in how well they improve the performance of surface impoundments over past practices. The Federal regulations require that new impoundments have a liner, and establish the minimum design and performance standard; i.e., a single liner intended to meet the narrative performance criteria stating that the liner must "prevent any migration" of waste constituents out of the impoundment during its active life.¹³⁰ Although these requirements for liners will reduce leakage, the literal narrative standard is probably technically infeasible. Lining materials have long been used to reduce seepage and economic losses of stored liquids, however the use of liners for pollution control is comparatively new. A great deal of R&D in liner technology will be required to meet these standards. Two researchers state the issue well:^{131 132}

There is a lack of formalized design procedures to accomplish the objective of pollution

*With a depth of 3.5 meters, ambient temperatures of 25° C, and wind speeds of about one-tenth mph.

¹²⁸Ibid., p. 81.

¹²⁹Steve James, project officer, Municipal Environmental Research Laboratory, personal communication, January 1982, 130FR 32,357, July 26, 1982.

¹³¹Folkes, op. cit.

¹³²R. E. Olson and D. E. Daniel, "Field and Laboratory Measurement of the Permeability of Saturated and Partially Saturated Fine-Grained Soils," Geotechnical Engineering Report CR 80-5, Department of Civil Engineering, University of Texas, June 1979.

control. Because of this lack, there is a tendency toward qualitative approaches to liner design. It is often assumed, for example, that liners are either impermeable or of such low permeability that further analyses are not required. The end result can be failure of the liner to perform as intended.

Similarly:

... in engineering, past practice has frequently meant to assume that fine grained soils are effectively "impervious" and to forego attempts to measure their coefficient of permeability.

The regulatory incentive for installation of double liners with leak-detection systems applies also to impoundments. However, in contrast to leak-detection systems currently used with landfills, OTA found that detection systems placed beneath the primary liner of an impoundment can be used to routinely remove the liquids from between the liners. This reduces the hydraulic pressure from the secondary liner. In some cases, this kind of leachate detection **and** removal system are already used to remove the liquids **expected to migrate** through the primary liner.¹³³ Ground water at sites which are especially vulnerable to contamination would be better protected by this system. Instead, the regulations allow the use of a single liner, and rely on an external ground-water monitoring net to detect waste constituents in excess of ground water standards.

As with landfills, a broad exemption from the requirement for any liner is allowed for existing impoundments. Development of remote-sensing techniques to detect leakage at existing sites has recently begun.¹³⁴ EPA is also investigating techniques for retrofitting synthetic liners at existing impoundments.¹³⁵ Combining these efforts with information about the char-

¹³³Peter Vardy, Waste Management Inc., personal communication, January 1983.

¹³⁴Waller and Davis, op. cit., in proceedings of the Eight Annual Research Symposium, EPA 600/9-82-002, March 1982.

¹³⁵John W. Cooper and David Schultz, "Development and Demonstration of Systems to Retrofit Existing Liquid Surface Impoundment Facilities With Synthetic Membrane," in *Management of Uncontrolled Hazardous Waste Sites*, conference proceedings, Washington, D. C., December 1982.

acteristics of the site and the waste could reduce reliance on detection monitoring and remedial action.

Federal regulations also require that impoundment dikes be designed and constructed to prevent massive failure. In the past, massive dike failure has been linked to damage caused by leakage from the impoundment. The regulatory criteria requires that liner leakage be considered in the design and construction of structurally sound dikes. To the extent that new dikes meet this requirement, sudden releases from impoundments should be reduced. In addition, new impoundments are to be designed to withstand certain storm and flooding events. However, as with landfills, siting requirements are minimal. Furthermore, existing sites are exempted from having to upgrade dikes and berms. In some cases, exempted impoundments may pose substantial risk of sudden releases,

Many of the regulatory requirements pertain to closure and post-closure responsibilities. At closure, impoundment operators have two options: to remove all remaining wastes and contaminated lining material for disposal at an approved RCRA facility or decontaminate, or solidify/stabilize, the remaining waste so that it can structurally support a final cover. If this second option is taken, the impoundment is essentially closed like a landfill, and similar monitoring and maintenance responsibilities apply. Long-term uncertainties related to liner life and cover integrity are similar to those discussed in the landfill section. Issues concerning lack of criteria for what constitutes adequate "stabilization" of the waste are similar to those discussed in landfill pretreatment requirements.

EPA is beginning to investigate the potential for air quality degradation resulting from impounded volatile organics and is planning research to identify appropriate regulation in this area. Some States, notably New York and California, are also investigating this issue.¹³⁶ Cal-

¹³⁶Thomas T. Shen, Senior Research Scientist, New York State Department of Environmental Conservation, personal communication, December 1982

ifornia has suggested both limits on the amount of volatile organic material that can be land-disposed and limiting the time certain wastes can be stored in impoundments as air quality control measures.¹³⁷

Underground Injection Wells

Injection of liquid waste into subsurface rock formations is a technology that uses porous sedimentary strata to hold liquid waste. The pores of all porous rock formations contain liquids, gases, or both. The gas or liquid is contained within the strata under pressure caused by overlying rocks. Internal pressures within strata can vary significantly, depending on the porosity of the formation, its depth, and other physical and chemical factors. Essentially, underground injection entails drilling a well to the depth required to intersect an appropriate geologic formation (known as the injection zone) and pumping the liquid waste in with pressure sufficient to displace the native fluids, but not so great as to cause fracturing of the strata or excessive migration of the waste. Formations suitable for waste injection should meet the following criteria:¹³⁸

- it should not have value as a resource—e.g., as a source of drinking water, hydrocarbons, or geothermal energy;
- it must have sufficient porosity and volume to be able to accept the anticipated amount of liquids;
- it should be sealed both above and below by formations with sufficient strength, thickness, and impermeability to prevent migration of the waste from the disposal zone; and
- it should be located in an area with little seismic activity to minimize both the risk of earthquake damage to the well and triggering of seismic events.

There is no standard injection-well design because design requirements are influenced by

¹³⁷State of California Air Resources Board, "Suggested Control Measure To Reduce Organic Compound Emissions Associated With Volatile Organic Waste Disposal," August 1982.

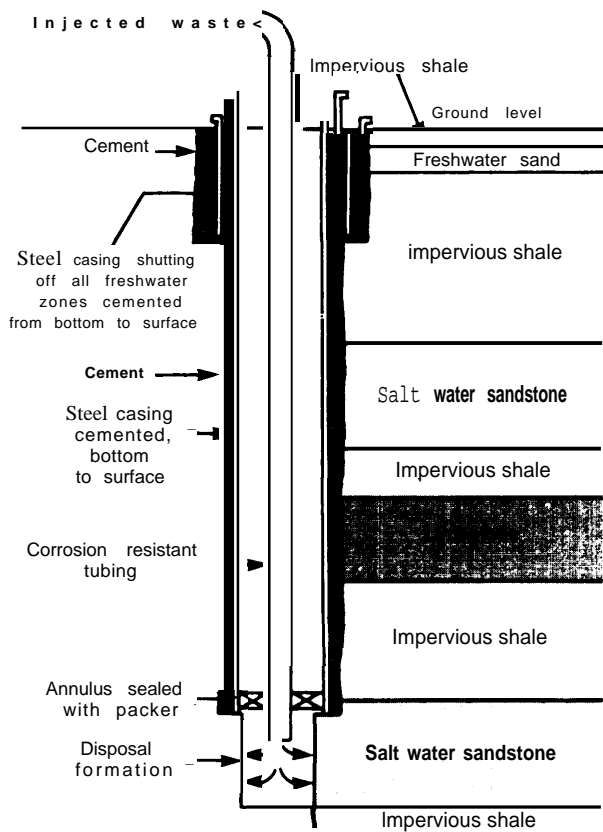
¹³⁸Don L. Winer and Jay H. Leher, *Subsurface Wastewater Injection* (Berkeley, Calif.: Premier Press, 1981), pp. 124-127.

site-specific geology. Figure 13 illustrates the design of an injection well that might be used for hazardous waste disposal. As shown in the figure, the well is constructed with three concentric casings: the exterior surface casing, the intermediate protection casing, and the injection tubing. The exterior surface casing is designed to protect freshwater in the aquifers through which the well passes and to protect the well exterior from corrosion. The casing extends below the base of aquifers containing potable water and is cemented along its full length. Similarly, the intermediate protection casing extends down and through the top of the injection zone and is cemented along its full length. The waste is actually transported through the injection tubing, the innermost casing. The tubing also extends into the top of the

injection zone; its endpoint is the point of waste discharge. The injection tubing is sealed off from the intermediate casing, creating an annular space between the injection tubing and the casing. The annulus is filled with fluid containing corrosion inhibitors to protect the casing and tubing metal. The fluid is pressurized between the sealing at the base of the well and the well head assembly.^{139,140} Since the pressure within the annulus is known, monitoring the pressure during the operation of the well can be a method of checking the integrity of the injection system. Anomalous drops in pressure indicate a leak, either in the injection tubing or in the outer casing.¹⁴¹

When injection operations cease, the well is plugged. Proper plugging is necessary to maintain the existing pressure in the injection zone, to prevent mixing of fluids from different geologic strata, and to prevent flow of liquids from the pressurized zone to the surface.¹⁴²

Figure 13.—Schematic of Typical Completion Method for a Deep Waste Injection Well



SOURCE: R. B. Pojasek, *Toxic and Hazardous Waste Disposal*, vol. 4, Ann Arbor Science, 1980.

Applicability

Injection wells are capable of accepting a wide range of waste liquids. The primary characteristics of a liquid that limit the applicability of injection well disposal are: high suspended solids content, high viscosity, and chemical incompatibility with either the formation or formation fluids. Before injecting a waste, its chemical characteristics must be compared with the mineral characteristics of the formation and the native fluids within the injection zone to determine their compatibility.¹⁴³ Chemical pretreatment of the waste can sometimes make them more compatible with a specific injection zone formation. Examples of waste that can be disposed via injection wells are:¹⁴⁴

- dilute or concentrated acid or alkaline solutions;
- solutions containing metals;
- inorganic solutions;

¹³⁹Waste Age, October 1982.

¹⁴⁰Ray "W. Amstutz, "Deep-Well Disposal: A Valuable Natural Resource," in *Toxic and Hazardous Waste Disposal*, Robert Pojasek (ed.), vol. 4, Ann Arbor Science, 1980.

¹⁴¹Warner and Lehr, op. cit., p. 295.

¹⁴²1 bid., p. 320.

¹⁴³Ibid., pp. 159-177.

¹⁴⁴Amstutz, op. cit., p. 285.

- hydrocarbons, including chlorinated hydrocarbons;
- solvents; and
- organic solutions with high biochemical or chemical oxygen demand.

Industries using injection wells for waste disposal are listed below in approximate order of predominance: 145

<i>Industry type</i>	<i>Percent</i>
Chemical and allied products	49
Petroleum refining.	20
Sanitary service	9
Oil and gas extraction	6
Primary metals	6
All others	10

Current Use

Estimates of the total number of injection wells currently in use are not in agreement. Some variance is due to the definition of injection wells used in conducting well inventories. Uniform Federal definitions for classifying injection wells became final in February 1982. Wells are now categorized into five classes:¹⁴⁶

1. Class I wells include those used for disposal of municipal or industrial waste liquids and nuclear waste storage and disposal wells that discharge below the deepest underground source of drinking water;
2. Class II wells are those used for oil and gas production;
3. Class III wells include mining, geothermal, and other special process wells;
4. Class IV wells are those which inject hazardous waste into or above an underground source of drinking water; and
5. Class V wells include all others (e.g., irrigation return flows) not in Classes I through IV.

Thus, wells used to dispose of federally defined hazardous liquid waste can fall into one of two classifications, Class I or Class IV. The distinction lies not in the characteristics of the waste injected, but in the discharge point relative to an underground source of drinking water. Class I wells discharge waste beneath the

deepest formation containing, within one-quarter mile of the well bore, a drinking water source. Class IV wells are those used to inject hazardous liquids **into** or **above** a formation which, within one-quarter mile of the well bore, contains a drinking water source.

Based on preliminary validation surveys of hazardous waste facility notification requirements, EPA estimates that 159 wells are currently in use for disposal of hazardous industrial liquids; this figure presumably includes both Class I and IV (see ch. 4). Earlier inventories generally indicate a greater number of disposal wells. Better information may become available when all States report their intentions to develop programs under the Safe Drinking Water Act.¹⁴⁷ The total rate of discharge for wells disposing of industrial waste is large. One source estimates that, based on volume, disposal of hazardous waste through injection wells was the predominant disposal method in 1981. An estimated 3.6 billion gallons were injected that year.¹⁴⁸ Information about the hazardous characteristics of these wastes is not available.

The majority of injection wells are located in States with a long history of oil and gas exploration. The geology in these areas is often well-suited for waste disposal zones; moreover, the geological characteristics are well documented because of petroleum exploration. For example, EPA Region VI contains almost 60 percent of the covered disposal wells inventoried in 1975.¹⁴⁹ The majority of these wells (about 58 percent) inject waste into comparatively deep stratum—e.g., at depths between 2,000 to 6,000 ft (600 to 1,800 m). In general, disposal into formations at greater depth are unlikely to contaminate surface or near-surface water. About 30 percent inject waste into formations less than 2,000 ft (305 m). The receiving formations are approximately equally distributed between sand, sandstone, and carbonate rocks.¹⁵⁰ Strata with this type of lithology

¹⁴⁵ W. J. Wines and Lehr, op. cit., p. 5.
¹⁴⁶ 47 FR 4992, Feb. 3, 1982.

¹⁴⁷ Jentai Yang, Office of Drinking Water, EPA, personal communication, January 1983.

¹⁴⁸ Part A Universe Telephone Verification, Contract No. 68-01-6322, prepared by Westat, Inc., for EPA, November 1982, p. 3.

¹⁴⁹ Warner and Lehr, op. cit., p. 3.

¹⁵⁰ Ibid., pp. 5-7.

can be water-bearing. Whether they are considered underground sources of drinking water depends on the quality and quantity of the water they contain and how economically accessible they are. All three factors vary across the Nation.

Effectiveness as a Disposal Technology

Technologies for constructing and operating wells for waste disposal is well established; much has been transferred from that used for oil and gas exploration. The ability of injection wells to keep waste isolated in the injection zone depends on many site-specific factors, including the well design and expertise of the operator. If a failure occurs, the consequent risk depends on the site geology, characteristics of the waste injected, the extent of the failure, detection of the failure, and whether corrective action is feasible and undertaken. The following list of potential contamination pathways resulting from faulty construction, operation, and/or deterioration of the well are briefly discussed below:¹⁵¹

1. injection into or above potable aquifers,
2. leakage through inadequate confining beds,
3. leakage through confining beds due to unplanned hydraulic fracturing,
4. displacement of saline water into a potable aquifer,
5. migration of injected liquids into the potable water zone of the same aquifer,
6. injection of hazardous liquid into a saline aquifer eventually classified as a potable water source,
7. upward migration of waste liquid from the receiving zone along the outside of the well casing,
8. escape into potable aquifers due to well-bore failure, and
9. vertical migration and leakage through abandoned or closed wells in the vicinity.

Some existing disposal wells probably threaten contamination of drinking water sources through the first pathway listed. These are the

Class IV wells which discharge waste into or above formations which, within one-quarter mile of the discharge point, are sources of drinking water. The exact number and location of these wells is not known.¹⁵² Federal policy requiring closure of wells discharging into a drinking water source is just beginning to go into effect. There is still no Federal policy for wells injecting **above** a drinking water source (see "Technical Regulatory Issues").

Leakage and migration of waste to a potential water source can result from inadequate confining beds, or unexpected fracturing of a confining bed (pathways 2 and 3 above). Techniques currently used for surveying the hydrogeology of a site prior to construction minimize unintentional breaches of the confining beds. However, if such breaches occur, they can generally be detected during the operating life of the well by monitoring of well-fluid pressures. There are corrective actions available that can potentially reduce the likelihood of contamination resulting from these kinds of failure, but they generally rely on changing the hydraulic gradient within the affected aquifer. Experience with these techniques is limited. Their use is not always possible nor completely effective.¹⁵³

Pathway 4 describes contamination of a potable water source with naturally occurring saline water that does not meet drinking water standards. This could occur if the pressure buildup resulting from waste injection within the receiving zone is sufficient to displace the native fluids into a potable water source. It should be possible to minimize this kind of contamination through careful surveying and selection of the injection zone,

The quality of water contained within an aquifer can vary considerably within a single water-bearing stratum. It is not unusual for the dissolved solids concentration within an aquifer to increase from the top to the bottom of an aquifer. Thus, water drawn from one location may meet drinking water criteria, while

¹⁵¹David W. Miller (cd.), *Waste Disposal Effects on Ground Water* (Berkeley, Calif.: Premier Press, 1980), p. 366.

¹⁵²Yang, op. cit.

¹⁵³William Thompson, Senior Scientist, Geraghty & Miller, Inc., personal communication, November: 1982.

water drawn from another location within the same formation may not. Large aquifers that exhibit this range of water quality can and are being used for waste disposal, provided that the discharge point and the estimated radius for waste dispersion remains within the area containing nonpotable water.¹⁵⁴ Pathway 5 describes contamination resulting from unexpected waste migration into the potable water zone. If waste-injection practices increased significantly, this pathway could become more prevalent in the future.¹⁵⁵

Contamination of an aquifer as described in pathway 6 is not a result of poor planning or technical failure. Rather, it could occur in the future as the criteria change for determining what levels of aquifer quality constitute an economical water source. Due to regional differences in the abundance and quality of surface and ground water resources, there are differences in the criteria used to define an underground water source for drinking supplies, agricultural, or industrial use. These criteria could be revised in the future to encompass currently uneconomical or less desirable water sources as increasing demands are placed on available ground water sources.

The potential for waste migration is generally considered greatest in the immediate vicinity of the well bore (pathway 7).¹⁵⁶ Waste can also migrate laterally through a breach in the well bore. This kind of well-bore failure can occur, for example, through corrosion or damage due to subsurface pressures exerted on the well.¹⁵⁷ ¹⁵⁸ Migration via these routes can generally be detected through monitoring of fluid pressures both within the well bore and within the annulus if the leakage occurs during the operating life of the well. In the event of leak detection, techniques are available to reconstruct well casings to reduce waste migration.

¹⁵⁴Ibid.

¹⁵⁵Miller, *op. cit.*

¹⁵⁶Warner and Lehr, *op. cit.*, p. 293.

¹⁵⁷"Mechanical Integrity Testing of Injection Wells," EPA contract No. 68-01-5971, prepared by Geraghty & Miller, Inc., April 1982.

¹⁵⁸"Technical Manual: Injection Well Abandonment," EPA contract No. 68-01-5971, prepared by Geraghty & Miller, Inc., April 1982.

The contamination pathway described as pathway 9, upward migration of waste through abandoned or closed wells, is particularly insidious because regions where waste injection is widely practiced also have a long history of energy exploration and development. Depending on the site geology, these wells provide vertical connections from deeper formations to near surface or surface formations. Many of these wells were drilled before plugging of abandoned wells was required. Often, their locations are not known and some may no longer be evident at the ground surface. One source estimates that there may be more than 1 million unplugged wells unlocated in North America.¹⁵⁹ To address this concern, current Federal regulations require potential disposers to calculate the subsurface area expected to be affected by the pressure of waste injection. Before new waste injection can begin, the operator is required to survey and to plug existing wells within this area.¹⁶⁰

Similarly, Federal regulations require that new wells must be plugged at closure to maintain pressure within the injection zone. There are no specific Federal requirements for well abandonment, because the procedures used depend on the well construction and site hydrogeology. Proposed plugging methods are evaluated by individual State-permitting authorities. Wells are plugged by selectively cementing sections throughout its length. There is no technical consensus over the placement of well plugs; their location and extensiveness are determined by State requirements and cost considerations.¹⁶¹ Some States require that plugs be set over the entire length of the injection zone, and extend 50 to 100 ft into the overlying confining beds. In some wells, injection can occur over hundreds to a thousand feet of formation. In addition, plugs are generally set above and below each aquifer that the well passes through.¹⁶²

¹⁵⁹R. Allen Freeze and John A. Cherry, *Groundwater* (Englewood Cliffs, N. J.: Prentice Hall, Inc., 1979), p. 455.

¹⁶⁰40 CFR 146.6 and 146.7.

¹⁶¹"Technical Manual: Injection Well Abandonment," *op. cit.*, p. 6.

¹⁶²Ibid., pp. 5, 6.

Although there is considerable documentation of well abandonment in the oil and gas industry, there is less information regarding potential problems with waste disposal well abandonment.^{163 164} In 1973, the State of Michigan surveyed 20 abandoned wells to determine the adequacy of the plugs. The wells were re-drilled to verify the position and condition of the cement plugs. Some plugs were never found; others had deteriorated and were soft.¹⁶⁵ More advanced well-plugging techniques should improve this record. Installation of effective plugs requires careful planning and considerable operator skill.¹⁶⁶ There is little experience with abandonment of waste disposal wells on which to evaluate the long-term integrity of well plugs.

There is currently little information about contamination incidents resulting from injection well practices for all classes of wells. Moreover, it is sometimes difficult to correlate a particular contamination incident with a specific well disposal practice. Past documentation of contamination has been attributed to a variety of injection well operations. For example, one survey conducted by the State of Texas between the years 1967 and 1975 reviewed 800 wells that had been used for oil and gas production. The wells were located by reports of water wells becoming contaminated with brackish water, of wells flowing at the ground surface, or by field investigations.¹⁶⁷ Research is underway to better define the correlation between ground and surface water contamination related to injection wells.

In addition to monitoring pressures within the well, there are several types of monitoring wells that can provide information on the effects of waste injection. Constructing monitoring wells in the receiving formation is the only direct method of detecting the rate and direction of waste liquid movement. However, sam-

pling from the receiving formation has the disadvantage of providing additional routes for contaminant migration.¹⁶⁸ Monitoring wells can also be constructed to sample from the confining beds or from aquifers above the injection zone. The usefulness of such wells may be limited by site-specific factors. There are cases, however, where monitoring wells sampling immediately above a confining bed have detected contamination from leakage which was not detected by monitoring well pressures. Also, the injection well itself can be adapted to monitor overlying aquifers.¹⁶⁹ State requirements for types and locations of monitoring wells vary.

Federal standards for Class I wells require that operators report "the type, number and location of wells" used to monitor pressures and migration of fluids into underground sources of drinking water, the frequency of sampling, and the parameters measured (40 CFR 146.13). These requirements are just now going into effect for States with approved programs. Currently, much of the direct sampling for contamination is conducted through water wells that are part of the facilities water supply system or which are near an injection site.¹⁷⁰

Technical Regulatory Issues

All classes of injection wells are regulated by the Underground Injection Control (UIC) program under the Safe Drinking Water Act (SDWA). Wells which inject liquid hazardous waste are regulated under both SDWA and RCRA. Because of this overlapping jurisdiction, injection-well facilities that are in compliance with a UIC permit and which meet general requirements for notification, manifesting of waste, annual reporting, and closure certification, will be considered to have a RCRA permit (F. R. 47, July 26, 1982, 322:81). Requirements for financial responsibility, post-closure care and corrective action responsibility have not yet been specified.

¹⁶³ *Ibid.*, p. 1.

¹⁶⁴ Warner and Lehr, *op. cit.*, p. 321.

¹⁶⁵ "F" Technical Manual: Injection Well Abandonment, " *op. cit.*, p. 9.

¹⁶⁶ *Ibid.*, p. 8.

¹⁶⁷ Kerr S. Thornhill, Environmental Laboratories, Ada, Okla., personal communication, January 1983.

¹⁶⁸ Warner and Lehr, *op. cit.*, pp. 310-311.

¹⁶⁹ *Ibid.*, p. 312.

¹⁷⁰ Thornhill, *op. cit.*

Further, the development of UIC standards is not complete. Specifically, there are no standards for Class IV wells that inject wastes above a drinking water source (F. R., *ibid.*). States with approved programs are required to eliminate waste disposal through a Class IV well injecting into a drinking water source within 6 months of receiving approval. To date, only nine States have approved UIC programs, although several more are currently being reviewed.¹⁷¹

Corrective measures are required if a failure occurs during the operating life of the well. UIC regulations require the installation and use of continuous recording devices to monitor injection pressure, annular pressure, waste volume, and flow rate.¹⁷² In addition, the well must be tested for mechanical integrity through a temperature or noise log test at least once every 5 years.¹⁷³ If a significant leak is detected, the well casing must be repaired or replaced.¹⁷⁴ Closure of the well must be certified.

In general, waste disposal through properly constructed and operated injection wells into deep formations below the lowest drinking water source are much less likely to contaminate surface or shallow aquifers than are landfills and surface impoundments. There do not appear to be requirements for corrective action for damage that might occur after well closure comparable to the requirements imposed on land-based disposal under RCRA. The Post-Closure Liability Trust Fund Act will provide funding for site maintenance and care, as well as a source of compensation for personal and property damage. However, it is unclear how the tax will be calculated for liquid waste injected into disposal wells.¹⁷⁵ The statutory language specifies that the tax be levied at a rate of \$2.13 per dry weight ton of hazardous waste delivered to an RCRA permitted facility.

¹⁷¹Yang, *op. cit.*

¹⁷²40 CFR 146.13.

¹⁷³40 CFR 146.8 and 146.13.

¹⁷⁴Yang, *op. cit.*

¹⁷⁵Eric Nagle, Environmental Law Institute, personal communication, November 1982.

Comparative Unit Costs for Selective Technologies

There is little consistent information available about the costs necessary to achieve a given level of control by waste treatment and disposal practices. This is due to a variety of factors: 1) lack of consensus about what constitutes comparable levels of control across technology alternatives, 2) the regulatory uncertainties of the evolving Federal program, 3) cost information that is generally specific to an application of a particular technology to a particular waste, and 4) the dynamic nature of costs as industry gains experience in responding to the regulatory requirements.

Almost all the studies that evaluated costs for different treatment and disposal alternatives considered the effect of the new RCRA regulations. Although tentative, given the lack of experience of the interim final relations, virtually all the studies point out two trends:

1. the post-closure, liability, and corrective action requirements will have a greater effect on land-based disposal options relative to treatment or incineration, and
2. the costs for any treatment option is affected by the waste type. Costs are most sensitive to waste characteristics for chemical and thermal destruction and less sensitive for landfills.

While cost data are scarce and only roughly comparable in general, those that reflect differences in waste form are even fewer. For example, fee schedules for commercial facilities that provide several treatment steps and final disposal are frequently determined after testing samples of the prospective waste stream. Rather, most of the economic studies completed to date have focused on the incremental cost increases—e.g., in administration, recordkeeping, security, personnel—required by RCRA regulations. Another very important economic lever that has been studied in detail is the effect of the liability requirements on the decisions made by treatment and disposal facility operators. This is because the liability and insurance requirements reflect, to a limited ex-

tent, the perceived sudden and non-sudden risks associated with types of waste treatment or disposal, facility designs, and operating practices.

This section presents a brief comparison of technology costs. All unit cost figures should be considered as approximate. Their usefulness is in general comparison. Costs were derived from three sources; all have limitations:

1. The Commerce study figures are based on treatment costs in the Great Lakes Region only. Unit costs are based on surveys of actual charges levied for wastes from three industry sectors. The surveys requested that the respondents factor their expectations of the increased costs of the interim status, not interim final, Federal requirements.
2. The EPA study, completed under contract by Booz, Allen & Hamilton, reports unit costs based on a survey of the nine largest commercial facilities. In 1980, these facilities treated an estimated 51 percent of the total national waste stream which was handled offsite, estimated at 3.7 million tons. The unit costs reported may be slightly overstated relative to the costs incurred by a generator with onsite treatment and

disposal facilities because these are prices charged to return an investment on a commercial service.

3. The cost figures reported in the California Air Resources Board study are based on surveys of commercial and onsite facility operators.

Table 34 presents costs by type of waste management used and general description of waste type. Table 35 presents a limited comparison of unit costs for treatment v. incineration for selected waste types, Table 36 presents a limited comparison of landfill and thermal destruction costs and illustrates the effect of waste form and waste type on these costs.

As illustrated in table 36, the cost for commercial landfill service ranges from between \$55 to \$240/tonne. This range covers the gamut from low-risk bulk waste to more hazardous drummed waste. These designations of hazardous characteristics are based largely on qualitative assessments. By comparison, the range of costs for commercial incineration is \$53 to \$791/tonne. This range of costs also reflects the relative technical ease of destroying comparatively clean combustible liquids as contrasted with highly toxic refractory solids and drummed wastes.

Table 34.—Comparison of Quoted Prices for Nine Major Hazardous Waste Firms in 1981^a

Type of waste management	Type or form of waste	Price 1981	\$/tonne ^b 1981
Landfill	Drummed	\$0.64-\$0.91/gal (\$35-\$50/55 gal drum)	\$168-\$240
	Bulk	\$0.19-\$0.28/gal	\$55-\$83
Land treatment	All	\$0.02-\$0.09/gal	\$5-24
Incineration clean	Relatively clean liquids, high-Btu value	\$(0.05)-\$0.20/gal	\$(13) -\$53
	Liquids	\$0.20-\$0.90/gal	\$53-\$237
Chemical treatment	Solids, highly toxic liquids	\$1.50-\$3.00/gal	\$395-\$791
	Acids/alkalines	\$0.08-\$0.35/gal	\$21-\$92
	Cyanides, heavy metals, highly toxic waste	\$0.25-\$3.00/gal	\$66-\$791
Resource recovery	All	\$0.25-\$1.00/gal	\$66-\$264
Deep well injection	Oily wastewater	\$0.06-\$0.15/gal	\$16-\$40
	Toxic rinse water	\$0.50-\$1.00/gal	\$132-\$264
Transportation		\$0.15/ton mile	

^aInterviews were conducted in May of 1980 and February of 1982

^bFactors used to convert gallons and tons into tonnes are described in the appendix

^cSome cement kilns and light aggregate manufacturers are now paying for waste

SOURCE Booz, Allen & Hamilton, Inc

Table 35.—Incineration v. Treatment: Range of Estimated Post-RCRA Charges for Selected Waste Types

	Costs per tonne	
	Incineration	Treatment
Waste oils	\$94	\$40
Paint sludges	453	94
Nonchlorinated solvents	94	61
Chlorinated solvents	206	161
Cyanides	211	297

NOTE Cost estimates are based on surveys of commercial treatment and incinerator facilities in the Great Lakes regions. Costs reported reflect the surveyed industries estimates of their charges based on compliance with RCRA regulatory requirements for Interim Status facilities. No specific information provided about type of process or incinerator used or characteristics of wastes/residuals.

SOURCE Office of Technology Assessment from Hazardous Waste Management in the Great Lakes Region Department of Commerce September 1982

In cases where a waste can be easily detoxified, or energy value recovered, unit costs for treatment or incineration can be lower than unit costs for landfilling. At the low end of the cost range, unit costs for particular wastes can be roughly comparable. It is at the high end of the spectrum where unit costs diverge greatly between the landfill and the incineration alternative. For example, incineration of solid or drummed waste costs in the range of about \$400 to \$800 per tonne as compared with about \$170 to \$240 per tonne for landfill disposal.

Midrange unit costs for land disposal of undifferentiated bulk waste and roughly designated waste hazard classes range from about \$55 to \$83 per tonne. These costs are comparable to the unit costs for various waste treatment processes (table 35), which range from about \$34 to \$260 per tonne, depending on the waste type. Unit costs for thermal destruction of waste fall generally at the upper middle

range, e.g., generally between about \$100 to \$400 per tonne, although specific costs can be much greater or much lower. In particular, OTA found that emerging thermal destruction techniques may be less expensive than conventional incineration techniques [see "Emerging Thermal Destruction Technologies"].

Available information on waste disposal clearly indicates that land-based disposal is currently the predominant waste disposal method. Landfill costs are generally less than costs for treatment and incineration and there continues to be great debate about whether these lower costs include all the costs of landfilling. Some of the cost differences depend on factors such as the capital required to implement technology, whether it is being operated for commercial or private purposes, and personnel requirements. These are all factors affecting the cost of any technology option.

More specifically, the essence of the debate concerns the extent to which the still unfolding Federal regulatory policy affects market decisions for selection of waste technology. The current Federal program requires that all facility operators demonstrate financial assurance for closure and post-closure care, and that they carry liability insurance. The estimated costs of these requirements for specific facility types are discussed in chapter 7. Note that the costs to meet these requirements are expected to be greater for landfills and surface impoundments than for incinerator facilities. Some contend that current Federal policy favors the land disposal alternative; others that the financial assurance requirements and the insurance re-

Table 36.—Unit Costs Charged for Services at Commercial Facilities

Form.	Type	Landfill	Incineration
		\$/tonne	\$/tonne
Drum	Bulk	\$168-\$240	Drummed \$120-\$400
		\$55-\$83	Liquids \$53-\$400
	Acids/alkalis	\$13-\$120	Relatively clean liquids with high-Btu value \$(13) ^a \$53
	Odorless waste ^b	30	Liquids \$53-\$237
	Low risk hazardous waste (e.g., 011 and gas drilling muds)	\$13-\$29	Solids and/or highly toxic liquids. \$395-\$791
	Hazardous	\$30-\$80	
	Extremely hazardous	\$50-\$140	

^aHazard designation based on California's Classification system.

^bSome cement kilns and light aggregate manufacturers pay for these comparatively clean, high energy value wastes.

SOURCE Office of Technology Assessment, compiled from Booz, Allen & Hamilton, quoted prices from nine major waste management firms, 1981 and from the California Air Resources Board, August 1982

quirements are sufficient to correct imbalances between current and future costs for facility operators, Demonstration of financial capability for corrective action that may be necessary in the future at landfills and surface impoundments is not currently required by the Federal regulatory program, although the issue is being considered. Corrective action costs are estimated to be greater than the present value cost of either financial assurance for post-closure maintenance or liability insurance. Moreover, these corrective action costs are annual expenditures. Actual field data about the time required to mitigate contamination to an aquifer are limited, but estimates are generally on the order of many years. Thus, demonstration by a facility operator of financial capability to mitigate potential ground-water contamination could have a greater economic effect on the

facility operator than the financial or liability insurance requirements currently in place.

It should be noted that transportation costs to waste management facilities can be quite substantial, with long distances increasing direct costs by as much as 50 to 100 percent. In some locations, there may be no near alternatives to land disposal, and the added cost for transportation makes land disposal even more attractive economically. Also, the smaller the quantity of waste handled, the greater the per unit treatment or disposal costs. There are, however, new commercial enterprises aimed particularly at the small generator market, and various techniques can be used to reduce handling costs, including using trucks that deliver chemical feedstocks to pick up carefully labeled and separated hazardous waste.

Ocean Disposal and Dispersal

Early in the 1970's, concern was expressed about the rapidly increasing quantity and variety of material that was being disposed in oceans. During hearings on the Marine Protection, Research and Sanctuaries Act of 1972 (MPRA) testimony before Congress emphasized the fragile nature of the marine environment and our lack of knowledge about effects of ocean waste disposal on human health and ocean organisms. With passage of MPRA, the ocean was given the status of a "last resort" disposal option, to be considered only after other alternatives had been exhausted.

Ten years later, controversy about the appropriate level of ocean protection and use continues. A new understanding of potential environmental risk resulting from land disposal practices has led some to reconsider the ocean as a disposal medium. Interest in using oceans for hazardous waste management has increased as the volume of waste, land disposal costs, and opposition to land disposal sites have increased. Even some dedicated proponents of ocean protection acknowledge that the ocean has a role, albeit limited, in waste disposal man-

agement, if there are assurances that ocean resources, especially fish, are protected from destruction or from being made toxic to humans. Certain types of wastes may be better suited for ocean disposal than others. For the most part, however, current scientific information will not resolve uncertainties.

Current Usage

After passage of MPRA, control over ocean disposal became apparent by decreases in the volume (5 million tons in 1973 to 3 million in 1980) and decreases in approved disposal permits (332 in 1973 to 26 in 1980). Currently, ocean disposal in the United States involves the following types of material:

1. The disposal of material produced by dredging activities necessary to keep the Nation's ports and harbors operating.¹⁷⁶ Under regulations established by the U.S. Army Corps of Engineers, dredge spoils

*¹⁷⁶ Lee Martine, "Ocean Dumping A Time to Reappraise?" Issue Brief No. 1b81088, prepared for the Library of Congress, Congressional Research Service, 1982.

are transported by ship or barge to sites approved by EPA. These materials account for an estimated 80 to 90 percent of all U.S. waste deposited in the ocean and for the most part would not be considered hazardous under the RCRA definition. In 1981, it was estimated that only 5 percent of this type of material would be considered hazardous using bioassay techniques.¹⁷⁷

2. Sewage sludge produced by municipal secondary treatment plants. In New York and New Jersey, sludge waste is transported daily by ship or barge to an EPA-approved site in the New York Bight. The volume of waste disposed in the Atlantic Ocean has increased. These wastes could contain variable quantities of toxic constituents and pathogens that would pose hazards to the marine environment and public health.
- 3 The discharge of municipal waste and some industrial waste through pipelines to ocean outfalls. This activity is regulated by EPA under the Federal Water Pollution Control Act of 1972 (FWPCA). Waste disposal through ocean outfalls is a practice used in Boston, on the west coast, in Hawaii, and in Alaska. Along the southern California coast, for example, 30 outfalls discharge an estimated 4.5 billion liters of sewage and sewage sludge daily.¹⁷⁶ As of January 1981, there were 232 land-based dischargers whose outfalls entered the territorial sea and beyond; 74 of these were from industrial sources. This material can pose hazards.
- 4, The disposal of acids. This activity occurs at three EPA-approved sites off the east coast and Puerto Rico. Due largely to efforts to recycle acids, the volume of this industrial waste decreased by 49 percent between 1973 and 1979. Of 150 industrial

ocean disposal permits that existed in 1973, only 13 remained in April 1979.¹⁷⁹ Acids can be considered as suitable waste for ocean disposal since they can be neutralized through the large buffering capacity in the marine environment. The mode of discharge, from a barge or vessel, is designed to maximize the initial dispersion and dilution in seawater; there is usually little density difference between the waste plume and the surrounding surface water after the initial few seconds. Acid wastes are almost immediately neutralized by seawater.

5. Marine incineration of toxic waste aboard specially designed vessels. This is not really ocean disposal, but rather thermal destruction of organic material at sea. Within the United States, experience has been limited primarily to experimental "burns" involving organic chloride waste, Agent Orange, and, most recently, PCBs.¹⁸⁰ Constraints on this method are discussed in the previous section on thermal destruction.

Legislative Background

The belief that ocean dumping was threatening both the value of the marine environment and human health led to national and international measures to limit, if not prevent, the continued use of the ocean for disposal of waste. Such measures included:

1. MPRA;
2. the Convention of the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, known as the London Dumping Convention, ratified by the United States in 1974; and
3. FWPC, which regulates waste discharges within territorial seas.

¹⁷⁷National Advisory Committee on Oceans and Atmosphere, "The Role of the Ocean in a Waste Management Strategy," A Special Report to the President and Congress (Washington, D. C.: U.S. Government Printing office, 1981).

¹⁷⁸A. J. Mearns, "Ecological Effects of Ocean Sewage Outfalls: Observations and Lessons," *OCEANUS*, vol. 24, No. 1, 1981, pp. 44-54.

¹⁷⁹P. W. Anderson and R. T. Dewling, "Industrial Ocean Dumping in EPA Region II—Regulatory Aspects," in *Ocean Dumping of Industrial Wastes*, B. H. Ketchum, D. R. Kester, and P. K. Park (eds.) (New York: Plenum Press, 1981).

¹⁸⁰K. S. Kamlet, "Ocean Disposal of Organochlorine Wastes by At-Sea Incineration," in *Ocean Dumping of Industrial Wastes*, B. H. Ketchum, D. R. Kester, and P. K. Park (eds.) (New York: Plenum Press, 1981).

The EPA has responsibility to regulate ocean disposal so as:

... to prevent or strictly limit the dumping into ocean waters of any materials which would adversely affect human health, welfare, or amenities, or the marine environment, ecological systems, or economic potentialities [Public Law 92-532].

The disposal of certain specific wastes (including nuclear materials and most biological and chemical warfare agents) is prohibited, and ocean disposal of other types of waste may be considered only after all alternatives have been exhausted. Although the Army Corps of Engineers has the responsibility for disposal of dredge spoils, EPA was given the authority to approve all disposal sites, including ocean, land, and wetlands.¹⁸¹

EPA is directed to establish criteria for review of ocean-disposal permit applications. In establishing or reviewing these criteria, the EPA Administrator is required to consider at least nine factors specified in MPRA, six are related to the effects on human health and the environment, two relate to the availability and effects of alternative methods of disposal, and one designates appropriate ocean sites.

The system established by EPA provides four classes of ocean disposal permits:

1. general permits for the disposal of relatively innocuous waste;
2. special permits for waste that would not "unreasonably degrade" the marine environment, as determined by the types and concentrations of constituents present;
3. interim permits, generally conditioned on an agreement to phase out the particular dumping activity; and
4. emergency and research permits.

Only when reviewing interim permit requests will EPA take into account the need for disposal of a specific waste and the limitation of land-based alternatives.

¹⁸¹William L. Lahey, "Ocean Dumping of Sewage Sludge: The Tide Turns from Protection to Management," *Harvard Environmental Law Review*, vol. 6, No. 2, 1982, pp. 395-431.

In 1977, congressional concern centered on the progress being made in phasing out the dumping of sewage sludge in the ocean. Thus, amendments adopted that year gave legislative force to EPA's regulatory effort to impose an absolute ban on all ocean disposal of sewage sludge after December 31, 1981. The regulations implementing this ban were challenged, however, by New York City, which sought an extension of its interim permit to dispose of sludge in the New York Bight. The U.S. District Court for the Southern District of New York ruled in favor of New York City. The Court required EPA to give New York City an opportunity to present evidence indicating that disposal of its waste in the New York Bight had "relatively inconsequential effects" and that land disposal of this material might prove far more harmful to the environment and human health.¹⁸² EPA was required to consider "all statutory factors relevant to a reasoned determination," including the costs and dangers of land-based disposal. EPA did not appeal the decision and is now in the process of developing new regulations to replace those that were invalidated by the Court.

Controversy Over Ocean Use for Hazardous Wastes

Arguments in Favor of Increased Ocean Disposal

Experience and research data obtained over the past 10 years and still being accumulated contribute to the debate regarding appropriate use of oceans in waste management. Arguments in favor of greater use conclude that the marine environment has the capacity to assimilate hazardous constituents. The assimilative capacity may be defined as the amount of a particular material that can be contained within a body of seawater without producing an unacceptable impact on living organisms or nonliving resources.

A recent scientific assessment supporting this conclusion was reported by the Regional Seas Program of the United Nations Environmental Program.¹⁸³ The results of the 4-year

¹⁸²Ibid.

¹⁸³Webster Bayard, "World's Oceans Became Cleaner Over the Last Decade, Study Shows," *The New York Times*, Nov. 7, 1982, p. 26.

study suggest that oceans are able to assimilate toxic substances in most areas without extreme disturbance of the ecosystem. In addition, a number of scientists report that the ocean has a self-cleansing ability that would enable it to absorb waste without unacceptable consequences.¹⁸⁴

There is evidence that, in some instances, the marine environment can recover within a few years from pollution previously perceived as heavy.^{185 186} Studies of the outfalls in coastal areas suggest that short-term effects of sewage on marine plant and animal communities do occur. However, over the long-term these communities appear to have the ability to recover. For example, when discharge was initiated at the Orange County outfall in 1972 (at a depth of 60 m), it took a full year for fish and benthic infaunal communities to show adverse effects. Conversely, after cessation of 15 years of continuous discharge at another site (a depth of 20 m):

... the infauna changed from deposit-feeding-dominated communities to the normal, suspension-feeding-dominated communities within three to six months. Copper concentrations in sediments returned to background within a year; trawl catches of bottom fish also decreased, relative to background, within one to two years of discharge termination.¹⁸⁷

similar recovery was evident at the sewage sludge site previously used by the City of Philadelphia.¹⁸⁸ Two years after disposal was terminated:

... bacteria and virus levels had declined sufficiently for the Food and Drug Administration to lift restrictions on shellfishing.

Such responses, however, depend on the physical, biological, and chemical characteristics of the sites. For example, sites in the New York Bight have poor dispersion capability, high susceptibility to deterioration of ecosys-

tern conditions (e.g., oxygen depletion), and accumulation of persistent chemicals in marine sediment. In contrast, a site 106 miles offshore from New York City does have dispersion capabilities. Disposal of sewage sludge at this site might enable natural biological and chemical processes to incorporate sludge without detrimental effects.

These somewhat positive experiences with the disposition of constituent fate and their effects have bolstered the cause for greater use of the ocean in waste management. However, these experiences, for the most part, have little relevance to most hazardous waste. Some scientists argue that effective plans can be developed for disposal of highly toxic substances without endangering public health.¹⁸⁹ It is argued that information on marine pollution gained during the past 30 years provides a basis for developing models that can be used to determine the assimilative capacity of coastal waters. Supporters contend that, as more information accumulates about life processes in the ocean, it should be possible to identify pollution problems and formulate remedial actions.

Arguments Against Increased Ocean Disposal

While few would maintain that oceans should be completely excluded from waste disposal, there are arguments against increased use of the marine environment in waste management. The ocean's status as a global commons makes it more vulnerable to misuse. The "not in my backyard" attitude that works to block siting of land-based waste facilities does not exist for the ocean. Economics also emphasize this vulnerability. While prod disposal forces cite the growing differential between land and ocean disposal, it is pointed out that there is virtually no cost for an ocean site itself; thus that option will always be cheaper than land-based alternatives.

The suggestion that managers now have adequate data and reliable models to predict and understand the effects of dumping in the ocean

¹⁸⁴Lahey, op. cit.

¹⁸⁵Mearns, op. cit.

¹⁸⁶W. Bascom, "The Effects of Waste Disposal on the Coastal Waters of Southern California," *Environ. Sci. & Technol.*, vol. 16, No. 4, 1982, pp. 226A-236A,

¹⁸⁷Mearns, op. cit.

¹⁸⁸Lahey, op. cit.

¹⁸⁹E. D. Goldberg, "The Oceans as Waste Space: The Argument," *OCEANUS*, vol. 24, No. 1, 1981, pp. 2-9.

also is disputed. The argument that current data show that impacts of disposal are less than anticipated 10 years ago is criticized on the basis that research efforts have not been sufficiently sophisticated to provide sound evidence.

The usefulness of existing models for assimilative capacity is also questioned. Such models attempt to describe the ocean's ability to achieve acceptable levels of concentration and distribution of hazardous substances. A number of weaknesses have been noted:¹⁹⁰

1. the lack of empirical data, limiting efforts to estimate appropriate concentrations of hazardous contaminants;
2. the lack of information on long-term fate of constituents and effects on the marine environment;
3. only single constituents are considered, ignoring any synergistic effects and thus, possibly underestimating damage to the environment; and
4. uncertainties about the relationship between amounts of waste deposited and the environmental response; unanticipated delayed responses can result in serious underestimation of environmental impacts.

It has been suggested that the assimilative capacity concept is useful as an organizing principle.¹⁹¹ If it is used to focus research and monitoring on relevant questions, the concept is beneficial. It can also be valuable in defining the lower limits of accepted environmental concentrations in the marine environment. Critics argue, however, that assimilative model assessments cannot, now or at any time soon, serve as a sufficient basis for predicting the hazard potential of persistent substances in the marine environment. A particularly important criticism is that such modeling may not reveal delayed concentrations of toxic substances in surprising places and ways.

¹⁹⁰Lahey, *op. cit.*

¹⁹¹K.S. Kamlet, "The Oceans as Waste Space: The Rebuttal," *OCEANUS*, vol. 24, No. 1, 1981, pp. 10-17.

There is a belief that the assimilative capacity concept is already failing.¹⁹² Assessments of single-constituent effects will not provide sufficient information; there are hazardous constituents existing in various forms being released in combination at different locations. A solution suggested by critics would be to develop closed systems that would eliminate any release of hazardous compounds from any disposal medium to the environment. With this approach:

... the costs of managing, including recovering or storing or detoxifying wastes, are appropriately assigned to the products of the industry, not diffused as a general cost onto the public at large.¹⁹³

Proponents of continued strict limits on ocean disposal do not suggest that the oceans should be inviolate. The value of multimedia management is recognized, but initial comparisons of the environmental merits of the various options are necessary. Once the medium of choice is determined, other relevant factors, including economics and technological feasibility, should be considered. There is clearly more support for using the oceans for the less hazardous, biodegradable (and less controversial) waste than for substances such as PCBs,

Effective management of ocean-disposal activities should be preceded by a thorough understanding of the fundamental biological, chemical, and physical processes in the marine environment. While such understanding has improved significantly during the past 10 years, particularly for deep-ocean waters, little or nothing is known about the long-term fate of these wastes "or the capacity of these pelagic oceanic regions to assimilate wastes without detrimental effects."¹⁹⁴ particularly, there is a

¹⁹²G. M. Woodwell, "Waste Disposal: Time for a New Approach," adapted from remarks made before joint meetings of the American Geophysical Society and the American Society for Limnology and Oceanography, San Antonio, Tex., Feb. 17, 1982.

¹⁹³*ibid.*

¹⁹⁴D. R. Kester, B. H. Ketchum, and P. K. Park (eds.), "Future Prospects of Ocean Dumping?" in *Ocean Dumping of Industrial Wastes* (New York: Plenum Press, 1981), pp. 505-517.

need to improve the assessment of the biological effects of pollutants in the marine environment. Current information, therefore, shifts the burden to potential users of the ocean to document and defend such use.

Future Research and Data Needs

This reassessment of the ocean's potential for waste disposal comes at a time when there are growing limitations on and increasing problems with land-based methods. More recent legislation than MPRA—i.e., SWDA and RCRA—have imposed new and stringent regulation on land-based disposal of waste. Well-publicized incidents such as the Love Canal have caused public acceptance of landfills and other waste disposal facilities near residential areas to plummet. It is recognized that the high probability that land-disposal activities might decline during the 1980's, may increase interests in ocean-waste disposal.¹⁹⁵ A Federal program is needed that would emphasize research and monitoring before allowing disposal of the most hazardous waste in various oceanic environments.

Because of the high value placed on marine biota as a resource, "the biological consequences of ocean dumping are generally regarded as establishing the acceptable limits of waste disposal in the marine environment." Thus, determining what biological parameters should be measured is seen as a major scientific problem. The International Council for the Exploration of the Seas identified four classes of data needs:

1. Bioassay measurements, ranging from determination of lethal concentrations for particular organisms to changes in growth rates brought about by various concentrations of a waste. Where possible, more extensive tests should address synergistic effects of multiple contaminants.
2. Physiological techniques for measurement of growth, scope for growth, and feeding rates—considered the best techniques for

assessing biological effects of contaminants on fish, crustaceans, polychaetes, and mollusks.

3. Biochemical measurements, such as reproductive biochemistry, hormone metabolism, and blood-chemical analyses.
4. Ecological assessments—the most direct and comprehensive approach to determining effects of constituent, but difficult to implement.

Several programs are available for obtaining these types of data and include EPA's discharge permit program (characterized as a load-assessment approach), the baseline studies program of the Bureau of Land Management (trend-assessment approach to identifying impacts), and the National Marine Fisheries Service strategy to assess the "health" of fisheries resources on the basis of periodic environmental measurements of selected parameters.

Past experience in "crisis response" may provide useful information for considering ocean disposal of hazardous waste.¹⁹⁶ Identification of common factors in environmental crises concerning mercury poisoning and contamination by DDT, PCB, and Kepone, if recognized and considered in future monitoring strategies, could lead to earlier warning of adverse impacts from ocean disposal. In each of these examples, there was a lack of understanding of the movement of the contaminant in the marine environment and of sensitive organisms or critical factors leading to the observed impact. Thus, future monitoring should be designed to consider fate of constituents and to identify the sensitive points in the ecosystem for each constituent of concern.

Certain types of waste maybe better suited for ocean disposal than others.^{*197} Water and air are dispersal media, whereas land is a containment medium. Waste management should consider whether a persistent toxic material is best disposed in a dispersal or a containment medium. For persistent synthetic

¹⁹⁵National Advisory Committee On Oceans and Atmosphere, 1981, op Cit.

^{*197}Kester, op. cit.

¹⁹⁷K. S. Kamlet, "Constraints on the Ocean Dumping of Hazardous Wastes," prepared for presentation at the Northeast Conference on Hazardous Waste, Ocean City, N.J., 1982.

chemicals, such as PCBS, Kepone, and DDT, isolation and containment or destruction to the fullest extent possible may be preferred to ocean disposal. For persistent, naturally occurring materials, such as heavy metals and petroleum hydrocarbons, a reasonable argument might be that dispersal is sensible. However, large or continuous additions of even such materials can produce harmful departures from background levels, particularly on a localized basis. For certain amounts of nontoxic or biodegradable materials, the assimilative capacity of specific ocean locations may be adequate. Acids, alkalis, and nutrients are examples. A management philosophy aimed at maximizing dispersal of such materials, while avoiding disruption of local ecological systems, might be most sensible.

When considering possibly acceptable ocean-disposal activities, it is also necessary to consider the various advantages and disadvantages of different sites. For example, shallow, continental-shelf waters offer the advantages of being better understood, based on experience and scientific research, requiring low-to-moderate transportation costs, and a localization of potential detrimental effects.¹⁹⁸ On the negative side, the resource value of these areas is typically greater. There also is a tendency for substances to accumulate in bottom-living organisms and sediments in these locations. Deep-ocean waters, on the other hand, offer the advantage of broader dispersion and dilution of waste and reduced conflicts with other marine resources. Disadvantages include uncertainties about the ultimate fate and effect of waste, with potential large-scale impacts, and a likely greater effect on planktonic and bottom-living organisms.

Technical Regulatory Issues

It is recognized that a number of important issues should be resolved before proceeding with widespread or indiscriminate use of the oceans for hazardous waste management. Thus, a current study recommends that:

Before it is too late and major investments

are made which may tie us into a long-term commitment, it would be best to:

1. test predictions against field experiments;
2. develop a waste management plan for coastal areas which considers effects of all pollutant sources;
3. design delivery systems which will minimize environmental degradation;
4. continue to work on developing pretreatment techniques that will 'per-m-it waste material to be considered as a resource rather than a waste.'¹⁹⁹

Scientists must determine what additional information is needed to evaluate oceanic discharge under the condition that oceanic resources must be maintained in renewable states and threats (even if long term) to human health are minimized. What are the long-term effects of the very low levels of constituents in the sea? What are the synergistic and antagonistic effects of collectives of constituents? While both general and specific stress indicators are available, such as those for metals and petroleum components, there remains a need to identify specific indices applicable to individual or classes of constituents. Work should be done to compare alternate ocean-disposal strategies, such as dispersing waste above or beneath the thermocline.²⁰⁰ Federal actions that should precede any widespread movement to use oceans for hazardous waste management include:²⁰¹

1. assessing the state of pollution in U.S. coastal and deep-ocean waters;
2. precisely defining present standards and criteria in terms of specific constituents and regional bodies of water;
3. developing an information system to routinely report what has been learned;
4. coordinating all research to achieve the maximum results from limited research funds;
5. implementing a cost-effective network of coastal water-quality monitoring;
6. simplifying regulatory procedures; and
7. continuously evaluating and reevaluating water-quality standards.

¹⁹⁹R. L. Swanson and M. Devine, "The Pendulum Swings Again: Ocean Dumping Policy," *Environment*, vol. 24, June 1982, pp. 14-20.

²⁰⁰Kester, op. cit.

²⁰¹J. P. Walsh, "U.S. Policy on Marine Pollution: Changes Ahead," *OCEANUS*, vol. 24, No. 1, 1981, pp. 18-24.

¹⁹⁸Kester, op. cit.

Uncontrolled Sites

This section discusses methods for the identification, evaluation, comparison, and remediation of uncontrolled sites. A number of policy issues associated with the CERCLA legislation and its implementation by EPA and the States are discussed in chapters 6 and 7. The objective of this section is to consider several technical areas related to cleaning up uncontrolled sites, including the problems of identifying sites, developing plans for cleanup, and selecting remediation technologies, *

The magnitude of the uncontrolled site problem is generally recognized to be substantial. Although the precise number has not been determined, there are probably some 15,000 uncontrolled sites in the Nation requiring remediation. Costs of remediation vary greatly but will probably average several million dollars per site. ** The total national cost of cleaning up uncontrolled sites is probably in the range of \$10 billion to \$40 billion, far more than the current \$1.6 billion estimated to be collected under IERCLA by 1985. A recent congressional analysis revealed that, through FY 1982, only \$88 million of \$452 million collected under CERCLA had been expended for cleanup, no cleanup funds had been earmarked or expended on 97 of the initial 160 priority sites determined by JPA, and only 3 CERCLA sites had been totally cleaned up (1 entirely with State funds).²⁰²

•For the purposes of this discussion, emergency response and immediate "removal" are not considered as remediation of a site. They are conventional actions associated with accidents and spills to remove immediate threats, generally followed by more technology-intensive and systematic efforts. Also, those activities defined within EPA's National Contingency Plan as "initial remedial" will not be considered as distinct, technologically, from remedial control technologies. Differences between these technologies concern timeframes, funding sources, and regulatory approaches rather than substantial technical differences.

•*For example, the cleanup of one of the initial 160 priority sites, the Seymour site in Indiana, is estimated by EPA to cost 2.7 million to remove 60,000 barrels of wastes and to clean up contaminated soil and ground water beneath the site. An example of a less costly remedial action is the Trammel Crow site in Texas where five sludge pits with over 5 million gal of waste were cleaned up onsite using a solidification process and cost 78,000. In both cases additional moneys were spent for initial studies of the sites.

²⁰²Study by the House Subcommittee on Commerce, Transportation, and Tourism, as reported in Hazardous Waste Report, IV, 1, 1982.

Uncontrolled sites fall into three categories:

1. Operational uncontrolled sites are those hazardous waste sites requiring, but not currently receiving, attention to ameliorate dangerous conditions. Either ongoing releases to the environment or the threat of imminent releases of hazardous waste would constitute such conditions,
2. Inactive sites are those sites no longer receiving hazardous waste and for which there is an identifiable responsible party or owner.
3. Abandoned sites are uncontrolled hazardous waste sites where no responsible party or owner has been identified, or where such parties lack the resources to take the steps needed to remedy dangerous conditions at the site.

Issues Concerning Effectiveness

The national effort to clean up uncontrolled sites is in its early stages. The magnitude of the problem, in terms of potential harm to human health and the environment and of potential costs of cleanup, is such that it is imperative to give considerable attention to three major issues, which are discussed below:

1. What basis should be used to determine the end point for a remedial action? This is sometimes asked as the question "How clean is clean?"

This question of extent of cleanup is often addressed by defining some nonharmful, or acceptable, level of contamination that may be left at a site after remedial actions are terminated. This approach, however, can be difficult to apply since the toxicological effects of many wastes and of low levels of some wastes are unknown. This could lead to somewhat arbitrary choices of acceptable residual chemical contamination.

Extent of cleanup can also be considered from the perspective of protection of the public and the environment in a cost-effective way. This may be accomplished by various approaches, such as:

- An alternate water supply might be provided for a community using contaminated ground water, rather than cleaning the original supply. Such an approach might be appropriate for small numbers of water users, particularly when there might be a natural reduction of the contamination in time (e. g., with biodegradable organic waste). Sometimes outright purchases of the affected homes might be the most efficient way to accomplish the goal of limiting human exposure.
- Parties responsible for a number of sites might propose a partial cleanup, less than might be necessary to eliminate all potential future risk. Thus, buried drums and the most contaminated soil might be removed, without extensive ground-water recovery and treatment. Long-term environmental monitoring then would be provided to assure that there is no release in excess of predefined action levels.

2. How can the relative cost-effectiveness of alternative cleanup approaches be determined?

There are many difficulties in trying to analyze the economics and cost effectiveness of various remediation options. There is no question, however, that the costs of remediating uncontrolled waste sites are high. For example, the initial phases of site identification, evaluation, and assessment may cost from \$50,000 to several hundred thousand dollars. The preliminary engineering efforts taken before remediation may cost several hundred thousand dollars more, and actual remediation generally costs from several hundred thousand dollars to several million dollars per site. There has not been enough accumulated experience to quantify and compare how effectively different technologies reduce risks. Some of the factors that affect analyses of cost effectiveness include:

- public policy regarding the level of acceptable risk subsequent to a site remediation remains unclear;
- the operating history of cleanup technologies at uncontrolled sites has not been sufficiently documented;
- the degree of success of the various technology options is sometimes site-specific. Therefore, the comparison of alternate technologies for a specific site remediation cannot always be extrapolated into a valid generic comparison;
- the long timespans involved in some of the technologies require assumptions regarding their long-term effectiveness. Some of the technology options generate future operation, maintenance, and monitoring costs that are difficult to estimate; and
- the possibility of systems failure and the need for subsequent remediation are difficult to predict. Only crude estimates of these potential “second-round costs” are available for comparison.

3. Which current technologies may create future problems? Some technological choices could create needs for future remediation, for extended operation and maintenance procedures, with continuing risks and costs.

The choice of a technology for site remediation can result in the need for certain long-term commitments. Such requirements might include physical maintenance of the grounds and site security if residuals of hazardous waste or other potential hazards remain after site remediation. Further, certain technologies, by virtue of the time needed for implementation (i.e. ground water recovery and treatment), involve long-term operation and maintenance costs. Also, there is a continuing level of risk during the implementation of these long-term technologies. These deferred costs, as well as the possible costs for alternate remedial technology if the initial control technology fails, should be considered when making a choice between an initially more expensive remediation (e.g., excavation with offsite disposal or treatment) and a long-term technology with lower initial costs (e.g., encapsulation).

Taking remedial actions that are effective in the long term is advisable because new uncontrolled sites are likely to be identified, requiring still further expenditures in the future. Current practices of land disposal of hazardous waste may be creating future needs for reined

al action. Disposal sites, even state-of-the-art installations meeting regulatory standards for design, operation, closure, and post-closure monitoring, do not always eliminate the possibility of releases of hazardous materials into the environment. Moreover, because of a number of exemptions in RCRA itself and of those resulting from administrative decisions, hazardous wastes are being disposed in subtitle D sanitary landfills that are not designed for hazardous waste. Such facilities have already accounted for large numbers of uncontrolled sites, and others will likely become uncontrolled sites.

Site Identification and Evaluation

The amount of information available regarding uncontrolled sites (e. g., location, number, and level of hazard) is generally recognized to be incomplete. There are continuing efforts at both the Federal and State levels to identify uncontrolled sites, with the problem being acute for abandoned sites for which there are no responsible parties available to provide detailed information (see ch. 7). It is generally accepted that many thousands of uncontrolled sites exist.

There are three means of identifying uncontrolled sites:

1. Federal and State efforts to prepare inventories of sites based on file information or on field investigations;
2. reporting by the general public and by parties such as developers that may discover sites accidentally; and
3. requirements that industries producing or managing hazardous wastes submit information on sites either created by them or known to them.

Following the identification of a problem site, considerable data is required for evaluation of the level of hazard posed by the site. Relevant data include both physical and descriptive factors. Physical considerations include the population or environment at risk; critical pathways; site conditions, including hydrogeologic characteristics; waste amounts,

forms, and compositions; and evidence of actual releases, Table 37 summarizes the types of data required. Nontechnical descriptive information might be collected concerning history of the site, ownership, adjacent properties, previous administrative or legal actions, associated potentially responsible parties such as generators and waste haulers, and other relevant background information. These nontechnical types of information are important for obtaining more detailed technical information, as

Table 37.— Data Required To Identify and Evaluate Uncontrolled Sites

Type of data—specific factors

Site **assessment**:

Wastes:

- Quantity
- Core position
- Form
- Condition of waste (containerized, bulk, buried, open lagoon)
- Acute hazards (acute toxicity, flammability, explosiveness, etc.)
- Chronic cumulative hazard (toxicity, mutagenicity, carcinogenicity, teratogenicity, radioactivity, etc.)
- Synergistic/antagonistic components

Site:

- Geological features
- Topographical features
- Vegetation
- Surface water
- Ground water
- Structures
- Access

Exposure:

Releases

- Past or present releases
- Potential for future releases
- Migration routes of releases (air, ground water, surface water, overland flow or runoff, etc.)

Potential exposure:

- Estimates of release quantities
- Exposure routes

Risk:

Environments:

- Waters
- Land areas
- Air
- Vegetation
- Wildlife
- Agricultural areas
- Recreational areas

Populations:

- Location
- Sensitivity
- Numbers

well as for other purposes, such as enforcement actions. This is necessary because site inspections are difficult, costly, and sometimes dangerous, and because there often is no immediate source of technical information.

A site inspection to observe surface conditions may include:

- sampling of wastes, and surface and ground waters,
- air monitoring,
- some random excavation to identify buried materials,
- magnetic surveys to locate buried metal (possible containerized material),
- resistivity surveys (to determine whether there is underground contamination), and
- an assessment of site conditions in general.

Determining what a site contains can present substantial problems of sampling and analysis. Only a limited number of samples can be taken because sampling itself can pose risks of release of hazardous materials from the site. With hundreds or thousands of drums that are often unmarked, and a relatively small number of samples taken, there is no assurance that analysis will accurately indicate the hazardous contents of the site, or that any hazardous materials will be discovered. There are also substantial problems concerning the detection of hazardous materials in underground water supplies. There is no consensus on drilling methods, sampling frequency or protocol, standard quality assurance procedures, or the number of wells needed to define problems. Drillers run the risk of contaminating clean aquifers while drilling into polluted ones.

There are also considerable problems concerning chemical analysis. Standard methods such as mass spectroscopy do not necessarily yield useful results for many chemicals. Newer, sophisticated laboratory procedures may require laboratory facilities not available to investigators. There are few standard testing procedures for complex waste constituents. Waste may contain byproduct chemicals, or altered chemicals, and laboratories may not have standards for their identification. There are indications of substantial problems concerning

quality control in both government and private laboratories.

Techniques for the comparison of sites often involve the combination of various "weighted" components of hazard into a single numerical measure for a site. Such values for various sites are compared in order to produce a ranked listing, from which remedial priorities are then established. (see chs. 6 and 7 for discussions of hazard evaluations, risk assessment, and ranking systems),

Site Cleanup Plans

Once a decision is made to proceed with remedial action at a site, it becomes necessary to establish a step-by-step procedure for implementation. The basic steps in remedial action or site cleanup are:

1. preliminary assessment,
2. feasibility study,
3. engineering design,
4. construction,
5. startup, trouble shooting, and cleanup, and
6. possible long-term operation and maintenance.

Following assessment and the decision to effect remediation, the feasibility study would identify alternative engineering options for mitigation, including limitations, costs, and effectiveness. The feasibility study should evaluate the various remedial technologies for the specific conditions at the site under consideration. The basic technological options are:

1. removal followed by appropriate disposal or treatment—e.g., fixation, neutralization, or any other conventional technology, or by treatment of the waste on the uncontrolled site (see discussion earlier in this chapter);
2. pathway control through encapsulation or containment, or by ground or surface water diversion;
3. mitigation of exposures by providing an alternate water supply, land use restrictions, or evacuation of people;

An important issue concerning the choice of remedial technologies, because of current EPA

policies (see ch. 7), is the difference in initial, capital costs v. longer term operating and maintenance (O&M) costs. The specifics of O&M depend on the technology chosen. Those technological options that permanently deal with the hazard often have high initial costs and low O&M costs. Conversely, those options that, for example, do not destroy or treat the waste to reduce risks are likely to have high and uncertain O&M costs. For example, excavation and removal followed by treatment or disposal would initially be both capital-intensive and labor-intensive, but subsequent O&M requirements would be minimal. Alternatively, encapsulation with ground water recovery and treatment would generally incur lower initial costs but have subsequent large O&M costs.

Implementation of engineered remedial activities at a site may require a wide variety of ancillary and support activities, depending on the conditions at the specific site and the choice of control technology. Epidemiological studies may be required when there has been a release of hazardous waste that may have affected public health or if there is a need for baseline data to monitor future effects arising from the choice of site-control technology. Chemical analysis may also be needed for many purposes, ranging from quality control work during cleanup, protection of onsite workers exposed to hazardous materials, to verification that the intended level of cleanup has been reached.

Technical Approaches for Remedial Control

The following review and discussion of the generic technology options is based on consultations with professionals working in the area of uncontrolled site remediation, a recent study for EPA of remediation technologies,²⁰³ and proceedings from annual conferences on uncontrolled hazardous waste sites.²⁰⁴ Any technological option for site remediation has limitations that will keep it from being effective under all circumstances. Examples of technol-

ogies are discussed below, and a summary of the advantages and disadvantages of primary technological options is given in table 38. A recent survey of technologies used at uncontrolled hazardous waste sites indicates the distribution of currently used technologies, as shown in table 39. These technologies may be grouped into two broad categories:

- . waste control technologies; and
- . environmental pathway control.

Waste control technologies for uncontrolled sites act on the amount of waste or on some hazardous property or constituent of the waste. Such methods include:

- Excavation and removal offsite of the hazardous waste.—This method is suitable for all sites with containerized or bulk disposal of waste. Normally it must be followed with some type of secondary clean-up of ground water if the materials deposited were water soluble, and evidence shows ground water contamination. While such techniques eliminate or minimize both future O&M costs and future risk to the public and environment, there are high initial costs, with possible higher risk of exposure during the period of excavation. To some degree, risk may be relocated depending on the offsite disposal option chosen. Populations and environments along routes chosen for transportation between sites and disposal facilities are exposed to risk of spills while wastes are in transit. Those responsible for the remedial action become generators under the provisions of RCRA with all the associated responsibilities and liabilities. Such methods are neither cost effective for large amounts of low-level hazardous waste, nor for uncontainerized buried waste dispersed through a large area.
- Excavation with onsite treatment.—This approach can be used for some onsite treatment technologies such as fixation, use of mobile treatment units for physical or chemical treatment or incineration, or for site preparation and lining prior to reinterment. Such methods can expose wastes quite efficiently to a treatment

²⁰³Environmental Protection Agency, "Handbook—Remedial Action at Waste Disposal Sites," EPA 625/6-82-006, June 1982.

²⁰⁴These volumes are published by the Hazardous Materials Control Research Institute, Silver Spring, Md.

Table 38.—Advantages and Disadvantages of Control Technologies

Type	Advantages	Disadvantages
Waste control technologies:		
Excavation and removal followed by treatment or disposal	a) Good for containerized or bulk disposal	a) High initial costs b) Potential higher risk during cleanup c) Relocation of risk unless waste is treated d) Not cost effective for low-level hazardous waste or uncontainerized buried waste in large area
Excavation with onsite treatment option	a) Expose waste to complete treatment b) No off site exposure	a) High initial cost b) Difficult to assure monitoring effectiveness c) Some risk of exposure d) Not cost effective for large amount of low-hazard waste
Neutralization/stabilization	a) Useful in areas where waste can be excavated prior to mixing b) Low risk of exposure if injection method is used	a) Limited application b) Requires long-term land use regulations c) Eventual off site migration if reaction is incomplete
Biodegradation	Low costs	Difficult to maintain optimum conditions to keep reaction going
Solution mining	Useful in homogeneous uncontainerized solvent-soluble, buried solid hazardous waste	Can result in uncontrolled release
Environmental pathway (vector) control:		
Isolation, containment, and encapsulation	Useful for large volumes of mixed hazardous and domestic waste, and low-hazard waste	a) Effectiveness depends on physical conditions at site b) Long-term O&M needed
Ground water diversion and recovery	Useful if soils are permeable or if there are high or perched water tables	a) Requires wastewater treatment option b) Process is slow c) O&M monitoring d) Not effective for insoluble or containerized material
Surface water diversion	a) Easy to implement b) No transport of waste off site	Can create flooding off site
Ground and surface water treatment	a) Can be used onsite or off site	a) May generate hazardous sludges, spent carbon b) Long-term monitoring
Gas collection or venting	Low costs	a) Site safety and fire hazards b) Off site air pollution c) Long-term monitoring and O&M

O&M—operating and maintenance

SOURCE: Office of Technology Assessment

process and, in some cases, may be less expensive than excavation followed by transportation to an offsite treatment facility. offsite populations are not exposed to possible spills. Future O&M costs are eliminated with future risks if waste destruction or detoxification options are also implemented. There is a high initial cost, and long-term monitoring is required when the reinterment option is chosen. Local population is subject to additional risks inherent in the excavation and exposure of buried waste, as well as those inherent in the

mobile treatment process chosen. This technology is not cost effective for large amounts of low-level waste and is not effective for uncontainerized waste dispersed through a large area.

- **Direct neutralization/stabilization/fixation.**—This technology is used primarily for large volumes of homogeneous uncontainerized liquids or sludges. Agents are injected directly into the ground where wastes are buried. Neutralization, an acid-base balancing mechanism, aids in the removal of hazardous constituents through

Table 39.—Types of Remedial Action Employed at a Sample of Uncontrolled Sites

Remedial action	Number of sites ^a	Percent of total
Waste actions:		
Drum and contaminant removal	126	410/0
Contaminant treatment	48	16
Incineration	3	1
D r e e d g i n g	5	2
Action on route of release:		
C a p p i n g / g r a d i n g	59	19
Ground water pumping	22	7
Ground water containment	23	8
E n c a p s u l a t i o n	8	3
Gas control	3	1
L i n i n g	7	2
	304	100/0

^aAs many as 25 spill sites may be included

SOURCE S R Cochran, et al., "Survey and Case Study Investigation of Remedial Actions at Uncontrolled Hazardous Waste Sites." In *Management of Uncontrolled Hazardous Waste Sites*, Hazardous Materials Control Research Institute, 1982 pp 131-135

precipitation. Fixation immobilizes soluble waste by binding them with a stable material. Thus, an immobile solid is formed. Onsite applications eliminate the need for offsite disposal areas or for site upgrading following removal of excavated materials. There is low risk of exposure to buried waste when the injection option is chosen. However, the technology has limited application and requires long-term land use restrictions at the site along with environmental monitoring. Reaction or immobilization may be incomplete, and there may be eventual breakdown and stripping from repeated flushing by ground water, resulting in subsequent offsite migration of hazardous waste.

In addition, other detoxification techniques to be used at the site are being researched. One method is a chemical dechlorination or dehalogenation process which uses a sodium or potassium polyethylene glycol reagent. The sodium reagent (NaPEG) patented by the Franklin Research Institute. EPA has been working with the Institute to find a faster acting reagent using potassium. In the envisioned practice, the reagent would be spread over a spill or dump site. Perhaps it would be covered for rain protection and to raise temperature, and perhaps reapplied in several days. In principle, a series of reactions

takes place, replacing at least some of the chlorine atoms with the reagent glycols theoretically forming less toxic and less bioaccumulative compounds. In unpublished EPA testing, a solution of 1,000 ppm hexachlorobenzene was destroyed with 95 percent efficiency in 7 days at room temperature, and reapplication achieved completion.²⁰⁵ However, the chemistry of this process at ambient temperatures and in the presence of water has yet to be proven, and little has been published. Important questions concerning the composition of the resulting compounds and their toxicities remain to be studied. Further, these reagents have not yet been applied outside the laboratory.

- **Biodegradation.**—Microbial degradation techniques have been applied to uncontainerized, biodegradable organic waste, usually for spills. It possibly might be used as a final step to remove low concentration residuals left at sites after the use of other technologies, such as excavation with offsite disposal or ground water recovery and treatment. Biodegradation is usually a low-cost option. However, the method requires acclimated organisms, and supplemental injections of nutrients or oxygen may be required to support biological action. The limited applications are slow and are affected by ambient temperature.
- **Solution mining.**—This method is restricted to limited (and unusual) situations where a homogeneous, uncontainerized, solvent-soluble, solid hazardous waste is buried. Solvent is injected into the site and recovered through a series of well points. Various applications of this technology use water as the solvent. Caution must be taken that dissolving nonmobile hazardous waste does not produce an uncontrolled release or leave behind dissolved and mobile material.

Environmental pathway control for hazardous waste sites attempt to inhibit offsite migration.

²⁰⁵Charles Rogers, Environmental Protection Agency, Office of Research and Development, IERL, personal communication, January 1983.

tion of hazardous materials by a number of methods, as discussed below. The most common route amenable to such controls is water—surface, ground, and rainwater; although gas controls are sometimes used at sites where methane or other gases are present. In most cases, there is a continuing need for monitoring and potential need for repeated remedial actions. Pathway control technologies include:

- Isolation, containment, and encapsulation techniques.—Mechanical barriers—e.g., in capping, bottom sealing, and perimeter containment barriers—use natural materials (e. g., clay) or synthetic impermeable materials (e. g., asphalt, cement, polymer sheet, chemical grout) that are either poured, injected, or placed into desired locations to provide containment or inhibit water intrusion on buried hazardous waste. Surface contour modifications and revegetation are used to enhance rainwater runoff or to capture it for subsequent removal via natural processes of evaporation and transpiration. Such methods are used in those situations where no onsite treatment or removal is planned or where there is a need to contain residuals from such actions. They are most practical at sites with extremely large volumes of mixed hazardous and domestic wastes or with widespread low-level contamination (e.g., mine tailings or contaminated soil) where costs of alternative actions are prohibitive. The costs of these techniques are favorable compared with those of other options, and exposure of buried waste is not required. The effectiveness of these methods, however, is greatly dependent on ambient environmental conditions, such as geohydrology, precipitation, and geomorphology. Long-term O&M as well as long-term monitoring are required.²⁰⁶ Failure

²⁰⁶A recent study on the use of slurry wall installations concluded: "Unfortunately, most of the slurry wall installations to date have been in the private sector, from which little monitoring data are available. Until such data are assembled and critiqued, it remains to be seen just how effective, and how long term this remedial measure is in controlling the spread of contaminated ground water." P. A. Spooner, et al., "Pollution Migration Cut-Off Using Slurry Trench Construction," in *Management of Uncontrolled Hazardous Waste Sites*, Hazardous Materials Control Research Institute, 1982, pp. 191-197.

may require additional remedial action. Security for this approach, where the water route is of concern, can be enhanced by combination with a ground water recovery and treatment system.

- Ground water diversion and recovery.—These methods make use of collection and diversion trenches or of well points with pumping, and sometimes in combination with subsequent up-gradient injection or percolation ponds to shift piezometric surfaces. The technology is useful in situations where underlying soils are permeable (e.g., sands or fractured shales where well points may be used) or at sites with a high or perched water table and underlying clay or other tight formations where trenches may be used. These diversion methods are effective for collecting highly contaminated leachate before dilution after mixing with main body of ground water. Effective recovery can be enhanced with up-gradient injection. Ground water flow rates consequently are increased, and an augmented volume of flush water is provided to wash soluble hazardous constituents from the site to the collection system. This technology generally requires waste water treatment, although collected water can be directly discharged to a surface stream if it meets applicable discharge standards. The process is slow and requires O&M and constant monitoring of the collection system and the offsite environment. It is not effective for containerized materials or insoluble waste.
- Surface water diversion.—These diversion methods are used where surface streams run through or near an uncontrolled site. Such systems are relatively easy to implement with existing technology. Addition of undesirable water on the site is not required, and associated offsite transportation of hazardous materials is reduced. However, offsite flooding problems may be created.
- Ground and surface water treatment.—These treatment methods may be used where there is a system to recover contaminated water and may be implemented either offsite or onsite. Treatment technol-

ogy is the same as for other aqueous wastes—biological, al, carbon absorption, physicalchemical, or air stripping. Various levels of treatment can be chosen in combination with appropriate collection methods. Effectiveness is limited by the ability of the associated collection system to contain and recover the hazardous waste. There have been some operational problems where waste characteristics vary, as is often encountered at hazardous waste sites that have a history of receiving mixed waste, although batching and equalization can minimize this problem.

- Hazardous waste in the form of sludges and spent carbon may be generated.
- Gas collection or venting.—These methods are used for collection of gases for treatment, or for controlled venting of gases generated at a site from decomposition of organic matter or from chemical reactions of waste. Such technologies provide methods of handling toxic or flammable gases that may present site safety and fire hazards as well as offsite air pollution threats. Long-term monitoring is required, and there are O&M costs.

Appendix 5A. —Case Examples of Process Modifications

Chlor-Alkali Process

The production of chlorine and sodium hydroxide is an important process in the chemical industry. These chemicals are major materials for the manufacture of many different consumer and industrial products such as pulp and paper, fibers, plastics, petrochemicals, fertilizers, and solvents. The production process is a large-scale system in which modifications have been extensively implemented in the past to achieve higher process efficiencies. Significant reduction of hazardous waste generation is possible through still further process modifications,

The chlor-alkali process is based on electrolysis of brines—i.e., an electric current is passed through a solution of sodium chloride to produce chlorine, hydrogen, and sodium hydroxide. Two basic process designs were originally developed: one incorporates a mercury cell and the other utilizes a diaphragm cell. Each type of cell has advantages and disadvantages which will be discussed below.

Mercury Cell Process.—This process yields a very high quality of sodium hydroxide. A disadvantage, however, is that it results in a large concentration of mercury discarded in process waste. Although this process accounts for only 25 percent of the chlorine production in the United States, approximately 42,000 tonnes of mercury-contaminated rine are disposed in landfills on an annual basis. Source segregation technologies do exist to remove some of the mercury from waste, but complete removal is not possible. Waste containing various chlorinated hydrocarbons also are produced.

Diaphragm Cell Process.—The advantage of this process is that it does not use mercury. If a graphite electrical terminal is used, the waste contains chlorinated hydrocarbons that are considered hazardous constituents (e.g., chloroform, carbon tetrachloride, and trichloroethane). Another source of hazardous waste using this process is the asbestos diaphragm. While not yet regulated under RCRA, disposal of asbestos is limited by regulations promulgated for the Toxic Substances Control Act.

Three modifications have occurred that reduce the amount of hazardous waste generated in a chlor-alkali process. The first has been substitution of a diaphragm cell for the mercury cell in most production facilities in the United States. This has been possible because of the availability of natural salt brine in this country, which is a preferred raw material for the diaphragm cell process. This substitution has been quite successful; in the last 15 years, no new mercury cell plants have been constructed.

A second modification has reduced successfully the amount of chlorinated hydrocarbons found in process waste. This was accomplished by replacing the graphite anode with a dimensionally stable anode (i. e., an electrical terminal). In addition to the reduction of hazardous constituents in waste, this modification contributed to a more efficient and longer cell life.

The third modification, development of a membrane cell, incorporates a major change in the type of membrane used in the diaphragm cell process. The asbestos membrane is replaced with an ion-exchange membrane, which generates a higher

quality of sodium hydroxide. This quality is similar to that produced by the mercury cell. Full development and use of this modification would reduce the amount of hazardous waste generated in two ways:

1. mercury contamination in chlor-alkali waste would be eliminated by a complete phase-out of the mercury cell process, and
2. the amount of asbestos waste would be reduced.

The membrane cell is a new modification and has not yet been incorporated on a large scale. A total of 25 units of various sizes have been built in the world. A small unit (1 I tonnes/day) currently is operating in a U.S. pulp mill. A larger unit (220 tonnes/day) will be in operation in the United States by late 1983. The capital investment required for incorporation of a membrane cell is slightly higher than a diaphragm cell that also offers a savings in energy costs. For those facilities with capacities of less than 500 tonnes/day, a membrane cell is more economical than a diaphragm cell. At greater capacities, neither system is superior, and other factors will determine the selection. These include the availability of appropriate raw material (e. g., natural salt brine or solid forms of sodium chloride) and ease of retrofitting an existing facility.

Vinyl Chloride Process

Vinyl chloride monomer (VCM) is one of many chemicals manufactured by the chlorohydrocarbon industry. This chemical is considered a hazard to human health, its production is regulated under the Occupational Safety and Health Act, and its disposal is regulated under RCRA. It is an intermediate product in the manufacture of PVC and can be produced by several different manufacturing routes.

About 92 percent of all VCM plants in the United States have both oxychlorination and direct chlorination plants onsite. The manufacture of VCM produces gaseous emissions of the monomer and liquid process residues that are a mixture of chlorinated hydrocarbons.

Incineration of these process wastes is used to recover hydrogen chloride, which is either recycled back to the VCM process or neutralized. Conventional incinerators designed for onsite treatment of many different wastes are not effective in the treatment of chlorinated hydrocarbons, as incomplete combustion results. Therefore, high-efficiency incineration specifically designed for liquid or gaseous chlorinated hydrocarbons is used. Although success with incineration systems has been mixed,

reliable performance has been demonstrated with relatively few operating problems,

Chlorinolysis represents a recovery option. High pressure and temperatures are used to reduce the liquid chlorohydrocarbon waste to carbon tetrachloride. This system has two major drawbacks: 1) the capital costs are high because of the high pressures and temperatures; and 2) the demand for carbon tetrachloride is decreasing due to regulatory restrictions on the use of products for which it is a raw material—e.g., fluorocarbons. Therefore, chlorinolysis is an unlikely choice in the future reduction of liquid waste from VCM production unless new uses are found for carbon tetrachloride.

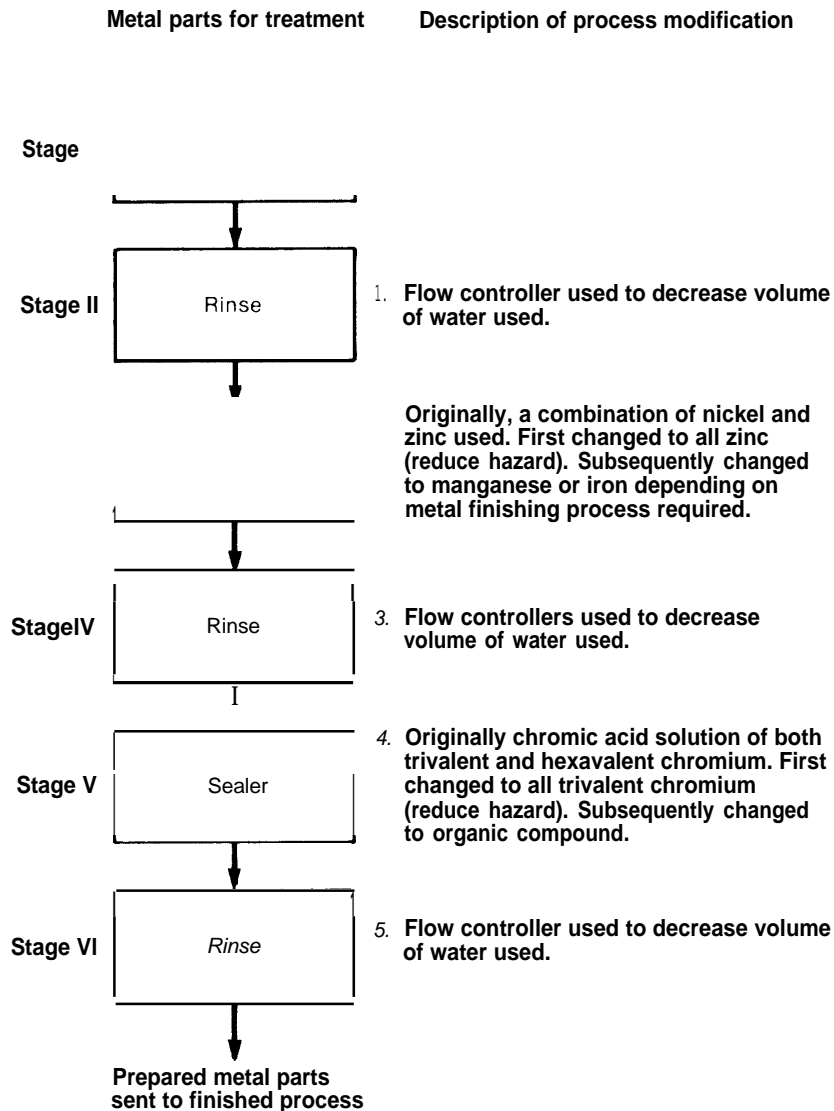
Another option for handling VCM liquid waste is to use a catalytic fluidized-bed reactor process developed by B. F. Goodrich. Hydrogen chloride gas is recovered and can be recycled without further treatment as feedstock in the oxychlorination process. The advantages of this system are low temperature operation, direct recycling of hydrogen chloride without additional treatment requirements, and energy recovery. The primary disadvantage of this recovery process results from restrictive requirements for application—i.e., only a plant using an oxychlorination process in conjunction with a fixed-bed reactor can accept the hydrogen chloride gas as feedstock. If an oxychlorination plant has a fluidized-bed reactor, the hydrogen chloride must be adsorbed from the gas stream and recovered with conventional recovery technology. The added cost of the absorption process makes this option prohibitive for fluidized-bed oxychlorination plants.

Metal-Finishing Process

Several modifications in metal cleaning and sealing processes have enabled the metal-finishing industry to eliminate requirements for corporation owned and operated wastewater pretreatment facilities. An example is provided in figure 5A.1. This process is designed to remove oil and grease from metal parts and seal the surface in preparation for application of a coating. The process consists of six stages. The parts are cleaned in stage I, rinsed in stage II, treated in stage III, rinsed in stage IV, sealed in stage V, and rinsed in stage VI.

The first modification is the incorporation of flow controllers to decrease the volume of water used in rinse. This results in a reduced volume of potentially hazardous sludge. While the flow in rinse stages IV and VI can be controlled without affecting other stages, any change in stage II will affect

Figure 5A.1.—Metal Preparation for Coating Applications



SOURCE Office of Technology Assessment

directly the quantity of chemicals required for stage III. For example, a decrease in rinsewater flow produces a more alkaline rinse. Thus, more acid is required in stage III. Increased acid levels also require additional amounts of metallic ions, such as nickel and zinc. Therefore, any changes in flow control for stage II must be carefully balanced with increased chemical requirements for stage III.

A second process modification occurs in stage III with the replacement of nickel and zinc by less hazardous metals. Zinc can be substituted for nickel

and, for certain applications, manganese or iron can be substituted for zinc. Presence of iron in wastewater actually can be beneficial for municipal waste treatment processes as it facilitates removal of phosphorus.

An acidic solution containing chromium in both the hexavalent and trivalent states is normally used in stage V. A third modification involves replacement of hexavalent with the trivalent chromium, reducing the hazard. The chromium can be replaced entirely with a biodegradable organic com-

pound. These modifications made in stages III and V permit discharge of metal-finishing wastewater directly into municipally owned treatment facilities. Such changes also eliminate formation of hazardous sludge.

Case Examples of a Recovery/Recycle Operation

Recycling of Spent Pickle Liquor in the Steel Industry

A major waste disposal problem for the steel industry concerns spent liquor from a pickling operation. The pickling process removes surface scale and rust from iron and steel prior to application of a final coating. The metal is immersed in an acid bath and as the scale dissolves, iron salts are formed. The contaminated acid bath is known as spent pickle liquor.

Approximately 500 million gal/yr of spent pickle liquor are generated from acid pickling. This solution contains 0.5 to 16 percent acid and 10 to 25 percent ferrous salts. Ninety percent of the total acid is hydrochloric or sulfuric acid; the remainder often includes nitric acid. The presence of nitric acid in spent liquor will determine which recovery option is possible.

Several disposal/treatment options are available:

- injection into deep wells;
- neutralization of the spent pickle liquor (using lime, soda ash, or caustic soda to increase the pH level) and landfilling the resulting sludge;
- recovery and regeneration of acid;
- byproduct recovery; and
- discharge to wastewater treatment facilities.

Because increased transportation costs and stricter regulations have limited the availability of suitable deep wells, costs for containing spent liquor have risen steadily. The gelatinous iron hydroxide sludge formed after neutralization creates a disposal problem, and costs of chemicals required for neutralization also have increased. Thus, the attractiveness of the first two options is reduced.

The remaining options involving some type of recycling and/or recovery have become more viable. Spent liquor can be used directly in treatment of municipal wastewater for removal of phosphorus. Addition of spent sulfuric acid has been shown to be particularly effective for water and wastewater treatment. Acid recovered from spent liquor can be recycled back to the pickling process. The salts formed (ferrous sulfate from sulfuric acid pickling and ferrous chloride from hydrochloric acid pickling) have several uses. For example, ferrous sulfate crystals currently are used in the manufacture of pigments, magnetic tapes, fertilizers, and in waste-

water treatment. Potential markets for recovered ferric oxide salts are in magnetic tapes, pigments, steelmaking, and sintering operations.

Sulfuric and hydrochloric acid pickling account for 85 to 90 percent of all pickling operations in the United States. Presumably, recovery of these acids for recycling could reduce spent liquor disposal by that same percentage. Because spent pickle liquor represents a large-volume hazardous waste, recovery and recycle could reduce the volume of hazardous waste disposed.

Recovery Technologies

Recovery processes are designed to recover either the free acid or both free acid and iron salts. Two methods are available for recovery of spent sulfuric and hydrochloric acid liquor. Cooling of the liquor results in separation of ferrous sulfate crystals. The unit operations required in this recovery system are: 1) precooking, 2) crystallization, 3) slurry thickening, and 4) crystal separation by centrifugation. Another process involves roasting the ferrous sulfate to produce ferric oxide and sulfur dioxide. The sulfur dioxide can be scrubbed to regenerate sulfuric acid. This is similar to the roasting process originally developed for recovery of hydrogen chloride.

Spent liquor from hydrochloric acid-pickling operations recovery technology is similar to the above sulfuric acid recovery technologies. Roasting ferrous chloride produces ferric oxide and hydrogen chloride gas. Auxiliary fuel is used to maintain reactor temperature at 1,500 F. The hydrogen chloride gas generated is absorbed in water to form hydrochloric acid for recycle. Unit operations include: 1) evaporation, 2) high-temperature decomposition, 3) absorption, and 4) scrubbing of vent gases.

Economic Factors .—The economics of acid recovery are based on cost and availability of acid, disposal cost of spent pickle liquor, quality and market value of byproducts (iron sulfate or iron oxide), and cost of selected recovery processes. Each of these factors is dependent on the particular plant and process involved.

Major economic advantages of acid recovery are reduced raw material costs, elimination of transportation costs incurred in disposal of spent liquor or sludge, and byproduct sales credits. The major economic disadvantages are utility requirements (primarily fuel requirements for hydrogen chloride recovery from dilute aqueous solutions) and capital investment requirements,

Byproduct recovery of spent liquor for wastewater treatment does not require a capital investment. This is a major advantage for this option. However, disposal costs and repurchase of acid have been estimated at \$110/tonne compared to recovery costs of about \$22 to \$88/tonne.

Corporate Factors .—Regional recovery/recycle facilities provide the opportunity of transferring burdens of investment cost from individual steel operations to a commercial recovery developer and offer reduced risk. However, regional facilities im-

ply increased storage requirements. Storage of spent liquor can create certain problems, e.g., premature precipitation of ferrous sulfate during periods of low temperature. In addition, early separation of acid from various sources of spent liquor may be required to eliminate potential contamination from proprietary chemical additives. Another disadvantage to a regional facility is added costs for transportation of spent liquor and recovered acid from the generator to the recovery facility and then to the consumer.

Table 5A.I.—Summary Evaluation of Liner Types

Liner material	Characteristics	Range of Costs ^a	Advantages	Disadvantages
Soils:				
Compacted clay soils	Compacted mixture of onsite soils to a permeability of 10 ⁻⁷ cm/sec	L	High cation exchange capacity, resistant to many types of leachate	Organic or inorganic acids or bases may solubilize portions of clay structure
Soil-bentonite	Compacted mixture of onsite soil, water and bentonite	L	High cation exchange capacity, resistant to many types of leachate	Organic or inorganic acids or bases may solubilize portions of clay structure
Admixes:				
Asphalt-concrete	Mixtures of asphalt cement and high quality mineral aggregate	M	Resistant to water and effects of weather extremes; stable on side slopes; resistant to acids, bases, and inorganic salts	Not resistant to organic solvents, partially or wholly soluble in hydrocarbons, does not have good resistance to inorganic chemicals: high gas permeability
Asphalt-membrane	Core layer of blown asphalt blended with mineral fillers and reinforcing fibers	M	Flexible enough to conform to irregularities in subgrade; resistant to acids, bases, and inorganic salts	Ages rapidly in hot climates, not resistant to organic solvents, particularly hydrocarbons
Soil asphalt	Compacted mixture of asphalt, water, and selected in-place soils	L	Resistant to acids, bases, and salts	Not resistant to organic solvents, particularly hydrocarbons
Soil cement	Compacted mixture of Portland cement, water, and selected in-place soils	L	Good weathering in wet-dry/freeze-thaw cycles; can resist moderate amount of alkali, organics and inorganic salts	Degraded by highly acidic environments
Polymeric membranes:				
Butyl rubber	Copolymer of isobutylene with small amounts of isoprene	M	Low gas and water vapor permeability; thermal stability; only slightly affected by oxygenated solvents and other polar liquids	Highly swollen by hydrocarbon solvents and petroleum oils, difficult to seam and repair
Chlorinated polyethylene	Produced by chemical reaction between chlorine and high density polyethylene	M	Good tensile strength and elongation strength; resistant to many inorganic	Will swell in presence of aromatic hydrocarbons and oils
Chlorosulfonate polyethylene	Family of polymers prepared by reacting polyethylene with chlorine and sulfur dioxide	H	Good resistance to ozone, heat, acids, and alkalis	Tends to harden on aging; low tensile strength, tendency to shrink from exposure to sunlight, poor resistance to O11
Elasticized polyolefins	Blend of rubbery and crystalline polyolefins	L	Low density; highly resistant to weathering, alkalis, and acids	Difficulties with low temperatures and oils
Epichlorohydrin rubbers	Saturated high molecular weight, aliphatic polyethers with chloromethyl side chains	M	Good tensile and tear strength; thermal stability; low rate of gas and vapor permeability; resistant to ozone and weathering, resistant to hydrocarbons, solvents, fuels, and oils	None reported
Ethylene propylene rubber	Family of terpolymers of ethylene, propylene, and nonconjugated hydrocarbon	M	Resistant to dilute concentrations of acids, alkalis, silicates, phosphates and brine, tolerates extreme temperatures; flexible at low temperatures; excellent resistance to weather and ultraviolet exposure	Not recommended for petroleum solvents or halogenated solvents
Neoprene	Synthetic rubber based on chloroprene	H	Resistant to oils, weathering, ozone and ultraviolet radiation; resistant to puncture, abrasion, and mechanical damage	None reported
Polyethylene	Thermoplastic polymer based on ethylene	L	Superior resistance to oils, solvents, and permeation by water vapor and gases	Not recommended for exposure to weathering and ultraviolet light conditions
Polyvinyl chloride	Produced in roll form in various widths and thicknesses; polymerization of vinyl chloride monomer	L	Good resistance to inorganic; good tensile, elongation, puncture, and abrasion resistant properties, wide ranges of physical properties	Attacked by many organics, including hydrocarbons, solvents and oils; not recommended for exposure to weathering and ultraviolet light conditions
Thermoplastic elastomers	Relatively new class of polymeric materials ranging from highly polar to nonpolar	M	Excellent oil, fuel, and water resistance with high tensile strength and excellent resistance to weathering and ozone	None reported

^aL = \$1 to \$4 installed costs per sq yd in 1981 dollars, M = \$4 to \$8 per sq yd, H = \$8 to \$12 per sq yd

SOURCE "Comparative Evaluation of Incinerators and Landfills," prepared for the Chemical manufacturers association, by Engineering Science, McLean, Va, May 1982