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MANAGEMENT OF HAZARDOUS INDUSTRIAL WASTES: RESEARCH AND DEVELOPMENT NEEDS

Report of the
Committee on Disposal of
Hazardous Industrial Wastes

NATIONAL MATERIALS ADVISORY BOARD
Commission on Engineering and Technical Systems
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The report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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This study by the National Materials Advisory Board was conducted under Contract No. 68-01-6084 with the U.S. Environmental Protection Agency (EPA) and the American Institute of Chemical Engineers (AIChE).

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ABSTRACT

The presently available technologies for the disposal of hazardous wastes were examined to identify their limitations and recommend research needed to support the development of new and improved methods.

This report contains the premises and assumptions used to guide the direction of the study; nontechnical issues, institutional in character and nationwide in scope, that influence hazardous waste management; details of various waste disposal technologies; and the overall findings of the committee presented as a series of conclusions and recommendations.

Some general conclusions and recommendations are:

- No new major and cost-effective technology exists or is likely to be developed that could be a panacea to dispose of all hazardous wastes.
- Disregarding cost, there exists some technology or combination of technologies capable of dealing with every hazardous waste so as to eliminate concern for future hazards. Therefore, periodically updated evaluation (including economics, availability, state of commercial development) of each hazardous waste disposal technology is needed.
- The disposal of hazardous industrial wastes should be approached in a hierarchical fashion, first attempting to minimize waste production through process modification and recycling, next seeking to convert the waste to nonhazardous or less hazardous forms, and finally making use of perpetual storage.
- Satisfactory management of hazardous industrial wastes is inhibited by nontechnical as well as technical factors. These include public attitudes and misconceptions and the lack of assurance of long-term reliability and consistency in the management of waste.
- The federal government should encourage the formation of centralized facilities for the treatment of hazardous industrial wastes.

- Research on the utilization of the treatment and assimilative capacity of all phases of the global environment is justified.
- The use of landfills should be minimized since constituents will very likely migrate over long periods (> 100 years) into groundwater.

Specific conclusions and recommendations for research and development are given for individual waste disposal technologies.

PREFACE

It is in the national interest to assure that all practical and economically feasible steps are taken to apply existing technology and to develop new technology to minimize the generation of waste products, detoxify waste, recover resources, and dispose of waste safely. To accomplish this, it is necessary to get the best solutions from industry, government, and academia and to pool this information for the benefit of all.

A study of the management of hazardous industrial wastes was contracted for with the National Academy of Sciences (NAS) under the joint sponsorship of the American Institute of Chemical Engineers (AIChE), represented by its Environmental Division, and the U.S. Environmental Protection Agency (EPA), Office of Research and Development. Since waste management is a common concern of the industrial and federal communities, it is appropriate that this study was funded equally by EPA and the AIChE representing a number of companies.

The project was conducted by a committee organized by the National Materials Advisory Board (NMAB). The committee members have expertise in chemical engineering operations, chemistry, geology, waste management, incineration, and biological and land treatment of wastes.

In Chapter 1 of this report the committee presents the premises and assumptions used to guide the direction of its study, and its overall findings are brought together in Chapter 2. Nontechnical issues, institutional in character and national in scope, that influence waste management are identified in Chapter 3. The various technologies related to waste management and disposal methods are discussed in detail in Chapter 4. Because of time and monetary restraints, the committee could not cover all aspects of the waste management problem. Therefore, the focus of the study was on the major areas.

I would like to extend my appreciation to the committee members and liaison representatives for their efforts in this study and to Stanley M. Barkin for staff support. The following individuals are offered thanks for technical presentations and contributions made during the course of the project: William Askins, Dennis Caputo, Fred M. Charles, Wayne Harrington, and James K. Petros, representatives of the Chemical Manufacturers Association (CMA); William Cawley and Norbert B. Schomaker of the EPA's Cincinnati Office; Peter Lovgren of Chemcontrol; R. Mahalingam of Washington State University; George Pierce of Battelle Columbus Laboratories; Philip T. Schaefer of Zimpro, Inc.; James Wallace of Law Engineering Testing Company; Donald Warner of the University of Missouri at Rolla; Gilbert Janauer of the State University of New York at Binghamton; R. Nagarajan of the Pennsylvania State University; and Amos J. Shaler of State College, Pennsylvania.

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INTRODUCTION

Hazardous industrial wastes, as defined by the Resource Conservation and Recovery Act (RCRA) of 1976 (Public Law 94-580), consist of ignitable, corrosive, reactive, or toxic materials. These hazardous wastes account for 10 to 15 percent of all industrial wastes or about 35 to 40 million metric tons per year, a quantity that is growing about 3 percent per year (Maugh 1979). The study that resulted in this report represents recognition by the study's sponsors--The American Institute of Chemical Engineers (AIChE) and the Environmental Protection Agency (EPA)--that better and more environmentally sound treatment and disposal options must be available for these hazardous industrial wastes. Specifically, the sponsors requested that presently available waste disposal technologies be examined to identify their limitations and that research needed to support the development of new and improved methods be recommended. Emphasis was to be on new technologies for managing hazardous wastes, but existing technologies were to be considered where specific needs have been identified.

Hazardous industrial wastes can be considered to be all the by-products of an industrial facility that have no apparent use or value and that can pose an unacceptable risk to people and the environment if discarded carelessly. The committee conducting this study, however, believed that this definition was too broad and chose to limit the type of wastes to be considered. The committee restricted its considerations to hazardous solid and liquid wastes generated by industry during the processing and synthesizing of materials, omitting hazardous waste materials covered under the Clean Air Act and the Clean Water Act and mine tailings and drainage, stack effluents, slag and ash, nuclear wastes, hospital wastes, municipal refuse and sewage, agricultural wastes, wastes at abandoned waste dumps, and improperly stockpiled material. In Figure 1, the general relationship among pollution control activities for industry is depicted. The shaded portion represents technologies or processes used by industry for manufacturing or for wastewater treatment that can influence hazardous waste management. Usually this influence occurs by process modification, resulting in solid or liquid hazardous wastes that are less in volume or degree of hazard. The committee provided examples of technologies that reduce volume or degree of hazard but did not address this area in detail because of the proprietary or highly specific character of these process modifications. Starting with a material that was generated and defined as a hazardous waste, the committee examined specific technologies for treatment, conversion, or perpetual storage as the primary focus of hazardous waste management.

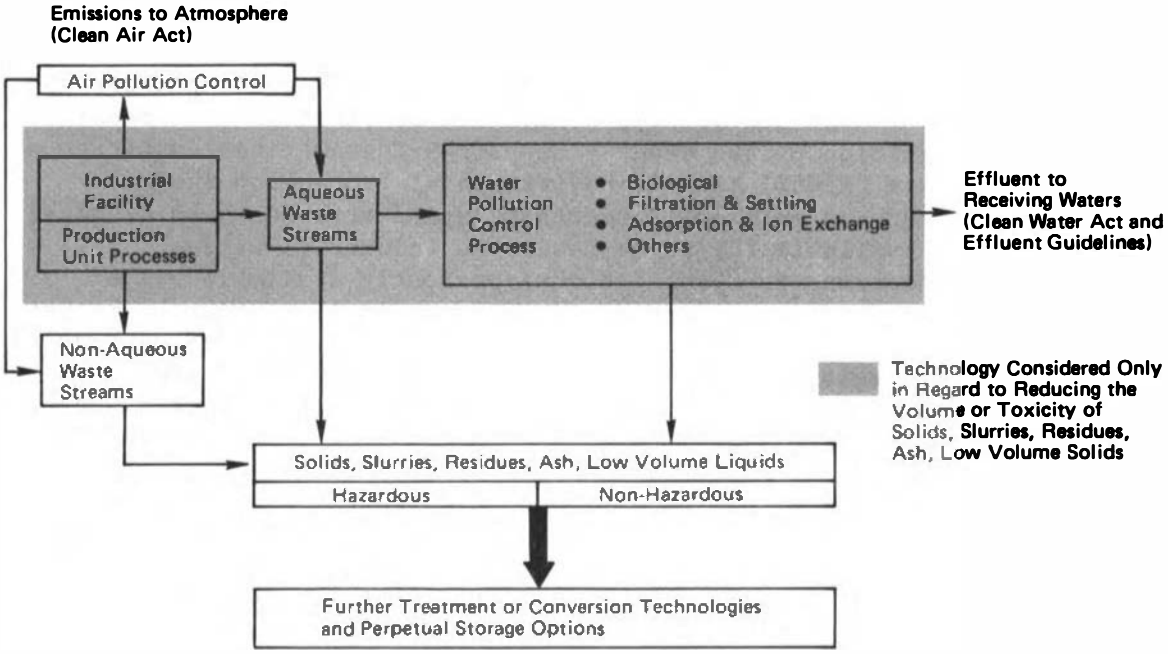

FIGURE 1 Generation of hazardous industrial wastes.

The committee's discussions of hazardous industrial waste problems and solutions were supplemented by presentations from academic, government, and industry experts involved in areas of hazardous industrial waste management and disposal. On the basis of these discussions and presentations, the committee set the objectives and developed premises and assumptions that provided direction for this report.

The committee concluded early on that public perception, sociopolitical forces, and other non-technical factors are substantial influences on the nationwide management of hazardous wastes. This linkage of technical and non-technical issues was subsequently developed in this report by a description by the committee (as a body of informed citizens in these non-technical areas) of the issues related to public perception and by a substantial description in this introduction of the assumptions, clarification of issues not elaborated, and the framework for organizing the specific technologies that were considered.

The committee recognized that any classification system for wastes, no matter how desirable, is artificial and designed to portray or explain a specific purpose. Such a simple classification system would not be capable of representing or even listing the total spectrum of known hazardous wastes, treatment and disposal technologies, and other chemical, physical, hazard- and cost-related parameters. Instead, the committee considered the wastes mentioned on page 1 and then defined broad-based technologies that might be appropriate for their treatment and disposal. During the committee's study, several waste classification schemes were reviewed; viz., process stream categories in RCRA, risk assessment and degree of hazard classifications being developed by the Office of Technology Assessment (1981), technology and chemical property matrices under study by the Chemical Manufacturers Association. These schemes were designed to serve a specific purpose and solve particular problems for the authors such as enforcement of and compliance with regulations, prioritization of wastes for disposal, research and development funding, and utilization of capital and equipment resources.

The specific premises and assumptions established by the committee are discussed in the following sections. Although each set of premises and assumptions is discussed separately, some overlap was unavoidable.

PUBLIC PERCEPTION

The segment of the public most concerned with hazardous industrial waste problems and solutions consists of those individuals who are or are likely to be directly affected by the problems and solutions. This group includes individuals who live adjacent to an industrial facility or disposal site, individuals who live downwind or downstream of a facility or site and may be affected by discharges from the facility or site, community leaders, and individuals who may benefit from the industry producing the wastes or the availability of the hazardous waste disposal site.

No single technique or method presently available or expected in the near future is a panacea for hazardous industrial waste management problems. Thus, a variety of methods and options must be used to manage these wastes in an environmentally sound manner. The public, however, appears not to appreciate the necessity for multiple approaches and continues to seek a single, simple solution. Unfortunately no such single solution exists. In addition, the public's lack of understanding of the issues makes it impossible to distinguish among clearly superior and inferior solutions to hazardous waste management problems. This lack of understanding about how hazardous wastes are generated and managed can have a number of adverse effects: Stifling of innovation, seeking of simplistic solutions, stockpiling of hazardous wastes, intervening by government, utilizing "quick fixes" (disposal by the most expedient available technology) and illegal methods.

The committee believes that overcoming this lack of understanding is an important hazardous waste management need. Although this issue was outside the scope of the committee's study, the committee emphasizes that the success of any technical, scientific, or research solutions it recommends is contingent on a change in this sociological situation. During its deliberations, the committee assumed that progress will be made and that the public will develop a more rational view of hazardous waste management.

GENERAL SOLUTIONS

A variety of approaches to the management of hazardous industrial wastes are outlined in Subtitle C of the 1976 Resource Conservation and Recovery Act (RCRA). These techniques as well as several other important methods for hazardous industrial waste management were considered by the committee (Figure 2). There are basically three general options: elimination or reuse of the hazardous waste, conversion of the hazardous waste into nonhazardous or less hazardous material, and perpetual storage. These general options differ substantially in terms of philosophy, time-frame, technique, and economics. At present, perpetual storage methods are the most prevalent and, hence, are the focus of attention for both regulatory and industrial personnel.

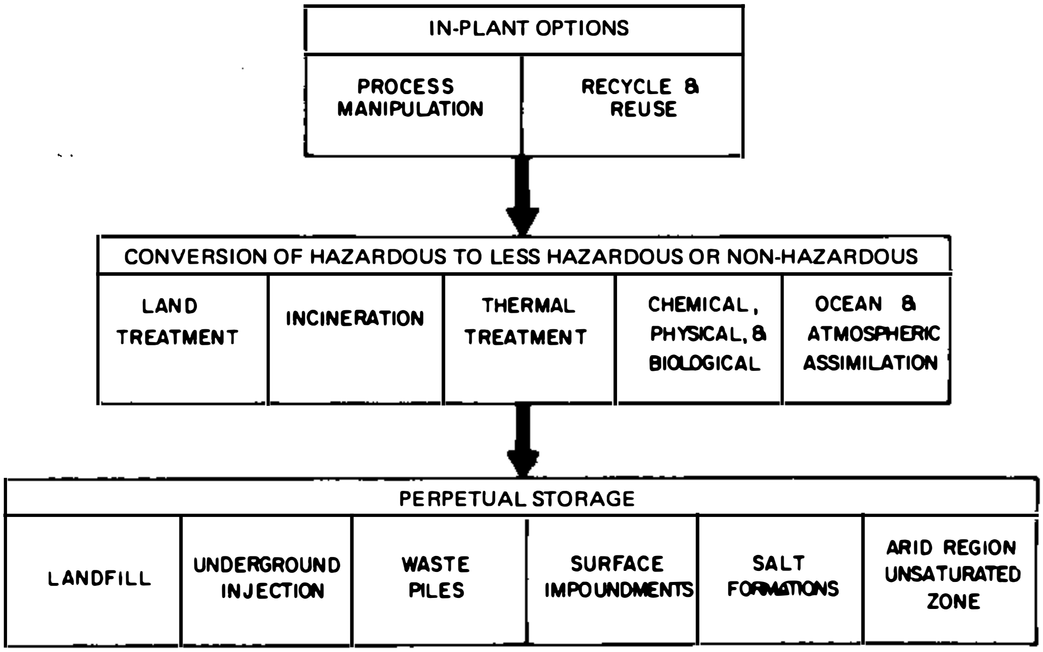

FIGURE 2 Hazardous waste management.

Optimum, successive utilization of the three general options would result in a decreasing amount of hazardous wastes as treatment proceeds in the direction of the arrows in Figure 2. Only small volumes of the more inert materials should be considered for perpetual storage. The hierarchy identified in Figure 2 should be followed in the management of hazardous wastes: (1) in-plant options should be used to reduce the volume and toxicity of generated hazardous wastes, (2) wastes that are generated should be converted to less hazardous forms and should be reduced in volume, and (3) remaining residues and wastes that are hazardous should be stored in a manner that minimizes risks to the environment and the public.

Identification and understanding of this hierarchy permits rational decisions to be made, best risk solutions to be identified, and better public understanding of the issues. The management approaches outlined in Figure 2 also stress that no one approach is sufficient to solve hazardous industrial waste management problems. Further, the concepts identified emphasize prevention and reduction rather than treatment and storage and aim to reduce the risk to the environment and public. Thus, the emphasis is on positive rather than negative management options.

IN-PLANT OPTIONS

In-plant options are probably the most effective and economical means of managing hazardous wastes. These options represent approaches that generally minimize impact on public health and the environment. Minimizing or eliminating waste production is substituted for end-of-pipe management. These options include:

1. Process modifications to eliminate or reduce the volume of specific hazardous wastes. These involve altering the chemistry or the chemical engineering operations to achieve the desired waste elimination or reduction within the constraint of acceptable and economical product manufacturing.

2. Recycle and reuse processes to prevent materials from being discharged from the plant as waste. Use of these techniques recognizes that the hazardous components of wastes may be usable reactant materials in other production processes.

As the costs of waste treatment and disposal increase, cost-reduction achieved through recovery of chemicals from the waste stream prior to disposal will become more important. The value of reclaimed chemicals plus the savings in not having to dispose of them could match or exceed the original disposal costs. An example may be cited from the leather and tanning industry: Chromium removal from wastes has been well demonstrated, but the net gains from recovery and sale on the commercial chromium market have been marginal. However, the substantially increased costs of secure landfill or even the lower cost of land treatment under pending RCRA regulations indicate that it will probably become significantly more cost-effective to remove the chromium from such wastes (Overcash 1980).

Because of the largely proprietary nature of the technologies, the committee decided not to undertake an extensive technical review of or make recommendations on process modification and recycle and reuse. However, the committee strongly recommends a major commitment, both philosophically and in funding, to approaches that prevent or eliminate hazardous materials from being discharged as wastes.

CONVERSION TECHNOLOGIES

Technologies that convert hazardous wastes into less hazardous or nonhazardous wastes fall into two classes:

1. Incineration, thermal treatment, chemical, physical, and biological processes, all of which convert wastes from a hazardous to a less hazardous or nonhazardous state. These processes produce a residue (either as a by-product or as a waste stream) that may or may not have an adverse environmental impact and that must be discharged to the environment or stored in an environmentally sound manner.

2. Land treatment that converts the hazardous wastes but also provides the ultimate disposal site.

Combinations of these conversion processes can be used to manage hazardous industrial wastes. These technologies are consistent with the philosophy of environmental regulations (i.e., to render hazardous industrial wastes nonhazardous).

PERPETUAL STORAGE

Perpetual storage is the most prevalent existing hazardous waste management practice. Each perpetual storage technology attempts to place the waste material in a highly condensed or concentrated configuration in which the hazardous constituents do not move. Generally little or no conversion from a hazardous state occurs, and, hence, care, monitoring, and migration prevention are required for an indefinite period. The committee decided that at least 500 years was realistic as a period of concern for hazardous wastes in landfills and perpetual storage options. Regulations under RCRA establishing the period of concern for landfills as 30 years were considered by the committee to be unrealistic. Careful attention to design for containment over such short control periods does not eliminate the probability of containment system failure after 30 years. Instead, the likelihood of adverse impacts and the realistic costs of perpetual care by compliance to the letter of the law are only masked.

The storage technologies clearly involve a long-term obligation because with time, particularly at a closed site, most of the changes that can occur are adverse (e.g., eventual penetration of a surface cover, gas diffusion and leakage to the atmosphere, and leakage of mobile constituents to groundwater). As an illustration, experience with some nuclear waste repositories (not specifically discussed in this report) provides an example of unsuccessful results with long-term storage. Despite the best intentions these have a proven record of leakage to the environment during a relatively short period amounting to a small fraction of the 500-year lifetime deemed necessary by the committee to be a realistic period for perpetual storage.

The central questions to be addressed with regard to perpetual storage concern the technology and the procedures for implementation. The question still not being widely addressed is how to accommodate these sites over their probable, greater than 500-year life. It is indeed possible that hazardous waste problems and consequences are merely being postponed and will have to be dealt with by future generations. If this could be argued convincingly (or even addressed), then a realistic consideration of the direction for hazardous waste management could be undertaken. The committee believes that this question, although it is not within the scope of this study, should be evaluated critically before public acceptance of perpetual storage of hazardous industrial waste can be expected. The committee concludes that it is desirable to select the perpetual storage alternatives that are the most stable and provide the maximum isolation from the rest of the environment.

TIME-FRAMES

The options noted in Figure 2 have different liabilities and time-frames associated with them. The in-plant options relate to very short time-frames (hours to days), with effects limited to those of short duration (i.e., those resulting from extreme operating conditions). They are subject to normal community acceptance and Occupational Safety and Health Administration considerations.

The environmental and societal effects of conversion technologies in Figure 2 involve an expanded time-frame (minutes to years). Short- and long-term effects on air and groundwater quality must be addressed. Dispersion occurs in a current time-frame and is taken into account as part of the design and monitoring approach. Its effects must not violate acceptable air, drinking water, and land use standards. Thus, the effects of these technologies are essentially short term.

For the storage category in Figure 2, the time-frame is much longer (decades to centuries). The liability is therefore likely to be shifted from those who generate or store the waste (the present generation) to future generations. These technologies could provide a potentially adverse environmental legacy.

For technologies in which the character of the hazardous waste remains for a long period (30 years) there is increasing likelihood of non-containment. Reliable containment for very long periods (1000 years) is an advantage when the true costs of monitoring and remedial action are included with the placement of a waste in such facilities. The shorter the lifetime of the hazardous waste technology, the better the control and the lower the dispersion potential generally associated with that technology. Longer storage periods create much larger unknowns and much less opportunity for management and control.

ZERO RISK AND ZERO DISCHARGE

The concepts of zero risk and zero discharge are interwoven explicitly and implicitly into most environmental discussions. That one cannot achieve zero risk or zero discharge is clear to the committee and has been basic to its discussions and recommendations. The laws of thermodynamics and probability assure that zero risk or zero discharge cannot be achieved. Although the committee did not attempt to assign quantitative values to acceptable risk, it recognized the critical need to develop methods of risk assessment and put them into practice.

It has been argued that zero risk and zero discharge serve as valuable goals for society even though they may be unachievable. Regulations have often accepted that philosophy. However, this impossible target has become a liability in achieving real progress. Goals of zero risk and zero discharge initially were effective in overcoming inertia but have since become an impediment to progress in hazardous waste management. Thus, the committee rejected the criteria of zero risk or zero discharge in evaluating the acceptability of technologies for hazardous waste management. To the extent that the public maintains a belief in zero risk and zero discharge, there will be major difficulties in managing hazardous wastes. The committee concluded that the major part of all risk and discharge must be assumed in a present day time-frame and not deferred to future generations.

In the area of risk acceptance, the committee believes that risk quantification is urgently needed. Most activities of daily life pose some risk of injury, sickness, or death. Similarly, there is some risk associated with hazardous waste management, and some alternatives have higher risks than others. It is critical that some level of risk assessment be put into practical use. This could occur through a combination of scientific and judicial review and opinion, regulatory practice, professional society standards, and public awareness and acceptance.

The Office of Technology Assessment (1981) approached this problem in terms of a degree-of-hazard concept applied to regulatory policies. This is a limited approach and focuses on criteria for defining a hazard. The broad and more important problem is the level of acceptable risk. That some technologies, when applied to hazardous industrial wastes, will have higher risk factors than other technologies must be considered in decisions regarding such wastes (including their management and/or ultimate disposal).

GLOBAL ASSIMILATIVE CAPACITY

As discussions in the committee proceeded, it became clear that the global environment (atmosphere, sea and estuarine systems, and terrestrial mass) should continue to constitute a source of usable, natural treatment processes. The committee's decision to consider all phases of the total earth environment was based, however, on the assumption that treatment, or dilution accompanied by physical or chemical action, could occur without serious or irreversible damage to the environment. The burden of proof as to the reasonable absence of potential environmental damage caused by such use should rest primarily with the waste disposer rather than with private environmental organizations or government agencies.

The critical requirement is that treatment (specifically, conversion to nonhazardous material) actually occurs. For example, the use of the upper two meters of soil to decompose and fix constituents of hazardous waste is a method that uses the terrestrial environment to accomplish treatment. Thus, land treatment was recognized by the committee as a proper use of the assimilative capacity of nature.

The committee also recognized that the atmosphere and ocean have an assimilative capacity for hazardous waste, although a policy of restricted use of the ocean assimilative capacity for hazardous waste is in direct conflict with some international accords. The scientific community is in disagreement over the advisability of using ocean assimilation (Goldberg 1981, Kamlet 1981) even though the assimilative capacity is acknowledged to exist. The committee recognized this conflict but concluded that further research and pragmatic approaches to assimilation by the global environment might be valuable in dealing with the international problem of hazardous wastes.

Research on the utilization of the treatment and assimilative capacity of all phases of the global environment was considered justified by the committee. Several statements summarize the committee rationale in this area:

1. The use of selected parts of the total earth environment has already been successful; thus, the existence of the earth's assimilative capacity has been demonstrated.

2. Within restraints that avoid environmental degradation, the use of the environmental assimilative capacity can be a continuing process. The use of such self-renewing techniques assures little or no burden on future generations, but only if the extent of the assimilative capacity is known. The challenge is to quantify the treatment potentials.

3. The more sensitive parts of the global environment have lower assimilative capacities, not zero tolerances. Economics will dictate whether a specific phase of the environment would actually be used, assuming that there are adequate controls over such use.

In general, the committee believes that with adequate testing, monitoring, and regulation, the successful utilization of the global environmental assimilative capacity, including that of the soil, atmosphere, and the ocean, could be a viable and justified technological alternative in the management of industrial hazardous waste.

ECONOMICS

The committee recognized that economics underlie almost all of the decision-making in selecting management options for hazardous wastes. Several facets of the economic picture appeared universal.

First, the use of all technologies, regardless of the present degree of development, will be improved if there are cost reductions. Those options that have the lowest costs and produce the best control will be more widely utilized. In many cases, the only existing economic analyses for newer technologies derive from small-scale, laboratory-level applications. Full-scale research or usage should result in a better knowledge of actual costs. The lack of specific recommendations by the committee regarding work toward lower costs should be construed only as recognition that such a need exists almost universally among hazardous waste management technologies.

Second, the committee determined that obtaining reliable cost estimates of ongoing hazardous waste management was an important need. It is esssential to know what typical investment and operating costs are at full-scale industrial facilities. This area is cloudy because both *a priori* calculations and commercial sales information are being utilized simultaneously in comparisons of alternatives. More actual systems evaluations are a universal need in the management of hazardous wastes.

Third, the committee concluded that cost comparisons must be made on an "environmentally equivalent" basis. Comparisons between technologies that detoxify wastes and those that store material for a 30-year period only confuse short- and long-term economics. From the standpoint of technology assessment, all alternatives should be evaluated using the same ground rules. The comparison should include costs from the time of hazardous waste generation until the hazardous characteristics have permanently disappeared or can be assumed immobilized even over very long periods.

This type of environmentally equivalent economic determination is certainly not being made for one notable technology--hazardous waste landfills. The present costs of operating these facilities do not include realistic long-term costs. There is an obvious preference for turning responsibility over to some level of government for long-term costs and liabilities. Thus, incomplete landfill costs are currently compared with those for a chemical detoxification facility or a land treatment system in which the hazardous wastes are rendered nonhazardous. Such comparisons are not environmentally equivalent and do not provide a true measure of societal costs.

The committee did not attempt to list in-place and operational costs for each environmentally equivalent technology. This, however, should not be construed to mean that economics is not an important factor.

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CONCLUSIONS AND RECOMMENDATIONS

GENERAL

Hazardous industrial wastes exist and must be dealt with in the context of present day society. Fewer hazardous wastes (in volume and degree of hazard) will be generated in the future as process changes and in-plant modifications are made. However, complete solutions for hazardous wastes will still require treatment, conversion, and perpetual storage of the lesser amounts of materials that cannot be otherwise eliminated or recycled.

The disposal of hazardous wastes is a national problem, one that affects the national economy and the national future. Academia, government, and industry should all play a role in meeting the research and development needs for hazardous waste management.

There currently exists some technology or combination of technologies capable of dealing with every hazardous industrial waste in a manner that eliminates the need for perpetual storage. At least in principle, inorganic components can be separated and reused and organic compounds can be destroyed. In general, however, the present state of development of many of the required technologies is such that they are not commercially available at a cost that makes their use feasible.

An objective of the sponsors was to have recommendations for new technological approaches to hazardous waste management. However, the committee found no major new and cost-effective approach. Since no single, existing technique is likely to be developed into a panacea, funding should be continued mainly to improve existing technologies, particularly for making methods more reliable in design and operation and more cost-effective for specific waste streams. Further, current technologies involving perpetual storage must continue to be used, at least for the immediate future, and the problems they cause must be faced.

All hazardous industrial waste disposal technologies involve some risk since zero risk and zero discharge are not achievable. It is essential that alternative technologies be subjected to a quantitative risk assessment that takes broad account of societal concerns. The committee concluded that the concept of "environmental equivalence" should be used in these comparisons. Such assessments must be acceptable to the public as well as to the scientists and engineers who are knowledgeable in the field.

All hazardous industrial waste disposal technologies need complete economic evaluation, so that comparisons can be made of their actual costs. Economic evaluations must include the long-term (sometimes in excess of 500 years) facets of certain hazardous waste management alternatives.

To a large extent, specific disposal technologies are particularly suited to specific hazardous industrial wastes. In general, therefore, wastes should not be mixed together or diluted without reason, and, in addition, the choice of disposal technologies should be based on specific waste disposal needs.

The disposal of hazardous industrial wastes should be approached in a hierarchical fashion, first attempting to minimize waste production through process modification and recycling, next seeking to convert the waste to nonhazardous or less hazardous forms, and finally making use of perpetual storage.

The committee recommends that:

1. A centralized, accessible, and periodically updated economic evaluation of each hazardous industrial waste disposal technology be developed, together with an assessment of each technology's availability and state of commercial development.

2. A methodology for hazard and risk assessment of hazardous industrial waste disposal technologies and transport be developed and applied. Both public and environmental risks should be covered in a manner that allows comparison with existing risks that are acceptable to society.

3. An educational program be established to provide the public and industry with soundly based information on the options and risks associated with the disposal of hazardous industrial wastes.

4. A methodology for dealing with the problems of siting of hazardous waste treatment and disposal facilities be developed, with particular attention to regional treatment facilities.

5. Resource recovery or waste elimination receive first emphasis in all considerations of hazardous industrial waste management.

6. Manufacturers of products plan ahead for the ultimate treatment and disposal of these products and the by-products of their manufacture so as to minimize technical problems and adverse environmental consequences.

INSTITUTIONAL CONSIDERATIONS

Progress toward the satisfactory management of hazardous industrial waste is inhibited by nontechnical as well as by technical shortcomings.

These factors are basically institutional in nature, and they are so fundamentally involved in any discussion of waste disposal technologies and technology applications that their consideration cannot be avoided.

Public attitudes toward hazardous industrial wastes and their disposal reflect a number of misconceptions. Among these are beliefs that hazardous waste generation can be eliminated, that waste discharges can be avoided, that waste disposal can be made risk free, and that hazardous waste disposal technologies are equally risky to the local environment and health. Satisfactory management of hazardous industrial wastes depends on an informed and enlightened public.

Long-term reliability and consistency in the management of hazardous industrial waste disposal operations must not be hampered by changes in regulatory philosophy, hasty legislative and regulatory actions in response to problem situations, inconsistent enforcement, and technically unachievable regulations that discourage all but minimum compliance with current requirements. Satisfactory management of hazardous industrial wastes depends on establishing goals for the long term and adopting a consistent, realistic approach to achieving them. The public deserves nothing less.

Local jurisdictions have generally been unwilling to act jointly to bring about the establishment of centralized waste treatment facilities, where larger scale operations would provide efficiencies in cost, environmental control, and resource conservation and recovery. A reluctance to deal with the problems of hazardous industrial waste management on the part of a single jurisdiction often rules out action on the part of others. Satisfactory hazardous industrial waste management depends on a commonality of effort to resolve a national problem.

The committee recommends that:

1. A program of public education, in the broadest sense, be initiated to inform and to provide a positive view of the necessity of overall management of hazardous industrial wastes, the nature of the alternative technologies, and the success of disposal operations that could serve as models for future developments.

2. Review and revision of existing legislation be considered to assure its consistency and technical validity, particularly with regard to the long term and the enforcement of regulations, and to establish reasons for public confidence in the goals set for the management of hazardous industrial wastes.

3. The federal government encourage the formation of centralized facilities for the treatment of hazardous industrial wastes by arranging to coordinate such activities, by seeking the removal of legal barriers at the national, state, and local levels, and by providing assurance to the public that concerns for health, safety, and the environment will not be neglected.

CHEMICAL AND PHYSICAL TECHNIQUES

Chemical and physical techniques, described classically as unit processes and unit operations, consist primarily of conversion (degradation) processes such as neutralization, oxidation, reduction, and precipitation and separation (concentration) processes such as distillation, filtration, and adsorption. A very large number of these techniques are available, and they are used widely in dealing with hazardous industrial wastes, both in manufacturing and treatment operations. Their application may come before, after, or as part of another treatment method or they may themselves be sufficient. Known wastes consisting of one or a few hazardous components can often be disposed of effectively using these techniques, but they are less suitable for wastes of mixed or variable composition. They have the advantage of being carried out under controlled conditions, and this allows risks to be minimized.

Although, in principle, chemical and physical techniques could be developed to dispose of any hazardous industrial waste, it is unlikely that this would be a generally cost-effective approach. However, even in current applications, improvements could be made if more fundamental data on the thermodynamic, kinetic, and transport properties of the waste materials were available. Particularly with organic materials, general property correlations would help in the optimization of separation processes and thus facilitate recovery of valuable compounds. Specific chemical procedures such as the reductive dechlorination of chlorine-containing organics, should be considered.

The committee recommends that:

1. Experimental determination of physical properties of various hazardous waste species and mixtures be continued. Additional research on predictive and correlational methods is warranted.

2. Processes for metal removal and recovery from hazardous industrial waste streams be investigated to improve the options for pre-treatment of wastes to be disposed of by biological techniques, land treatment, and incineration. Ion exchange, adsorption, and liquid extraction methods are likely candidates for development.

3. Separation processes based on supercritical fluids, liquid membranes, and foam fractionation (especially microgas dispersions) be developed further. Separation of organics from largely aqueous waste streams would allow the use of incineration.

4. Research be directed toward a low-cost process for removing water from slimes and sludges, so that the chosen disposal method (perhaps by land treatment, permanent storage, or landfilling) can be simplified.

BIOLOGICAL TECHNIQUES

Biological waste treatment processes have been widely used for the treatment of both municipal and certain industrial wastes, and the technology is well established in these areas. Although there can be applications to hazardous industrial wastes, biological treatment processes will generally constitute only one step in a hazardous waste treatment and disposal system. There are a large number of biological treatment processes that use indigenous or adapted microbial organisms for the removal or detoxification of hazardous industrial wastes. In these systems, waste constituents can also be removed by air stripping, volatilization, and adsorption on solids. As with chemical and physical processes, biological processes are carried out under relatively well-controlled conditions of residence time, temperature, and pH.

Biological waste treatment processes can be adapted to liquids, slurries, and solid organic wastes. Toxic constituents can inhibit microbial growth in such processes, and there can be difficulties in maintaining a sufficiently diverse population of microorganisms to metabolize the waste materials at desired rates. Detailed information is needed on the ability of biological treatment processes to detoxify specific hazardous industrial wastes using both indigenous and genetically manipulated organisms.

The committee recommends that:

1. The mechanisms of hazardous industrial waste removal be studied in one or more existing or clearly usable biological treatment processes so that better utilization of this alternative can be developed and the transfer of toxic pollutants from one medium to another can be minimized.

2. Analytical measurement techniques, beyond fish bioassay methods, be developed to provide measures of detoxification when biological treatment processes are used.

3. Genetic engineering of microorganisms be investigated as a means of improving detoxification of hazardous industrial wastes. Competition from naturally occurring organisms should be investigated.

4. Thermophilic biological techniques be studied to determine if improved detoxification and removal can be achieved economically with these processes.

LAND TREATMENT

Land treatment makes use of the assimilative capacity of the environment in the disposal of hazardous industrial wastes, taking advantage of natural biodegradation processes as well as environmental chemistry. Organic materials are metabolically degraded, and both organic and inorganic materials are subject to oxidation or reduction and to immobilization by adsorption and reaction in the soil. Land treatment has been applied successfully in the disposal of municipal and non-hazardous industrial wastes as well as in the treatment of hazardous industrial wastes.

In principle, land treatment is capable of handling all hazardous industrial wastes. In practice, the capacity of the land for specific waste components may be limited by the cost of land areas to match assimilative capacity to waste generation. Therefore, pretreatment of the waste may be required to achieve reasonable costs. Pretreatment may also be considered as a means of extending the life of land treatment systems receiving constituents that accumulate. The behavior of the constituents in a land treatment system can affect air and water receiver systems, and therefore, designs for land treatment must take into account both short-term and long-term environmental effects.

The committee recommends that:

1. The data base for the design of a land treatment system be expanded, with emphasis on transferable laboratory- or pilot-scale information and refinement of this information in selected field-scale systems.

2. The economics of full-scale hazardous waste land treatment systems be further documented.

3. Process modification and pretreatment be investigated as adjuncts to land treatment.

4. An effort be made to make industry aware that land treatment has technical and economic potential.

OCEAN ASSIMILATION

Ocean assimilation, like land treatment, makes use of the assimilative capacity of the environment for the disposal of hazardous industrial wastes. Many of the same assimilative processes operate to degrade and detoxify wastes, but here particular attention must be paid to impacts on marine life and the overall ecological system because of the relatively rapid dispersion which occurs.

Indiscriminate ocean dumping of waste materials has led to banning any form of ocean disposal. This, however, should not preclude investigations into the use of the oceans for hazardous industrial waste disposal under strictly controlled conditions; the oceans, which occupy some 70 percent of the earth's area, may indeed provide a valuable self-renewing resource. Except in connection with past problems caused by specific wastes, often in specific locations, relatively little is known about the degradation of wastes in the marine environment. High dilution is likely to make such studies difficult, but it may well facilitate the degradative processes by minimizing the impact on the marine environment. As with land treatment, pretreatment of wastes to remove specific components may be required.

The committee recommends that:

1. The effects of selected past ocean disposal (dumping) of wastes be determined to assess the possible consequences of ocean disposal of hazardous industrial wastes.
2. The dispersal and degradation rates of hazardous industrial waste constituents in the marine environment be studied.
3. Systems be developed to monitor ocean disposal processes and their impact on marine ecology.
4. Modeling of ocean assimilation be studied.

INCINERATION

Incineration is a useful technique for the conversion of hazardous industrial wastes to less or non-hazardous materials; it is applicable to all organic materials provided the necessary temperatures and residence times can be achieved. It finds widespread use in a large variety of installations, among them boilers, kilns, furnaces of special design, open pits, rotary hearths, and vertical shaft incinerators. These can be powered by both hydrocarbon and refuse-derived fuels. In some cases, energy can be recovered with the co-generation of heat or electricity.

For many organic materials, incineration affords the most complete means of waste management available via current technology, but emission controls are frequently required to prevent air pollution. The inorganic components present in waste produce slag and ash that must be disposed of and, on occasion, toxic volatile materials that must be collected. Shipboard and ocean platform incinerators avoid some of the problems associated with emissions but entail significant transport problems for all but hazardous industrial waste generators located near ocean coasts. With more precise information on the temperature and time requirements and design parameters for specific classes of wastes, a more extensive use of incineration would become feasible, particularly if processes were to be developed for existing industrial boiler systems.

The committee recommends that:

1. The rates and products of combustion of hazardous industrial wastes be determined as a function of waste type, temperature, and residence time to assess the feasibility of widespread use of existing systems for incineration.

2. Fuel additives and improved scrubbing systems be studied and developed for improved control of incinerator emissions.

3. Operational studies of offshore platform incineration be carried out.

4. Policy and economic studies of ocean shipboard incineration be undertaken.

THERMAL METHODS

Thermal methods utilize heat rather than the open flame of incineration to decompose and detoxify hazardous industrial wastes by oxidation and pyrolysis. Examples include catalytic and reactive fluidized bed systems, molten salt reactors, plasma arcs and torches, microwave systems, and pyrolytic processes. Of these, only pyrolytic processes have been widely used in industry. Thermal methods are generally applicable to hazardous industrial wastes, but they are usually more costly than incineration and are more suitable for disposing of specific wastes for which conventional incineration is not readily adapted.

Although higher heat transfer coefficients may result in lower temperature requirements for destruction than with incineration, several of the thermal methods, particularly those involving microwaves and plasmas, require high energy inputs that make them less economically attractive. On the other hand, fluidized bed media can be selected to react with inorganic components such as chlorides, thus reducing or eliminating problems with emissions. In addition, a number of thermal methods are suited to operation on a scale smaller than that of conventional incinerators, making portability of the treatment facility possible. Overall, thermal methods offer considerable promise for disposing of specific, difficult wastes.

The committee recommends that:

1. Operating parameters for the destruction of specific hazardous industrial wastes in molten salt, fluidized bed, wet air oxidation, and pyrolysis systems be determined.

2. The selection of materials of construction for molten salt, fluidized bed, wet air oxidation, and pyrolysis systems be studied to improve corrosion resistance and operating life.

3. Plasma and microwave systems be investigated for destruction and detoxification of hazardous industrial wastes that are difficult to handle.

4. Pyrolysis methods be developed for organic wastes as a means of detoxification and conversion to usable forms, such as fuels.

5. Evaluation of co-catalyst systems for use in conjunction with specific technologies (i.e, wet air oxidation, fluidized beds, and specific waste streams) be investigated.

LANDFILLS

Landfill is currently the major method used for the disposal of hazardous industrial wastes. In the past, landfills were indeed "toxic dumps," but today, since they are regulated, they are better described as "secure landfills," intended basically as permanent storage that provides "perpetual" isolation from the environment. To assure perpetual isolation, however, requires perpetual care at a cost that is generally being ignored.

For the immediate future, landfills represent a necessary technology for disposal of hazardous industrial wastes; but, for the long term, they may not remain the major alternative for perpetual storage. In the future, only non-reducible inorganic residues might be considered for any perpetual storage alternative. The contents of a landfill are recoverable, at least in principle, to the extent that the landfill is properly managed and controlled. There is, however, a good deal that is not known about long-term landfill behavior, and policies for long-term care and management of landfills have yet to be established.

The committee recommends that:

1. The use of landfills be minimized to prevent the likely migration of constituents of the waste into groundwater.

2. Systems be developed for improved sampling and monitoring of hazardous industrial wastes in soils and leachates.

3. Modeling of migration from landfills be studied.

4. Liner and cover materials be evaluated for long-term performance.

5. Materials and methods of encapsulation and solidification be investigated, with particular attention to long-term behavior.

PERMANENT STORAGE OR DISPOSAL

Permanent storage or disposal involves deep well injection or underground burial, with or without barriers to migration and with or without immobilization by solidification or fixation. Currently, deep well injection is practiced fairly extensively with liquids, but, like landfilling, the practice has been declining. With disposal in mines and salt domes, wastes are, in principle, recoverable. However, these techniques approach disposal with the expectation that the wastes will be so isolated by distance or by degradation that they will never again encounter the biosphere.

A variety of sites are available for this method of disposal, among them solution cavities, worked-out and abandoned mines, and geological basins. Such locations, however, have not been adequately inventoried and characterized, and there is not much known about the degradation and reaction rates of wastes and their possible migration in many potentially usable regions.

The committee recommends that:

1. An inventory of possible sites for permanent disposal be generated, with information on site characteristics and potential problems in handling the disposal of solids, liquids, and slurries.
2. A more concerted and directed research effort be made to assess the feasibility of using as burial sites for hazardous wastes the thick unsaturated zones (water free) underlying much of the western United States. The utility of these zones may be pivotal in providing a reasonable solution to the whole problem of disposal of hazardous wastes.
3. Chemical degradation and reactivity studies of liquid hazardous industrial wastes in the injection environment be carried out, taking account of the temperatures, local brine chemistry, pressure, and fluid migration rates.
4. The long-term stability of containers and encapsulated or solidified materials in the disposal environment be investigated.
5. The long-term stability and performance of various kinds of barriers between wastes and the local environment be studied.

INSTITUTIONAL CONSIDERATIONS

A series of nontechnical issues is seen by the committee (as a body of informed citizens) to be very important to any future progress in hazardous waste management and thus must be addressed to place the technical aspects in proper perspective. These issues are primarily institutional in character and national in scope. In any specific situation, the institutional problems can be quite complex; however, a few issues arise frequently and are sufficiently important to be identified as institutional needs related to hazardous waste management.

PUBLIC PERCEPTION

In the opinion of the committee, several examples of public attitudes that inhibit solutions to hazardous industrial waste management problems are:

1. Zero discharge is an achievable goal
2. Hazardous waste generation can be precluded from a region or community
3. There is no acceptable level of risk
4. All management options have similar risks because the wastes are hazardous.

To the extent that new and superior approaches to hazardous waste management are precluded from implementation because of incorrect public perception, then both the public and the waste generators will suffer very substantially. A concerted public education program is needed to stimulate the change in public perception.

An education program must provide more than just information on alternatives to overcome the adverse history of the environmental impact of certain hazardous waste sites in the United States. A specific educational program might begin with a detailed evaluation of how public attitudes arose and what educational materials are needed to change faulty perceptions. Information from a successful operating facility such as that of Kommunekemi in Denmark generally would be very effective. Information presented by academic professionals might be more effective than that presented by government or regulatory personnel because of the present general public mistrust of these officials. A specific program then could be developed by community, state, or regional teams.

Public attention should be directed toward the overall issue of managing hazardous wastes instead of focusing on a specific grievance involving one facility or past situation. Unless public perception is effectively addressed in this larger context, every action or facility for managing hazardous waste will require considerable expenditures for persuasion with no guarantee of acceptance. In other words, the educational approach should be directed at the general climate of attitudes to allow positive movement toward implementation of state-of-the-art hazardous waste management technology in the United States. Although changing the general attitude may seem an inefficient approach, one must contemplate the large number of facilities to be sited in the future and the decisions to be made in the public and institutional area related to hazardous wastes. These individual situations are very difficult to implement without a generally more realistic and hence more positive attitude toward management of hazardous wastes.

PUBLIC ASSURANCE OF LONG-TERM RELIABLE OPERATION

High-quality design and construction of hazardous waste management facilities will not in themselves assure successful performance with respect to environmental and health standards. This is determined by the actions of responsible, trained management. At present, apprehension exists on the part of the public concerning the reliability of operation of hazardous waste facilities. It would be natural to assume that the public would depend on regulatory organizations to enforce operational standards established for protection of health and the environment. This is not the case, for the public does not generally trust regulatory organizations to remain both permanent and rigorous in enforcement. Although the degree of mistrust varies, it is rare that the public is comfortable with the enforcement power or the commitment of government.

The regulatory authorities themselves are often at a disadvantage because the regulations to be enforced may not be completely consistent and, in some cases, are technologically unachievable at reasonable costs. Thus, the best opportunity to educate the public, through actual demonstration that hazardous waste can be correctly managed, is lost. Errors, of varying magnitude, are made by all groups, these include citizen unwillingness to understand and discern among alternatives; marginal facility operation within the regulations; and opposition to strict enforcement.

Solutions are difficult to find and not readily agreed upon in detail. However, there must be a starting point leading to a series of definitive improvements. As the most centralized and technically based element in hazardous waste management, the regulations are clearly the place to begin. In the ideal, good regulations encourage strict enforcement. The major concern of the committee with regard to present legislation is the absence of consideration for the time period during which wastes remain hazardous.

Given consistent, technically sound legislation that accurately accounts for the long term, the enforcement mechanism must develop improved capabilities. Enforcement must prove to be rigorous, sufficient to detect noncompliance, and less impacted by factors not related to the environment or health. Industrial firms must support and strictly enforce such a policy because it is in their own interest as well as that of the community. The public, in turn, must become more perceptive of good management and the inherent technical limitations in the management of hazardous wastes. With these changes, based firmly on improved legislation and enforcement, the general climate and further refinements in technology will improve the hazardous waste management situation. The public will have a guarantee of long-term reliable operation.

REGIONAL OR CENTRALIZED HAZARDOUS WASTE TREATMENT FACILITIES

A hazardous waste treatment facility established to encourage interstate or intercounty transfer of materials to a centralized location is referred to as a regional center. At present there are no such centers in the United States because local jurisdictions have had an adverse attitude toward other communities' hazardous wastes and have lacked a commitment to joint management of hazardous wastes. In Europe such regional centers do exist: Kommunekemi at Nyborg in Denmark, GRAAB-Kemi at Goteborg in Sweden, GSB at Ebenhausen in West Germany, Plaforo at Lyon in France, HIM at Frankfurt in West Germany, and Daester-Fairtec at Baden-Brugg in Switzerland. In the United States, only one facility, near Cleveland, is being implemented. The number and usage of treatment and recycle/reuse processes at existing regional facilities can change depending on economic and other considerations. However, the concept of such regional arrangements remains valid and a sound objective.

The incentive for regional centers is based on the economic and environmental control efficiency derived from large-scale operations. By reducing costs and assuring the availability of options for managing hazardous wastes, illegal activities would probably be reduced and the ability to enforce regulations on industrial facilities of all sizes would be increased. The viability of such regional centers is primarily dictated by institutional considerations.

A regional facility would employ various processes for the management of inorganics, waste oils, and organic materials. Waste oil could be processed to regenerate usable petroleum materials and, thus, would yield revenue. At present, one waste oil recycling plant using modern technology exists in the United States (Felder et al. 1980). Inorganic materials would be treated by such processes as neutralization, dewatering, ion exchange, chemical reaction for detoxification, and precipitation. Organic materials might be reclaimed by solvent extraction or distillation. Alternatively, organic destruction could be accomplished by incineration in plants dedicated to handling specific waste compositions (e.g., high halogen content versus low halogen or sulfur content). At the Danish regional facility, a scheme has been developed that places wastes into 50 categories, each of which receives a different combination of treatments.

The organization of successful centers in Europe is based on government participation. That participation can be direct (e.g., partial or total government ownership) or indirect (e.g., assignments of regions to be served by single facilities). In the case of indirect participation, government would be involved in permitting, enforcement, and rate structures. Without government involvement on an interstate basis, these centers generally cannot be established because of the uncertainty of permits, a lack of commitment for the long term, and the absence of data on safety and health to assure public acceptance. Regional centers are accompanied by collection networks and transfer points and these must be well designed and well operated. Institutional changes are needed to educate the public and assure acceptance of regional facilities.

Projected costs for regional facilities in the United States appear to be considerably higher than those for their European counterparts. The cost of facilities must be reasonable if the concept is to be accepted by smaller industries. Therefore, it is important to determine whether these projected costs are accurate because competition may be restricted if such centers are constructed.

The two broad technical research needs for regional centers are improved processes and definitions of the wastes to be handled. These needs, of course, are not unique to regional centers. In addition, health studies of workers and the neighboring populace should be considered during the initial phases of operation of a regional center. Economic optimization studies concerning transfer and collection points and transportation are essential for the implementation of this entire concept.

REFERENCE

Felder, R. M., R. M. Kelly, J. K. Ferrel, and R. W. Rousseau. 1980. How clean gas is made from coal. Env. Sci. and Technol. 14:658-66.

HAZARDOUS WASTE MANAGEMENT

CHEMICAL AND PHYSICAL TECHNIQUES

All the disposal methods discussed in this report involve chemical and physical techniques. Even those that appear to be simply storage methods involve physical and chemical techniques if one considers long-term problems of corrosion or mobility of chemicals in the environment. There are a large variety of hazardous wastes and a substantial number of chemical and physical processes. The engineer must consider the alternatives for disposal of each waste. Research must continue to the point at which the characteristics of each applicable process are understood sufficiently for design and economic evaluation.

The chemical engineering community traditionally has characterized chemical and physical techniques in terms of unit operations for the physical processes and unit processes for classes of chemical reactions. Berkowitz and coworkers (1978) reviewed many processes and operations and discussed the characteristics and perceived prospects for waste treatment using each of these operations and processes. They also identified those requiring additional research. Most of these unit operations and unit processes are listed in Table 1.*

A few of the unit operations listed (e.g., adsorption and ion exchange) are effective in removing trace components from a gas or liquid effluent stream, applications generally excluded from this study. When a dilute aqueous waste stream, however, is treated by a typical biological process, very minor amounts of toxic constituents may inhibit biological activity or may concentrate in the sludge and preclude an inexpensive sludge management option. It might be necessary to remove or chemically modify highly toxic trace components prior to biological or other treatment. For this reason, all unit operations and unit processes have been left in Table 1 simply because many applications would be for dilute wastes.

Many of the unit operations and unit processes in Table 1 were developed 40 or more years ago. There is a common misconception that the

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*Four were judged to be inapplicable for the treatment of hazardous waste, seven are based on biological treatment and are discussed later in this report, and some were combined.

TABLE 1 Physical and Chemical Treatment Processes

Physical Processes or Unit Operations

- Stripping--air or steam
- Suspension freezing or freeze crystallization
- Adsorption (on carbon, resin, or other adsorbers)
- Centrifugation
- Distillation (including steam distillation)
- Electrodialysis
- Evaporation
- Filtration
- Flocculation, precipitation, and sedimentation
- Solid-liquid extraction or dissolution
- Flotation and foam fractionation
- High-gradient magnetic separation
- Ion exchange (solid-liquid or liquid-liquid)
- Liquid-liquid extraction (including liquid membranes and supercritical technology)
- Reverse osmosis
- Ultrafiltration
- Crushing and grinding
- Cryogenics

Chemical Techniques or Unit Processes

- Calcination and sintering
- Catalysis
- Chlorinolysis
- Electrolysis
- Hydrolysis
- Microwave discharge
- Neutralization
- Oxidation
- Ozonolysis
- Photolysis
- Reduction

research needs in these processes must be negligible. However, engineers attempting to apply liquid-liquid extraction for hazardous waste management, for example, often find the needed basic or fundamental data to be very meager.

Selected areas in which research should lead to new applications of technology are discussed below.

Thermodynamic and Transport Properties of Hazardous Materials

Information on thermodynamic and transport properties is required for most of the techniques listed in Table 1. There is a continuing need for the experimental determination of physical and chemical properties (in the broadest sense) of various chemical species and their mixtures. There is also a need for improving correlations by which these properties can be estimated in the absence of reliable experimental data.

Supercritical Fluids

A supercritical fluid with applications to hazardous waste treatment may be thought of as a solvent, used somewhat above its critical temperature and critical pressure. The solvent is normally predominantly a single substance (e.g., water or carbon dioxide) but other components may be present in addition to the waste being treated. Superior solvent properties are often accompanied by higher mass transfer rates.

There is currently renewed interest in the use of supercritical fluids in separation processes. Most applications involve fluid-liquid or fluid-solid extraction, but a hybrid process combining distillation with extraction might be developed. Examples are the use of supercritical CO_2 as an extractant in the food industry and of supercritical toluene for the extraction of coal liquids. These processes seek to utilize the superior solvency properties or unusual thermodynamic properties of supercritical fluids to achieve difficult separations.

Supercritical CO_2 has been used to regenerate carbon used for pesticide adsorption (Modell et al. 1980) and to extract polychlorinated biphenyls (PCBs) from oil (deFilippe 1982). Supercritical water oxidation has been tested for destruction of PCBs and several chlorinated hydrocarbons (Modell 1982).

Once a hazardous material is dissolved in a supercritical fluid, a number of possibilities for further treatment exist. The waste may be concentrated by further extraction or by distillation for subsequent disposal by another technique. If the waste molecules are relatively large, elevated pressure and temperature may cause enough bonds to be broken that the material is no longer hazardous. If the fluid is water, many organic materials can be oxidized to such species as water and carbon dioxide by introducing air or oxygen to the fluid. The process then becomes an application of wet air oxidation, which is discussed later in this report. Detoxification with reactants other than oxygen might be attractive in certain applications.

Research needs obviously depend on the proposed application, but there are some common aspects of the research required. If the supercritical fluid is water, the high temperature and pressure required pose difficult problems in selecting materials of construction. Thus, corrosion and similar studies are needed. Since the success of these processes depends on the unusual thermodynamic properties of the supercritical fluid, these properties must be measured carefully. Specific heat and heat of mixing data become more important as the latent heat of vaporization becomes a smaller factor or irrelevant. Solubility studies may also be required. Diffusivities of different substances in supercritical fluids and mass transfer coefficients at solid-fluid and liquid-fluid interfaces also should be measured.

Liquid Membranes

Liquid membranes refer to a relatively new development that might be considered a variant of liquid-liquid extraction. In a liquid membrane system, small droplets of water containing a surface active agent form an emulsion in an organic medium such as kerosene. This emulsion phase is contacted, perhaps countercurrently, with an aqueous solution containing hazardous wastes. The object is to move the hazardous waste molecules from this second aqueous phase through the organic oil layer and into the internal water droplets of the emulsion phase. The driving force for the mass transport is achieved by providing a chemical species inside the drops that reacts with the hazardous waste. The resulting species must have low permeability through the organic oil layer surrounding the droplets so that the product formed from the hazardous molecules does not diffuse back into the aqueous liquid being detoxified. The method is applicable to the removal of relatively small amounts of toxic molecules from predominantly aqueous mixtures. An example could be the removal of phenol from water. A base such as sodium hydroxide could be the reactant inside the spheres. Performance of the system would be influenced, of course, by the nature of the organic oil as well as by the other chemical species involved in the separation.

Liquid membrane development began in about 1970 (Li 1971a and 1971b). As with other techniques, the method has advantages and disadvantages. Additional research on these systems is warranted from the standpoint of potential applicability to hazardous waste treatment.

Similar liquid membrane systems can be formulated without the oil to improve membrane stability characteristics. Instead of the thick oil layer, a bimolecular layer (e.g., 50 angstroms thick) of a surface active agent is used as the membrane. Such spherical bilayer membranes, called vesicles or liposomes, are extensively used in biochemical and biomedical research. Conceptually, the vesicles are the closest analogs of biological membranes and can be used for any membrane-based chemical separation. The separation can be enhanced by proper selection of the surface active material as well as the reactive species encapsulated inside spheres. Research on the design of vesicles for practical separation is in its early stages, and more work is warranted to define the potential of these systems.

Flotation and Foam Fractionation

Bubbles rising through a liquid may separate material from the liquid by the three processes referred to as conventional flotation, microflotation, and microgas dispersion (MGD) separation. The first two methods, used extensively in the mineral industries, undoubtedly have applications in the concentration of hazardous wastes. The purpose of this section, however, is to call attention to the newer MGD method, which was invented in 1971 (Sebba 1972).

An MGD consists of a uniform dispersion in a liquid of extremely small gas bubbles. Because of the presence of surface active molecules at the gas-liquid interface, the liquid in this region has different properties from the bulk liquid. As a consequence, the bubbles do not coalesce readily when they meet and instead rise unchanged in size to the top of the column of liquid without releasing any of the material they have adsorbed (Sebba 1975). An MGD can be held for some seconds or minutes before it breaks, depending on the concentration of surface active material in the solution in which it is made (Shea and Barnett 1979). It can, therefore, be prepared in one apparatus and pumped to another (e.g., a column). Generation of an MGD is described elsewhere (Sebba 1971, Shaler and McLean 1975, Shea and Barnett 1979).

When MGD bubbles meet, they become linked to one another by bridges between the outer surfaces. Such aggregates of many tiny bubbles behave somewhat like much larger drops of low-density homogeneous liquids. Upon arrival at the surface, the bubbles in the MGD retain their adherence to each other and do not tend to scatter or lose the material they have adsorbed. The layer of "loaded" linked bubbles at the surface can be overflowed and allowed to break, forming a concentrate of the contaminants, or it can be dried directly.

One common requirement of MGD formation and utilization is the introduction of a surface active chemical into the liquid of which the MGD is made. Its function in the formation of the MGD has been discussed (Sebba 1975). As with conventional flotation and microflotation, the adsorption function that makes the bubbles useful for extraction purposes is aided by the presence of a surface active agent on the bubble surfaces; therefore, the surfactant reagents used must be compatible with both the MGD generation process and the particular extraction purpose toward which the MGD flotation is directed. This makes the selection of the optimum surfactant (as well as the optimum pH of the influent and the use of flocculants) more complex when MGDs are used than it is in the less interrelated processes of conventional flotation or microflotation.

MGDs have the potential for extracting toxic materials from water. There is an art, so far only partially developed, for picking a suitable surfactant for removal of a particular material. There are probably unsolved problems concerning the collapse and ultimate disposal of the foam containing the toxic materials. The committee is not aware of a commercial application of MGD technology. For at least some potential applications, the problem seems to be more economic than technical. Continued research is warranted on the use of MGDs for removal of toxic substances from liquids.

Adsorption and Ion Exchange

The use of ion exchange (IEX) and sorbent materials (porous resin beads without exchange sites) in water treatment, chemical separations, and a variety of analytical methods is well established. Major advantages of these materials are high capacities for exchange or adsorption, relatively fast mass transfer rates, chemical and mechanical stability, suitability for continuous and recycling operations, and versatility. Cost of the resin and regenerating chemicals as well as ultimate disposal of the concentrated material are inherent problems. Most uses of ion exchange or adsorbent materials for toxic and hazardous waste control would fall into one or both of two major categories:

1. Concentration, isolation, removal

2. Decontamination, detoxification.

To illustrate applications for these materials that should benefit from future research, two specific problems are discussed below.

Treatment of Leachate from Landfills

A variety of toxic species can leach from dumping grounds, landfill sites, and leach fields. Heavy metal ions are, of course, among the offenders and could be removed by chelation onto solids in a variety of ways (e.g., Chelex resins in the Ca^{2+} form, precipitating resins, liquid chelating agents supported on inert materials). It would be important--as in most other applications--to minimize the possibility of "fouling" of resins by appropriate pretreatment, by adjusting to conditions (pH, etc.), and by using resins that are least prone to fouling.

Besides the obvious heavy metal ions there are numerous organic species that are likely targets for removal by IEX. Chlorinated phenols (especially pentachlorophenol and 2,4-dichlorophenol) similar to other substituted phenols, including nitrated phenolics, could be removed by anion exchange resins of the conventional type since they are very strongly adsorbed.

Other organic species that cannot be removed this way could be oxidized prior to such a removal operation (phenolic and carboxylic groups are created which will permit anion exchange sorption). On the other hand, prior reduction of nitro compounds to amines would make possible their removal by strong acid cation exchangers ($RNH_2 + H^+ \longrightarrow RNH_3^+$) that would, in any event, pick up most aromatics and heterocyclics containing tertiary nitrogens (e.g., Atrazine, Paraquat, "BZ"). The possibility of detoxification by adsorption or ion exchange prior to landfill also should be considered.

Application to Various Liquid Waste Streams

Dilute aqueous industrial waste streams should be easy to concentrate (volume reduction) by IEX, and toxic traces could be removed in the same step. There are many possibilities (e.g., the corrosion inhibitor wastes from cooling tower blow-down) for application of IEX or, more likely, reactive ion exchange (RIEX). A more difficult problem is posed by concentrated liquid waste because: (1) the "selectivity" of conventional ion exchangers is greatly reduced by indiscriminate electrolyte invasion (i.e., the exchanger no longer "prefers," for example, Pb^{2+} over Na^+) and (2) the resins are soon exhausted at high electrolyte concentrations. Still, there are various possibilities, depending on the task at hand.

Special conditions will exist for almost any type of waste (e.g., electroplating waste presents different problems from photo finishing waste). However, the use of high capacity ion exchangers, including inorganic exchangers (e.g., zeolites) should be investigated because of the ease of solid-liquid phase separation and the outstanding possibilities for high selectivities based on chelating and other reactive systems (redox, precipitation).

The potential for recovery of strategic and other valuable materials should be considered in conjunction with the pollution problem. Ion exchange (in conjunction with other treatment steps) may be an appropriate technique to use. Selective *in situ* reactions with exchangers in continuous fluidized bed operations should be considered among other approaches.

Dewatering of Sludge

A waste disposal problem that has resisted economic solution by such unit operations as evaporation, centrifugation, filtration, and sedimentation is the dewatering of certain slimes and sludges. Currently these materials often are placed in "settling ponds" where the desired evaporation or settling fails to occur and the land area set aside for these ponds continues to expand. There is a need for research directed toward a low-cost process for removing the water from these materials so that ultimate disposal (perhaps by land treatment, permanent storage, or landfilling) can be simplified.

BIOLOGICAL TECHNIQUES

Biological waste treatment is used widely for municipal and some industrial wastes but is less widely used for hazardous industrial waste treatment and disposal. One notable exception is the biological degradation that is part of the land treatment process used for industrial wastes. A discussion of land treatment is presented later in this report.

Biological treatment involves the degradation of organics either by an indigenous microbial population or by organisms adapted to act specifically on a compound or group of compounds. Both aerobic and anaerobic processes are used. The most common biological treatment methods include activated sludge, aerated lagoons, trickling filters, stabilization ponds, and anaerobic digestion. Table 2 lists these and other biological treatment processes that can be used for the degradation of organic wastes. These processes are generally used for the treatment of liquids or slurries. Certain processes (composting and digestion) can be used for slurries and solids. The design details and operational characteristics of these systems are described in many texts and references (Clark et al. 1977, Loehr 1977, Metcalf and Eddy, Inc. 1979).

Only organics that can be metabolized by the microorganisms present in the biological treatment processes and under the operating conditions (temperature, residence time, pH) of the reactors will be removed. In addition, there will be incidental physical removal of metals and nonbiodegradable organic toxic pollutants in biological treatment systems. Thus, although biological treatment systems are designed to remove organics by microbial degradation, there actually are several removal mechanisms that result in the detoxification of hazardous industrial wastes in such systems: microbial degradation, air stripping, volatilization, and adsorption to the sludge or other solids in the treatment system. Other possible mechanisms include hydrolysis and photolysis, but they play a minor role in biological treatment processes.

In the treatment or disposal of hazardous industrial wastes, biological treatment processes are normally only one component of the system that is used (see Figures 1 and 2). To realize the full potential of biological treatment for the control and detoxification of hazardous industrial wastes, additional information is needed on the mechanisms of hazardous waste removal in biological systems, on unconventional biological treatment processes that can be used, and on approaches to define the lower levels of toxicity of hazardous industrial wastes.

Insufficient information exists on the mechanisms of removal of hazardous organic and inorganic pollutants in biological treatment systems. Although abundant information is available on the concentrations of conventional and some toxic pollutants in the influent and effluent of a biological treatment process or system, there is only a limited understanding of how toxic pollutants are removed. Treatment process performance data that permit input and output mass balances of pollutants in all parts of a treatment system must be obtained if the

TABLE 2 Common Biological Treatment Processes.

Process	Aerobic	Anaerobic	Attached Growth	Suspended Growth	Waste Treated		
					Liquids	Slurries (Sludges)	Solids
Activated sludge	X			X	X		
Aerated lagoons	X			X	X		
Oxidation ditch	X			X	X		
Oxidation ponds	X			X	X		
Trickling filters	X		X		X		
Rotating biological contractors	X		X		X		
Liquid aerobic composting	X			X		X	
Expanded bed reactors	X	X	X		X		
Anaerobic lagoons		X		X	X	X	
Anaerobic filters		X	X		X		
Anaerobic digesters		X		X		X	X
Composting	X			X		X	X
PACT process[a]	X			X	X		

[a] A modification of the activated sludge process that incorporates powdered activated carbon in the aeration basin.

mechanisms of toxic pollutant removal are to be determined. With such fundamental knowledge available, better treatment processes can be developed and designed, better detoxification can be obtained, improved system performance can be attained, and transfer of toxic pollutants from one medium to another can be minimized.

Studies to identify the mechanisms of removal that occur in biological treatment processes (stripping, adsorption, degradation, sedimentation, etc.) and to relate these mechanisms to the amount and type of toxic pollutant removal that does occur are appropriate. These studies should evaluate processes (e.g., those in Table 2) actually being or likely to be used to treat hazardous industrial wastes. Initial studies should include an intensive evaluation of available literature to identify and evaluate data on the mechanisms of toxic pollutant removal in biological treatment processes. In addition, studies with commonly used biological treatment processes could identify the toxic pollutant removal mechanisms that occur under varying operating conditions. Other studies could investigate biological treatment processes that are not in common use but that have promise. Ultimately, large-scale studies are needed to verify results from literature and laboratory studies.

The common biological waste treatment processes are identified in Table 2; however, there are other processes and approaches that have shown promise and deserve further evaluation for use with hazardous industrial wastes. Among the more intriguing of these other processes and approaches are thermophilic aerobic treatment and genetic engineering.

Thermophilic processes are high-temperature (greater than 35 to 40°C) processes. Almost all conventional biological treatment processes operate in the mesophilic temperature range (about 10 to 30°C) and, in the winter, may operate in the psychrophilic range (less than 10°C). Under normal conditions, thermophilic processes are rarely used for biological waste treatment because of the costs of maintaining high temperatures. However, with smaller volumes of concentrated organic wastes (e.g., some industrial wastes) thermophilic processes may have more potential.

Thermophilic temperatures are automatically achieved by composting processes. Traditional composting can be used with solid wastes and "liquid composting" can be used for slurries or concentrated liquid organic wastes. In addition, many industrial wastes have temperatures considerably above ambient, thus making consideration of thermophilic processes more feasible.

At high temperatures, metabolic reaction rates are increased, volatilization rates are enhanced, pollutant removals are increased, and reactor volume requirements are reduced. Certain hazardous industrial wastes have characteristics that are amenable to thermophilic processes (high organic solids concentrations, above ambient temperatures). If successful, thermophilic processes can achieve significant detoxification of hazardous wastes under technically and possibly economically feasible conditions.

Almost nothing is known about actual hazardous waste removals and detoxification with thermophilic biological treatment processes. A research effort is warranted to explore thermophilic processes as potentially feasible biological detoxification processes. The effort should determine: (1) the removal of toxic compounds that takes place in thermophilic biological treatment systems and (2) the pertinent design and operating parameters that affect such removals. Initial efforts should identify the effect of process variables (e.g., temperature, pH, oxygen transfer, solids concentration, retention time) on the amount of detoxification that occurs. Subsequent efforts should involve larger scale studies with actual wastes to verify and extend available information, evaluate relative economics, and develop realistic design criteria.

Advances in molecular genetics in the past decade have made possible the rearrangement of genetic information in microorganisms. Improvements in the biodegradation of toxic pollutants through genetic engineering will ultimately rest on the type of genetic manipulations that have only recently been possible.

Although there has been rapid progress in the use of genetic engineering to produce specific biochemicals, progress in the development of pollution control technologies based upon genetically manipulated organisms is in its infancy. Specific problems still to be resolved include: (1) the ability of such modified organisms to survive in a treatment system, (2) their performance in the diverse nature of organic compounds in a typical industrial waste, and (3) the potential effect of introducing novel organisms into the environment.

Because a biological treatment system is not a closed, environmentally controlled system and because the wastes being treated are likely to contain numerous organic compounds, genetically manipulated organisms would have to exist and compete with indigenous organisms. However, it might be possible to have the genetically engineered organisms exist long enough to accomplish the desired degree of detoxification. A specific treatment or detoxification process will have a somewhat special set of conditions (temperature range, characteristics, concentrations, etc.) that will affect the design and operation of a genetically engineered system. National Institute of Health (NIH) guidelines on the release of genetically modified DNA to the environment will have to be reviewed and followed in developing any system using genetically engineered organisms to detoxify hazardous wastes.

Attempts to use genetically engineered organisms for control and detoxification of hazardous industrial wastes have not been extensive. Because many wastes identified as hazardous are halogenated compounds, one possible fruitful research area could be the use of genetically engineered organisms to enhance dehalogenation reactions. Efforts in this area should include identification of: (1) genetically adapted microorganisms that can degrade potentially toxic organics better than existing microorganisms, (2) the removals that would occur with such microorganisms under closely controlled conditions, (3) the ability of such microorganisms to survive and compete in actual systems, and (4) any potential danger should these modified organisms remain in the environment.

In addition to considering dehalogenation, a literature review and data evaluation of the possibility of genetically adapting microorganisms for the degradation of other hazardous industrial wastes should be conducted. The process and operating conditions under which the adapted microorganisms could be utilized to detoxify different hazardous wastes should then be identified.

Biological treatment processes are designed and operated to meet specific performance criteria. Normally, these criteria relate to the reduction of conventional pollutants affecting factors such as biochemical oxygen demand (BOD) and total suspended solids (TSS). Methods for measuring BOD and TSS are well established and used routinely.

Biological treatment processes used to detoxify hazardous industrial wastes have as their objective reducing the toxicity of hazardous industrial wastes as well as the BOD, TSS, and other conventional parameters. Unfortunately there are no simple, readily available methods that treatment plant personnel can use to establish when adequate detoxification has occurred. Thus, there are no accepted performance parameters that can be used for the design and operation of biological detoxification systems for hazardous industrial waste. Biological measuring methods, such as BOD, produce erroneous results if the microorganisms are inhibited by toxic compounds.

To overcome this difficulty, broad spectrum and specific chemical analyses are being developed. The broad spectrum analyses attempt to quantify a range of specific chemicals or classes of chemicals found in industrial wastes. Specific chemical methods of analysis measure the presence and concentration of a compound or class of chemicals. Such analyses will not identify if a "hazardous" constituent is being degraded unless the constituent is known. More appropriate methods, short of fish bioassay methods, must be developed to: (1) determine if treated industrial waste is toxic, (2) estimate the degree of toxicity that may exist, (3) determine the amount and rate of detoxification that occurs with biological treatment processes, and (4) provide measures of performance that can be used for design and operation of biological treatment systems for hazardous industrial wastes.

Measurement of potentially toxic organics in industrial wastes, effluents, and stabilized solids continues to be costly and is not done routinely. Less costly and more rapid analytical approaches are needed to reduce monitoring and compliance costs and to provide greater information on the amount and type of toxic materials entering and being discharged from hazardous waste treatment facilities. These approaches also are needed to determine when a waste is no longer toxic and to establish system performance and goals (i.e., the satisfactory level of detoxification and the degree of treatment that should be achieved).

Although such toxicity assay methods are relevant to other treatment and disposal processes, they are particularly pertinent to biological treatment systems. Biological system performance depends on factors that affect biological activity rather than on the identity or destruction of specific chemicals. Thus, it is important to develop more routine analytical methods that can estimate or measure the toxic pollutant, the pollutant removal that occurs in biological treatment processes, and the impact of toxic pollutants on many forms of biota in the environment (i.e., microorganisms and higher forms of aquatic and terrestrial life). The methods should be suitable for analysis of wastewater, sludge, soil, and the atmosphere.

In summary, several major research efforts are needed to achieve better use of biological treatment processes for the control and detoxification of hazardous industrial wastes. The major research needs are:

1. Identification of the removal mechanisms for components of hazardous industrial wastes so that better treatment processes can be developed and so that transfer of toxic pollutants from one medium to another will be minimized.

2. Evaluation of aerobic thermophilic processes for detoxification of hazardous industrial wastes; such processes may be technically and economically feasible with concentrated organic industrial wastes.

3. Evaluation of the potential of genetically adapted microorganisms to detoxify specific hazardous industrial wastes.

4. Determination of analytical methods, short of fish bioassay methods, that can provide measures of detoxification when biological treatment processes are used; such methods should be capable of routine use.

LAND TREATMENT

Land treatment is the use of a soil system or a vegetation-soil system as the ultimate receiver of a waste. The hazardous waste materials applied to the land may be slurries, sludges, untreated wastes, residues, or solid wastes. Typically, the wastes are mixed with or applied to the surface zone (0-1 ft) of the land. Chemical and biological reactions then break down a portion of the waste, adsorption and fixation occur for other portions, and controlled migration (within drinking water standards) is allowed for certain anionic inorganic fractions of waste (nitrate, chloride, etc.). Land application is not landfilling or waste storage; rather, it is a viable method of long-term treatment. Within a short period after closure of an area used for land treatment, such a site, if designed appropriately, can be used for agricultural production (i.e., the land area is not rendered permanently restricted in use).

It must be recognized that land treatment systems may require substantially more design and monitoring than other more widely used and/or recognized technologies. Active full-scale system monitoring and research are presently being undertaken on air emissions, hazardous organic compound degradation, and closure or long-term agricultural or societal use. However, the technical capability to manage virtually all types of wastes and the generally attractive economics make land treatment viable, even with design and monitoring requirements, in a substantial number of situations.

The key to hazardous waste land treatment systems is the utilization of an overall design approach (Brown and Associates, Inc. 1980, Loehr 1976). This is necessary to land treat the widest variety of hazardous industrial materials under very diverse site conditions. Most wastes, including those containing industrial organic and inorganic compounds, high levels of metals, toxic compounds, priority pollutants at any concentration, salts, acids or bases, pathogens, large liquid volumes, and a variety of other species, have been treated successfully by land application within the assimilative capacity of the soil. At present there are approximately 200 hazardous waste land treatment systems in the United States and over 1000 such systems for nonhazardous industrial waste.

The design of industrial land treatment systems for hazardous wastes centers on two primary tasks: (1) the detailed specification of the land treatment area required and the critical waste constituents controlling this land area and (2) the engineering specification of the land treatment components necessary to implement a complete system.

The first of these tasks involves comprehensive waste characterization (typically 20 to 30 parameters) and the very important assessment of the actual site capabilities (vegetation, topography, groundwater, soils, etc.) for land treatment. Many areas of expertise are necessary to accomplish this first task so that the objective of successful, long-term performance without adverse environmental impact is realized in management of hazardous wastes.

The second design task involves some of the land treatment system components most commonly associated with the land application of all types of waste. The most familiar are the equipment used to spread waste on the land surface (e.g., spray irrigation, tanker hauling and spreading, center pivots, soil injection). However, many more components such as monitoring, land preparation, agricultural or silvicultural crops, storage, transmission, buffer zones, closure and post-closure procedures, security, and aesthetics must be considered in the overall system design. Only with detailed specification, preparation of drawings and/or manuals, and inclusion of all essential components of a land treatment system will this hazardous waste management option be assured of successful, cost-effective, and efficient operation and performance.

Increasing numbers of industrial facilities representing virtually all of the standard industrial categories are adopting land treatment for hazardous wastes because of its very distinctive economic and technical advantages (Brown and Associates, Inc. 1980). Thus, it is correct to state that almost all hazardous wastes (except radioactive materials) can be managed by a land treatment system meeting high levels of environmental and health standards. However, this approach may not be cost-effective in every instance because of the amount of land required. Thus, the economics of land treatment systems as well as the technical design criteria determine whether the land application alternative is selected for management of hazardous wastes.

Based on a comprehensive review of land treatment of hazardous wastes, the committee identified a variety of research and development needs. These are described below in approximate order of importance.

In an emerging technology such as land treatment, information on the behavior of waste constituents in soil from readily available sources, when verified, allows transferability of design criteria. This reduces the need for extensive research efforts on every waste and every site. For each category of industry, waste composition and strength varies considerably from plant to plant. Such variations make experimental determinations of land application loading rates infeasible for each industrial facility. A further disadvantage of the repetitive experimental approach of field tests for each new waste or site is the time for completion. One to three years of testing imposes a substantial economic penalty due to inflation. These and other factors lead to the conclusion that *a priori* design tools are an essential need for this technology.

The assimilative capacity of a terrestrial environment is determined by the rates of degradation and/or the amounts of organics that are degraded, the hazardous waste components that are rendered nonhazardous, and the inorganic contaminants (including metals) that are immobilized. The capacity is variable, depending on specific site conditions, waste properties, environmental conditions, and management. The techniques used to determine the assimilative capacities are not completely standardized, and further research on assimilative capacities is needed so that the design and operation of land treatment facilities can be optimized. Both field and laboratory techniques can be effective in determining assimilative capacities.

The determination of assimilative capacity for organics centers on measurements of half life and other pertinent factors in the loss rate from a soil system. Organic adsorption and mobility are important factors. Immobilization reactions and equilibria in soils are the basis for managing metals and, thus, determine the assimilative capacity when these are present. These same phenomena dictate the response of vegetation to metals and, hence, closure restrictions.

Documented economic studies are also important in the acceptance of a technology even when it is low cost. Thus, economic evaluation research is critical to the broad use of land treatment. Estimates of the design costs for individual components (storage, application systems, monitoring, etc.) and the overall industrial costs for operating hazardous waste land treatment systems should be made. Common economic bases should be used to allow comparison to other hazardous waste technologies.

A wide range of land treatment systems is being used for the management of hazardous wastes even though the costs have not been thoroughly analyzed or published. These systems vary in terms of the type and location of land areas used and the physical and chemical characteristics of the waste treated. The determination of capital and operating costs as well as the technical specifications for these systems will provide a good overview of the economics (mean values and extremes) of land treatment. These data should be organized to establish the effect of size and other relevant variables and should provide regulatory bodies and industry with the information they need on land treatment to make decisions regarding hazardous waste alternatives. Further, a more detailed understanding of land treatment system economics and efficiency can be gained by developing cost curves for the individual equipment and facilities that comprise full-scale industrial systems; information on as many of the existing land treatment sites as possible should be included.

In certain hazardous waste management situations, the combination of land treatment and waste modification in-plant or by pretreatment can cost less than land treatment alone. For example, selective reduction of certain fractions of the waste may minimize the overall cost of a pretreatment and land application system. This balance of options should be examined in detail as a mechanism for reducing the cost of hazardous waste management by land treatment.

The plant-soil system has a unique capability for treating hazardous wastes. The limitation on these capabilities is that some constituents require more land area than others, based on the mass present in the waste and the assimilative capacity of the given plant-soil system. Research is needed to establish what pretreatment or in-plant options are available to reduce the amounts of those constituents that most influence the amount of land required. With the definition of available pretreatment technology, the levels of removal and the corresponding costs must be documented. Comparisons can then be made between these pretreatment or process modification expenditures and land treatment costs to establish a cost-effective combination that will meet all environmental standards.

The design criteria and procedures exist to land treat almost any industrial waste (hazardous or nonhazardous). However, many industries and plant personnel have only a vague concept of land treatment and, hence, are unaware of this technology for their specific use. To solve this problem, a series of industry-specific documents and other information transfer aids are needed. Wide distribution and use of such documents should increase the use of land treatment or pretreatment and land application for hazardous wastes.

Land treatment is currently used most widely in the food and petroleum industries. There is a need to identify, with some priority, other waste categories that can be treated by this technology. Since a very large number of categories will probably be involved, this research should focus on those designated as having the greatest impact with respect to hazardous industrial wastes.

In conclusion, several major research and development investigations are necessary to broaden significantly the use of land treatment for hazardous wastes. These major needs are:

1. Substantial expansion of the system design data base for land treatment with an emphasis on transferable laboratory-scale information and verification in selected field-scale systems.
2. Documentation of the economics of full-scale hazardous waste land treatment systems, including costs of the individual field components of the total system.
3. Technical and economic consideration of process modifications or pretreatment in combination with land treatment to yield a lower total system cost than land treatment alone.

OCEAN ASSIMILATION

For many years industrial waste has been dumped into the oceans. All too often, this has been done indiscriminately, with little thought given to regional characteristics, waste type, oceanic conditions, and the presence of endangered species. Excessive levels of hazardous pollutants in near-shore locations, increased concentrations of toxicants in marine life, and curtailed recreational and commercial opportunities have resulted.

Various nations have responded to the threat, and some, including the United States, have simply banned ocean waste disposal operations. It is the opinion of this committee that the complete ban that was to be effective December 31, 1981, should be reconsidered. A cohesive research and development program should be designed and implemented to identify conditions whereby the oceans could be used for disposal without harm to the public or the environment. The committee recommends the consideration of two approaches for utilizing the ocean for assimilating wastes: controlled ocean dispersal systems and controlled ocean confining systems.

Controlled Ocean Dispersal Systems

The assimilative capacity of the ocean for waste has long been discussed. Both the positive and negative factors have been considered. During the 1970s there was general opposition to ocean dumping. This attitude was similar to the concerns about open-burning dumps in the 1950s and about polluting incinerators in the 1960s. The public opposition to uncontrolled open-burning dumps and polluting incinerators stimulated the development of sanitary landfills and modern resource recovery plants. Likewise, the concern about ocean dumping should stimulate development of a new concept, that of controlled ocean dispersal systems.

The word "controlled" refers to the science and engineering that minimize environmental damage and to the use of reliable equipment and the achievement of a reasonable cost. The word "ocean" includes the Pacific, the Atlantic, the Caribbean, and the Gulf of Mexico (i.e., the bodies of water contiguous to the continental United States). The word "system" refers to the total process, starting at the port. Included in the system are any portside pretreating processes of mixing, physical-chemical treatment, encapsulation, etc., loading onto ships (or into pipelines), and transport. The most important activity in the system, however, is the actual dispersion of selected wastes into the ocean.

The committee's opinion is that a total ban on ocean disposal of waste is unnecessarily restrictive and not in the public interest. Rather, it believes that a controlled ocean dispersal system, when used properly, can be an effective technique for waste management. No technique of waste disposal is without problems. Continental landfilling can pose the threat of drinking water contamination. Land-based incineration and energy recovery systems, even though optimally controlled, can still emit submicron-size particles and gases that are objectionable. The committee recognizes the need for a considered balance between land and ocean operations, both properly controlled.

Considerably more information is presently available regarding the interaction of wastes with marine and fresh water systems than was the case even three or four years ago. Efforts by such groups as the Environmental Protection Agency; universities along the Atlantic, Pacific, and Gulf Coast; public and private research laboratories; oceanographic institutes; and, in the case of the Great Lakes, the International Joint Commission and Canadian Center for Inland Waters have added considerably to the body of knowledge concerning marine physical, biochemical, and chemical processes. Additional basic data on water mass movements, transport rates from water to sediments, biological mobilization of materials, and other pertinent processes also are available. Information like this can be incorporated into the mathematical models of ocean dispersal that are under development.

This is not to say that all of the questions have been answered or even addressed but only that a reconsideration of ocean dispersal in the light of the current state of the art is warranted. For example, there is a serious pollution problem of unproven origin in the Baltic Sea (Davis 1981). The coastal areas of Poland, Latvia, Lithuania, Estonia, and the Gulf of Finland near Leningrad are extensively polluted. Dead fish and fish with carcinomas and melanomas are being caught. Some claim that the situation is not related to ocean waste disposal whereas others blame such practices. Implementation of a properly designed controlled ocean dispersal system should prevent such conditions; however, before proceeding too far, the United States must understand the causes of this and other phenomena.

The older ocean dispersal procedures need to be reviewed for their relevance to the principles of RCRA. Part of this review has been accomplished in support of the New York 106-mile acid bight. The International Agreement on Ocean Disposal of Waste (the London Convention) that limits ocean dumping also needs to be considered.

A tiered decision-making approach needs to be developed. This could take the form of a series of screening approaches or could use a critical path scheme, a decision tree, or some other management tool.

Numerous scientific issues need to be researched. These include:

1. Classification of different sites for different kinds of wastes.
2. Determination of the time of day or tide position most appropriate for discharge.
3. Determination of whether seasonal variations affect the applicability of this technique.
4. Identification of conditions for utilizing the continental shelf or the trough or the slope in the abysmal regions.
5. Identification of available dispersion techniques.
6. Development of time release methods.
7. Development of monitoring procedures.
8. Development of models of sufficient accuracy to predict the transport, the ultimate fate, and the ecological impact of dispersing wastes.
9. Identification of special procedures required for special wastes (e.g., PCBs).

10. Identification of synergistic effects of combining pollutants.

11. Determination of maximum allowable concentration levels for various substances.

12. Tracking of discharges, both spatially and temporally.

13. Identification of animals and vegetation that should be protected and animals and vegetation to be sampled as effective predictors of adverse affects.

14. Biological concentration of toxic materials.

The objective of this research is to develop a collection of knowledge that makes possible the use of controlled ocean dispersal systems to dispose of selected wastes on a continuing basis in the ocean with negligible damage. The output of the research is essential to the treatment, storage, and disposal community that desires to practice controlled ocean dispersal and to the U.S. Environmental Protection Agency and other regulators that must approve or disapprove of such plans.

Controlled Ocean Confining Systems

In contrast to the concept of controlled ocean dispersal systems, there is the potential for proper waste management in the development of controlled ocean confining systems. This concept attempts to take advantage of natural material "sinks" in the ocean.

Research is needed to determine whether waste can be adequately confined by placement in deep trenches where the flow velocity is very low. Possible ecological consequences and containment requirements should be identified.

Grabens are elongated depressions of the earth's crust between two parallel faults. Often these grabens are filled with sediment. Hazardous wastes could be injected into these sediments if it could be determined that this resulted in immobilization. The locations of appropriate grabens and the techniques needed to utilize them need to be investigated.

Sub-seabed or "at-sea deep well" injection has been mentioned as a method to store waste in a concentrated form (Davis 1981). Appropriate under-seabed formations such as salt domes are known, and shafts could be sunk and waste injected. The technique is the same as land-based deep well injection, except that the injection point at sea would be an off-shore platform or a ship. Recent discovery of a natural suction flow of seawater beneath certain areas of the ocean may provide clues for locating feasible injection regions (Davis 1981).

INCINERATION

The thermal oxidation in excess air of industrial organic waste in a combustion reactor where ash, combustion flue gases, and heat are produced is commonly called incineration. Typically CO_2, H_2O, and ash are produced, but other combustion products such as SO_2, NO_x, HCl, and metal oxides may be present and require control.

Pyrolysis is differentiated from incineration only in that the starting materials are heated in a deficiency or absence of oxygen (i.e., less than stoichiometric) to yield products such as CO, NO, HCl, Cl_2, volatile hydrocarbons, pyrolytic oils, metals in the vapor state, and char. Sometimes, to produce the required heat, limited amounts of pyrolytic gas or oil products are recycled to the reactor. Manufacturers offer thermal reactors both for incineration (excess air) and pyrolysis (air deficient) applications.

Thermal reactors for the disposal of hazardous wastes can be categorized as follows:

1. Afterburning combustor
2. Catalytic incinerator
3. Cement kiln with waste as a fuel supplement
4. Conventional boiler with liquid waste as a fuel supplement
5. Conventional boiler with refuse derived fuel
6. Electric furnace
7. Fluidized bed incinerator
8. Gas and fume incinerator
9. In-drum pyrolyzer
10. Liquid injection chamber
11. Mass burning refuse furnace
12. Microwave plasma energization
13. Modular package refuse incinerator
14. Molten salt reactor
15. Open pit burning
16. Plasma arc

17. Rotary hearth (single and multiple trays)
18. Rotary kiln
19. Solar furnace
20. Spouted bed
21. Submerged flame incinerator
22. Supercritical water reactor
23. Vertical shaft--moving bed (vertical packed bed)
24. Wet air oxidation

Many of these reactors can be operated in either the incineration or the pyrolytic mode. Often a pyrolytic unit is followed by an afterburning combustor that immediately converts the pyrolysis gases to fully combusted flue gases. Reactors are designed considering the variables of waste input type, temperature, residence time, air supply, and turbulence.

Waste input types can be solids, sludges, slurries, liquids, or gases. A differentiating character of the waste input type is the refractory nature of the waste. The term "refractory" refers to the difficulty of destruction, usually meaning a need for greater temperatures, longer residence times, increased air supply, and higher turbulence. Pyrolysis proponents advocate carrying out incineration processes in two stages, for refractory wastes can often be treated using less extreme values of these four variables in an initial pyrolysis reactor.

Incineration Research and Development Needs

For already proven technologies, research and development needs can be listed as follows:

1. Improvements in destroying refractory wastes
2. Lower (pyrolysis) or higher (incineration) temperatures
3. Shorter (incineration) or longer (pyrolysis) residence times
4. Less excess air and higher efficiency
5. Higher (incineration) or lower (pyrolysis) turbulence
6. Longer operating cycle times without damage to materials of construction (refractory brick and steel boiler tubes)

7. Greater destruction efficiency
8. Higher scale-up quantities
9. Safer (nonexplosive) operating conditions
10. Ability to accept greater variability in input waste characteristics
11. Better environmental controls
12. Improved materials handling and feeding techniques
13. Lower costs and higher energy revenues
14. Portability for use at different locations
15. Wide ranging turn-down and turn-up ratios
16. Less use of energy to drive the thermal process
17. Improved catalysts and cocatalysts for special systems
18. Faster sensors and continuous monitors for better control

This is a listing of the evolutionary developments needed so that existing commercialized systems can operate in an improved fashion. The committee believes that research and development to advance technology is a continuous and never ending challenge in these areas. The exact nature of the research and development needs varies depending on the reactor type, the manufacturer, and the reactor model.

Use of Existing Boilers

Presently, RCRA rules exclude from regulatory consideration hazardous waste material that is used as a boiler fuel to produce usable steam regardless of the fuel's inherent hazardous properties. At some future time when the need for and the kind of regulation has been determined these fuels may be regulated more closely by RCRA. The committee endorses the controlled recovery of the thermal values in this manner, provided that this is done safely and without adverse environmental effects.

It is well known that boilers optimally designed for combustion of a particular fossil fuel (coal, oil, or gas) are not designed for combustion of another fossil fuel or other miscellaneous materials. Coal fly ash, for example, can clog spaces in the closely positioned tubes of a gas-fired boiler. Conversely, natural gas combustion products will pass wastefully through the large open spaces between the tubes of a coal-fired boiler.

Considering waste as a fuel, it is important to note that each waste has combustion characteristics that vary from batch to batch. Nevertheless, hundreds of different kinds of wastes could be used to fuel boilers if safe operating parameters were known.

Some plant engineers and boiler operators may not know the combustion conditions in their furnaces and boilers (i.e., the residence time, temperature, turbulence, excess air, etc.) because such knowledge previously was not critical. Even assuming that these conditions are known, they have generally not been compared with the conditions required for the proper destruction of organic wastes that might be injected.

Research is needed to relate the operating conditions in existing furnaces and boilers to the destruction requirements for various industrial wastes.

In summary, the general research need is to determine the conditions under which existing furnace and boiler systems will destroy hazardous industrial wastes without attendant problems.

Ocean Platform Incineration

Drilling platforms no longer in use have been proposed as potentially environmentally safe sites for research and operational studies of incineration (Johnson et al. 1981). Results of a preliminary study (Johnson et al. 1981) indicate that a rotary kiln incinerator with a high temperature afterburner capable of destroying a wide range of waste types at a rate of up to three metric tons per hour can be installed on a typical platform along with the necessary support facilities. An environmental assessment of worst-case air and water quality impact from routine waste incineration at one specific platform revealed insignificant effects on air quality at the nearest land point and on the platform. Effects on water quality will not be significant for most wastes.

Research should consider the probabilities and consequences of major upset conditions. In addition, portside siting, design, and construction must be investigated. Using a distant platform for combustion does not eliminate public questions on safety in the port city. Inland transportation infrastructures such as rail and trucking must also be studied. When these matters are resolved, an incinerator should be set up on a platform and a thorough evaluation of its performance in disposing of hazardous wastes should be undertaken, paying particular attention to those aspects that are peculiar to ocean-based operation.

Ocean Shipboard Incineration

Policy research is needed to clear the air for future action with regard to ocean shipboard hazardous waste incineration. Europeans have been incinerating in this manner for years. The <u>M/T Vulcanus</u>, the <u>K/B Vesta</u>, and the <u>Mathias II</u> currently operate from Europe, and experience is extensive. In the United States in recent years, numerous studies have been performed by consultants and a government interagency ad hoc work group (U.S. Maritime Administration 1980). On December 19, 1980, a meeting was held in Reston, Virginia, and critical comments on environmental compromises and special marine financing were made by representatives of the land-based incineration industry. Since that time, the government has halted funding of the development of shipboard incinerators and the privately funded construction of five American vessels has been announced. On the other hand, the West German government is preparing a ban on incineration of toxic organics at sea (European Chemical News 1981).

The recommendations of the interagency ad hoc work group for the Chemical Waste Incinerator Ship Program (U.S. Maritime Administration 1980) have been reviewed by the committee. These provide important input to future research and development planning. Identifiable areas where research is needed include:

1. Performance of different thermal reactors under varying conditions of pitch, yaw, and vibration as well as in the salt water environment.

2. Studies of the state of the art leading to evolutionary development of better ships by studying operations on the *M/T Vulcanus*, the *K/B Vesta*, and the *Mathias II*.

THERMAL METHODS

Thermal methods of hazardous waste disposal include broad categories of technology that are based on the application of heat (energy) to accomplish decomposition and/or detoxification of hazardous materials. These methods generally result in a transformation of the chemical composition of the material being treated (e.g., combustion producing CO_2, H_2O, etc. or pyrolysis producing oils, lighter hydrocarbons, etc.).

Conventional incineration and similar open flame combustion processes have already been discussed and will not be considered further here. Rather, this discussion will focus on lesser known and lesser developed thermal degradation methodologies such as plasma arcs, fluidized bed combustion methods, molten salt systems, pyrolysis processes, and other related options.

Thermal methods of disposal of hazardous industrial wastes offer several distinct advantages over some alternatives such as landfilling, not the least of which is that the waste is essentially totally destroyed and detoxified immediately. Toxic materials are converted to basic constituents such as water, CO_2, and other "safe" molecular species that can be handled readily in emissions and effluents using conventional technologies (e.g., nitrogen and sulfur oxides and halogen acids can be removed by effluent scrubber systems). In addition, thermal methods offer alternative possibilities with respect to the recovery of inorganics, metals, and energy. The thermal methods discussed here, however, are expected to be more costly than conventional incineration and would be applicable primarily in special situations involving difficult waste materials that are not readily amenable to conventional incineration. Such materials include corrosive compounds (e.g., halogenated organics), thermally stable molecules (e.g., aromatics), acutely toxic compounds (e.g., cyanides), and explosives.

Although these thermal waste destruction technologies in many cases are designed and tailored for specific waste types, overall research needs and opportunities can be identified.

1. General applicability to specific waste types (i.e., solids, halogenated organics, sulfur-containing wastes, etc.).

2. Emission and effluent control of decomposition products using physical techniques (i.e., scrubbers, filters, etc., for removal of metals, ash, acids, and salts) and chemical processes for ensuring complete destruction of dioxins and other potential gaseous pollutants and for recovery of vaporized metals.

3. Energy or power consumption effectiveness.

4. Materials of construction.

5. Design, size (scale-up), portability.

6. Process optimization and cost-effectiveness.

More specific research needs include:

1. Operating parameters for the destruction of specific hazardous industrial wastes in molten salt, fluidized bed, wet air oxidation, and pyrolysis systems should be determined. Systematic evaluation and screening programs for various waste streams, reactor systems, and operating parameters should be encouraged to extend the number of wastes capable of being detoxified and destroyed effectively.

2. The selection of materials of construction for molten salt, fluidized bed, wet air oxidation, and pyrolysis systems should be studied to improve corrosion resistance and operating life.

3. Plasma and microwave systems should be investigated for destruction and detoxification of hazardous industrial wastes that are difficult to handle.

4. Pyrolysis methods should be developed for organic wastes as a means of detoxification and conversion to usable forms such as fuels.

5. Co-catalyst systems for use in conjunction with specific technologies (i.e., wet air oxidation, fluidized beds) and specific waste streams should be evaluated to aid the destruction of difficult waste streams (e.g., PCBs, chlorinated hydrocarbons, pesticide residues).

6. Development of energy recovery systems to minimize power consumption and/or recover energy resources should be undertaken where it appears to be feasible in the destruction process.

7. Design of engineering controls for combustion products, emissions, and effluents should be included as part of the development of new hazardous waste destruction processes.

Illustrative specific thermal methods are described in Table 3 and discussed below.

Research to evaluate these specialized thermal techniques as solutions for disposal problems peculiar to specific waste situations not readily capable of utilizing conventional incineration technology should be encouraged. As a minimum, these and other innovative thermal destruction techniques should be screened and evaluated for a variety of "problem" wastes.

Fluidized Bed Incineration

This technique uses a moving fluidized bed of material as an intimate heat exchange medium or, alternatively, as a catalyst system to promote the transformation of waste material under milder operating conditions (lower temperature and pressure and with minimum volumes of oxygen) than would otherwise be feasible. In general, the bed material may function to react with halogenated organic compounds or other materials containing atoms besides carbon, hydrogen, and oxygen (e.g., sulfur, phosphorus, or nitrogen) and capture the halogen or other atom. The bed subsequently is regenerated and the hetero-atom is removed as an innocuous chemical compound (e.g., chlorine is removed as NaCl).

The reported advantages of this type of process derive from its relatively long residence and contact times, which result in more complete combustion and fewer potential organic compounds being emitted as air pollutants, and from its relatively low operating temperatures and costs (compared with those of conventional incineration) for difficult waste materials (e.g., PCBs). The technique is applicable to many liquids, high-viscosity systems, and shredded solids.

TABLE 3 Thermal Methods

Technology or Concept	Applicable Waste Type	Comments
Fluidized bed incineration	Liquids, high-viscosity systems, shredded solids, halogenated organics, organo phosphates, organo sulfates, etc.	Generally applicable to any combustible material; cost-effectivess compared with simpler incineration techniques is the determining factor.
Molten salt reactors	Liquids, shredded solids, halogenated organics, organo phosphates, organo sulfates, etc.	
Plasma arc (torch)	Liquids, stable molecules, pesticides, very toxic materials	Some solid waste (metal) systems reported to undergo destruction; materials of construction and control of waste gases and vapors (e.g., metals) may be a problem.
Microwave radiation (conceptual stage)	"Super toxics"	
Pyrolysis	Broadly applicable to all wastes	Produces energy or fuel as a by-product; residues require alternative disposal (i.e., landfills).
Wet air oxidation	Dilute aqueous waste streams of organic materials	Resource recovery (e.g., inorganic salts and energy) is possible; organics can be detoxified or destroyed by oxidation; cocatalysts can be employed to destroy difficult molecules.

Rockwell International Corporation's Energy Systems Group has reported successful demonstration of a fluidized bed incineration process for PCBs (Chemical and Engineering News 1981, Chemical Week 1981). Destruction efficiency of more than 99.9999 percent was reported using a transformer fluid waste that contained 52 percent by weight of PCB and 48 percent by weight of trichlorobenzene. The process developed by Rockwell and the U.S. Department of Energy (DoE) at a Colorado facility operated by Rockwell for DoE featured a fluidized bed combustor followed by a catalytic afterburner. Temperatures in both units were less than 695°C. The fluidized bed system employed a chromic oxide catalyst on alumina and granular sodium carbonate to neutralize in situ the HCl released. The process unit may be able to be mounted on rail cars for portability.

Molten Salt Reactors

In molten salt reactors, molten salt is used as a medium for destruction of combustible wastes, particularly organic materials having hetero-atoms in their structure. In the most studied system, the combustible material and air are introduced continuously beneath the surface of molten sodium carbonate at a temperature ranging from 800 to 1,000°C. Chemical reaction products of the waste with the salt and air depend on waste constituents. Carbon and hydrogen are converted to CO_2 and H_2O (steam); halogens form corresponding halide salts; and phosphorus, arsenic, sulfur, and silicon (from glass or trash in the waste) form oxygenated salts (i.e., Na_3PO_4, Na_2SO_4, etc.). Ash and other noncombustibles build up in the melt and must be removed. Test results on specific molten salt reactors have been reported to show destruction efficiencies as high as 99.9999 percent for chlorinated hydrocarbons (Ames 1981).

Extensive testing of bench-scale and pilot-plant size molten salt units, including investigations of the disposal of PCBs and other chlorinated hydrocarbon and pesticide wastes, has been reported by Rockwell International Corporation (Rockwell International Corporation 1982, Johanson 1981). This work was supported under contract by the EPA.

Depending on the size of the unit, molten salt incineration disposal systems appear to offer opportunity for mobile systems and for small systems that could be attractive for use by small- to medium-sized manufacturers for waste disposal.

Plasma Arc (Torch)

In the plasma arc (torch), an electrical discharge is used to convert a low-pressure gas into a plasma. The plasma can be considered to be an energy conversion and transfer device. The electrical energy is converted to high-intensity thermal energy. Temperature equivalents of 50,000°K have been reported (Barton 1981, and Barton and Arsenault 1981).

Waste feed materials fed into the plasma absorb energy and are atomized and ionized on interaction with the reactive plasma species. The process has been described as one of molecular fracture rather than of chemical oxidation, which is typical of incineration.

Reportedly, huge quantities of electrical current (power) are required to generate the plasma arc. Cost-effectiveness studies have not been carried out to assess the commercial feasibility of this type of technology for general use. Applications for certain specialty uses (e.g., PCB destruction) are being pursued by one research group. The process may be particularly advantageous for smaller quantities of wastes.

Variations of this technique include co-use of oxygen as reactant/plasma medium and other sources for generating the plasma. One such process, which uses a magnetohydrodynamic (MHD) generator, is under study at the University of Tennessee Space Research Center at Tullahoma, Tennessee (*The Sun* 1981).

Microwave Radiation

The microwave radiation technique employs microwave radiation to generate very high energy to transform chemical compounds (e.g., to bring about the conversion of highly toxic materials to less toxic or nontoxic compounds). Although currently in the research concept stage, some limited test results have been reported (Ames 1981).

Pyrolysis

Pyrolysis is defined as transformation of a compound into one or more substances by heat alone (i.e., without oxidation). Thus, it is similar to destructive distillation. Pyrolysis has been known for many years and has been applied by chemists to a variety of feedstocks (Weitzman 1981). Processes such as the gasification of coal to produce fuel gas (CH_4, etc.) and the liquefaction of hydrocarbons to produce lighter oils and gasoline/fuel cuts have been utilized commercially over the years.

Larger-scale pyrolysis of wastes, including hazardous wastes, to produce synthetic fuel oils and other products has been investigated. Waste feedstocks studied have included heterogeneous solid waste as well as liquids. Pyrolysis processes having application to special wastes have been studied (e.g., for use in recovering usable materials from scrap tires). Reportedly, a pyrolysis process for destruction of PCBs with recovery of fuel oils is under development.

Wet Air Oxidation

Wet air oxidation (Randall 1981) refers to the aqueous phase oxidation of dissolved or suspended organic substances at elevated temperatures and pressures. Water, which makes up the bulk of the aqueous phase, serves to catalyze the oxidation reactions so that these proceed at relatively low temperatures (200 to 320°C) and, at the same time, serves to moderate the oxidation rates removing excess heat by evaporation. Water also provides an excellent heat transfer medium that enables the wet air oxidation process to be thermally self-sustaining with relatively low organic feed concentrations.

The oxygen required by the wet air oxidation reactions is provided by an oxygen-containing gas, usually air, bubbled through the liquid phase in a reactor used to contain the process. The process pressure is maintained at a level high enough to prevent excessive evaporation of the liquid phase, generally between 300 and 3,000 psi.

Wet air oxidation is used primarily as a method for wastewater treatment but may be useful in a number of other ways. Destruction of high concentrations of organic substances makes the recovery and reuse of many inorganic chemicals both practical and economical. In addition, the highly exothermic nature of the wet oxidation reaction makes the generation of by-product process steam or electrical power possible.

Wet air oxidation has been known in the United States for more than 25 years and has specifically been applied to industrial wastes. However, of the 150 or more worldwide wet air oxidation installations, only 12 treat pure industrial wastes and only one is in the United States (Pradt 1972). Commercial wet air oxidation systems have been developed extensively and marketed by Zimpro, Inc. (Zimpro, Inc., 1981) and are commonly referred to as Zimpro oxidation processes or Zimpro waste disposal systems.

Several of the more environmentally persistent chlorinated systems and other difficult to degrade organic molecules found to be resistant to conventional wet oxidation conditions were discovered to be readily degraded using a variety of liquid phase catalyst systems in the process. A large number of substances has been studied for catalytic activity, including both soluble homogeneous (metal ions and peroxides) and heterogeneous (metals and oxides) systems. Cupric ion has shown remarkable catalytic activity in many systems. In addition, a number of proprietary co-catalysts has been developed for specific waste streams.

Wet air oxidation processes have also been coupled successfully with biological treatment and filtration processes to treat industrial wastes (Wilhelmi and Ely 1976). Other combinations of this technology with pretreatment or final processing may provide feasible solutions to complex hazardous industrial waste disposal problems.

The general advantages of wet air oxidation systems include the following:

1. Compared to conventional incineration, fuel requirements are significantly lower--in the range of 500 Btu/gal compared with 20,000 Btu/gal for a waste low in organics.

2. Wet air oxidation lends itself to energy recovery schemes; basically it is a confined process operating at high pressures.

Its disadvantages include the following:

1. Specialized reactors and construction of individual components may be required depending on the nature and quantity of the waste to be processed.

2. Materials of construction may be subject to corrosion by various wastes.

Specific research needs will vary with the mix of particular waste streams. In general, research areas identified for wet air oxidation disposal of wastes include:

1. Screening and evaluation of various waste streams for general applicability, including pesticide wastes, mixed plant effluent streams, etc.

2. Evaluation of catalyst systems such as metals and activated carbon to enhance degradation of difficult molecules under milder conditions.

3. Evaluation and development of energy recovery schemes.

4. Evaluation and development of resource recovery (e.g, inorganics in organic streams).

LANDFILLS

An estimated 90 percent or more of U.S. solid wastes, including hazardous industrial wastes, are currently disposed of in landfills (American Chemical Society 1978). Landfills have become the major method of disposal of hazardous industrial wastes primarily because of their perceived cost-effectiveness in comparison with other hazardous waste disposal technologies. However, as discussed below, the premises on which these cost comparisons are based are frequently ill-founded even though they reflect today's socioeconomic and regulatory climate.

Landfills can be classified as sanitary landfills, which provide for disposal of municipal refuse, and secure landfills, which are designed for more or less permanent isolation (storage) of materials defined as "hazardous industrial wastes." Under RCRA regulations, the terms "secure landfill" and "hazardous waste landfill" have become synonymous. RCRA uses the terminology "hazardous waste landfill."

In many instances, sanitary landfills have become known notoriously as "dumps" or "toxic dumps" because all kinds of substances, including industrial refuse with hazardous properties, have been improperly disposed of there. At these sites, materials were literally "dumped" and left, with only minor, if any, regard for their environmental fate. Secure or hazardous waste landfills can be considered to be special cases of the category of waste treatment classified as permanent storage and are in conformance with present regulatory statutes.

Although sanitary landfills per se will not be discussed, it should be noted that sanitary landfills as well as improperly functioning approved hazardous waste landfills could be a significant source of groundwater pollution. Under the proposed RCRA regulations, "small" generators of hazardous industrial wastes are not subject to the same stringent requirements as major generators. Small generators are allowed, in many cases, to dispose of a wide variety of wastes defined as "hazardous" under RCRA in sanitary landfills. However, if enough hazardous wastes from individual small generators are aggregated in one sanitary landfill, then significant problems can clearly result from leaching, etc., which would cause groundwater contamination by the hazardous wastes. With respect to such landfill problems, the concept of "degree of hazard" should be considered (Office of Technology Assessment 1981).

The present discussion will deal only with disposal of hazardous industrial wastes in secure landfills. Remedial action technology needed to restore abandoned and/or uncontrolled sites will not be discussed. These needs are addressed by the "Superfund" law (Public Law 96-510, Comprehensive Environmental Response, Compensation and Liability Act of 1980). Methods of permanent isolation and storage of hazardous wastes other than secure landfills are discussed later in this report. Secure landfills are emphasized because they currently are the major method of disposal of hazardous industrial waste.

The objective of secure landfills is the physical (hydraulic) isolation of waste from the environment. In simple terms, a secure hazardous waste landfill is designed to provide long-term entombment of wastes, and one of its prime purposes is to prevent contamination of groundwater by preventing "leaching" of material from the site.

The design, operation, and monitoring of contemporary secure landfills constitute an essentially new technology, one less than a decade old. Prior to the 1970s, the terms "sanitary landfill," "municipal landfill," and "dump" were almost synonymous. However, in many cases, attempts were made to design landfills suitable for chemicals and other industrial wastes using concepts that exceeded then-accepted practice and art for waste disposal. Consideration was given to groundwater protection and permanent entombment of these industrial wastes. A major problem, in retrospect, is that the collective technical knowledge and experience did not enable management of long-term problems.

Although a number of other options have been or are being developed for the proper management of hazardous wastes, many of these, even if technically successful, cannot be instituted overnight. Thus, secure landfills must be used until more advanced methodologies become viable industrial processes. Moreover, even the new waste disposal technologies now undergoing research and development will not be a panacea and eliminate all hazardous waste disposal problems. At best, there will be special technologies for detoxifying difficult wastes and, more important, for providing volume reduction for the total hazardous waste disposal burden. After many of these other technologies are employed, some material, albeit a smaller but finite quantity, still will require disposal (e.g., ash from incinerators, sludge from waste treatment plants, concentrated metals and compounds from chemical treatment systems, and inorganic residues from chemical processing). Any exploration of new waste disposal technologies should include the economic practicalities as well as technological feasibility. Evaluation of alternatives for hazardous waste disposal should recognize that a balancing of risks with cost-effectiveness will be necessary rather than treatment for treatment's sake.

The use of secure landfills that meet strict technological requirements is a viable and acceptable disposal method for certain hazardous wastes for the immediate future. However, for the longer term, other hazardous waste disposal options must be pursued and developed to minimize burial of hazardous materials. Landfill must be considered as the last alternative after all waste treatment technologies, including detoxification, volume reduction, and resource recovery, have been explored. As a minimum goal, the use of secure landfilling must be coupled with other hazardous waste disposal techniques to reduce the total volume of material buried (Senkan and Stauffer 1981). For example, in both Germany and Denmark, organic hazardous waste cannot be landfilled.

In addition, the true cost of long-term secure landfilling, including monitoring and perpetual care insurance, must be used in cost-effectiveness comparisons of this technique with alternatives such as incineration and chemical detoxification. The short-term cost of this technology may be low, but the true costs to be incurred for perpetual care and monitoring for a period that, realistically, may exceed 500 years is significantly greater and this cost should be used in comparison with other disposal options.

The advantages of the secure landfill disposal method are summarized as follows:

1. The technology is defined, and facilities are available.

2. Economics are perceived as favorable compared to alternatives (e.g., incineration).

3. Properly designed and operated facilities reduce the mobility of wastes (e.g., to groundwater), minimize the release of wastes (e.g., to air), minimize the hazard (e.g., provide isolation), and allow reclamation of valuable materials when technology becomes available.

4. Geological properties make very low risk sites available in some areas.

Its disadvantages are as follows:

1. The risk of causing health and environmental problems may be higher than with other perpetual storage options.
2. The long-term integrity or security of sites (e.g., liner integrity and stability) is not well established.
3. A public acceptance of landfills and perception of safety are generally lacking.
4. Long-term (perpetual) management is required.
5. Waste volume reduction and resource recovery are not necessarily encouraged.
6. Low risk landfill locations are not evenly dispersed around the country.

Several general research needs have been identified for secure landfill disposal of hazardous wastes (Schultz 1981). These may be divided into the following broad categories:

1. Landfill design and operation, including cover design and liner performance studies (natural, synthetic).
2. Closure-leachate collection, analysis, and treatment including sampling (wells) and leachate treatment.
3. Site monitoring including pollutant movement and sampling and interactions of soil, wastes, etc.
4. Waste pretreatment or chemical stabilization, including fixation, encapsulation, and solar evaporation.
5. Modeling and projections for long-term ($>$ 500 years) care.

Many aspects of these research needs are currently being studied. However, ongoing research in these areas should be continued and new research programs to develop new concepts, materials, and techniques for landfilling and techniques for monitoring and predicting mobility, etc., should be encouraged. Illustrative examples of specific research needs in several of these areas are given below.

Standard Sampling Techniques

Standard sampling procedures, including collection, preservation and storage of samples, do not exist for solid and semisolid wastes. Existing procedures for sampling liquid effluents and soils should be adapted to make them suitable in a variety of circumstances. In addition, sampling and preservation techniques acceptable for groundwater monitoring of potential leachates should be developed.

Pollutant Migration

Procedures should be developed for using the soil as a predictable attenuation medium for pollutants. Research should focus on understanding the processes and on predicting the extent of migration of contaminants (e.g., heavy metals) from waste disposal sites, including laboratory and field verification studies. Mathematical hydrogeological simulation models for predicting the movement of leachates (solutes) in both saturated and unsaturated soils are needed.

Liner Performance and Cover Design

Liner and cover materials should be evaluated to determine their suitability for eliminating or reducing leachate from landfill sites. Both laboratory screening of new materials and field evaluation of existing liners--natural and synthetic--should be carried out.

Waste Modification (Chemical Stabilization)

Encapsulation is achieved by incorporating the solid and liquid phases of waste into a relatively inert matrix that exhibits increased physical strength and protects the components of the waste from dissolution by rainfall or by soil water. If this slows the rate of release of pollutants from the waste sufficiently and no serious stresses are exerted on the environment around the disposal site, the wastes have been rendered essentially harmless and restrictions on siting will be minimal. A variety of solidification and encapsulation techniques have been studied and are being developed (Maugh 1979, Schultz 1981). Specific research needs include identification of new encapsulation and solidification materials, determination of long-range stability with respect to leaching, and ability to withstand "weathering" after prolonged periods of time.

PERMANENT STORAGE

If the present, generally negative public attitude toward the utilization of incineration, burial in landfills, subsurface injection in liquid form, and other means for the ultimate disposal of hazardous industrial wastes is considered, it becomes obvious that society is faced with a dilemma. Given the public attitude and the fact that hazardous wastes are, and will continue to be, generated as by-products of the attempt to meet the needs and desires of modern society (Senkan and Stauffer 1981), there are, in fact, only a few alternatives for the ultimate disposal of these wastes. One of these alternatives is the permanent storage or burial of hazardous waste in the subsurface.

Detailed review of RCRA makes clear the expectation that large volumes of hazardous wastes will be disposed of in the terrestrial environment (Maugh 1979) and that a considerable amount of the material will be disposed of in deep subsurface zones.

Wastes can be disposed of in the air, in water including the deep sea (Goldberg 1981), on land, deep underground, or by chemical conversion. It is possible that the wastes can be disposed of by means suggested for highly radioactive wastes (i.e., sending wastes to the sun, shooting them into interstellar space, or disposing of them in the subduction zones of tectonic plates), but these are not practical solutions to the problem (Energy Research Development Agency 1976). With the present legal restraints on the disposal of hazardous wastes in the air and water, the need to prevent the dispersion of hazardous wastes, and the concern for long-term safety and isolation from the biosphere of these wastes, it becomes obvious that land disposal, more particularly permanent burial in the subsurface, is one of the principal methods for dealing with the "final" hazardous wastes generated by society.

Acceptance of the need for subsurface burial leads to the necessity to consider what research is required for a proper understanding of the problems related to the permanent and/or ultimate disposal and storage of the worst wastes.

Before moving to a discussion of required research, one point needs clarification. From the public perspective, burial and isolation of hazardous wastes are commonly viewed as fundamentally the same; they are not. Burial of wastes is not a difficult technical problem. Wastes can be buried in essentially any location desired. However, providing the long-term isolation of hazardous materials from the biosphere is more difficult. This concern for providing isolation is predicated on what is considered to be one unalterable fact. After all efforts have been expended to render hazardous wastes nontoxic, to reduce them in volume, to recycle or reuse them, etc., most of the remaining nonreducible toxic materials ultimately will be disposed of by burial in the deep subsurface, thereby isolating them from the biosphere. This is the final step in disposal. Few other options for handling such wastes are available.

The problem of permanent disposal or storage (the term "disposal" is preferred because retrieval from permanent storage is not generally contemplated, and henceforth, this term will be used) can be divided initially into two parts: disposal of liquid wastes and disposal of solid wastes. In both instances, existing technical and engineering methods allow the burial of the wastes in the subsurface. Questions arise with regard to the long-term isolation, dissolution, immobility, and chemical reactivity of the wastes.

Assuming a specific toxic waste must be disposed of in the subsurface, two principal questions arise: Is the technology for disposing of the wastes safe and available? Will the waste and the hazard associated with it remain permanently isolated from the biosphere? Using this approach, it is assumed, of course, that some of the disposed of wastes degrade or are indeed immobilized.

Liquid Wastes

Subsurface injection is a technically acceptable method for hazardous liquid waste disposal or long-term isolation of toxic pollutants whereby the wastes are injected in deep subsurface aquifers that are of no or little value for other purposes. It is the committee's judgment that the technology for injection of liquid wastes into the subsurface at the required depth is available; thus, the greatest concern is with the question of permanent isolation of the injected waste from the biosphere.

Two subsurface disposal areas that have considerable potential for the disposal of hazardous industrial wastes (both solid and liquid) are salt domes and arid region unsaturated zones. A salt dome is a permanent structure with a central, nearly equidimensional, salt plug. The structure is generally 1 to 2 km (occassionally more) in diameter and has risen through enclosing sediments from a mother salt bed 5 to 10 km or more beneath the surface. An unsaturated zone refers to a specific subsurface horizon or level that is devoid of water. Many of the data on salt domes generated in study of problems related to disposal of high-level radioactive waste have applicability to problems of disposal of hazardous industrial wastes.

In the discussion that follows, it is assumed that subsurface injection of hazardous liquid wastes will continue to be used in the future as one means of hazardous industrial waste disposal, provided that all criteria regarding technological safety and isolation are met.

To assess properly the effects of permanent disposal of liquid wastes, particularly those of extreme stability posing a potential long-term threat, better information and more research are urgently required in the general areas described below.

Degradation, Migration, Short-Term Reactivity

A better understanding of the degradation products formed and the rates of degradation of the individual hazardous wastes is needed. It is essential to know if the degradation products are themselves hazardous. It is necessary to understand how degradation rates and products are affected over long time periods by the temperatures encountered in the different subsurface disposal horizons. As depths greater than 10,000 feet are considered for injection of these wastes, more attention will have to be directed to chemical reactions proceeding at a greater rate owing to the greater temperatures encountered with increasing depth of burial. For many liquid wastes, isolation from the biosphere will require deep injection or burial after solidification.

Once introduced into the subsurface, the short- and long-term migration rates and directions of migration of the fluids in the subsurface disposal zones must be examined. When migration is likely to occur, it is imperative to understand explicitly the heterogeneous chemical reactions that can occur between the naturally occurring brines and the degradation products of the specific toxic wastes. It is important to determine which of the potential chemical reactions can occur spontaneously and to know the thermal conductivity and specific heat capacity of the rocks and fluids in the disposal horizons. For many of these questions, answers are available when dealing with most sedimentary rocks such as shale (Brookins 1976), limestone, and sandstone, but for other rock types such as anhydrite, dolomite, granite, gneiss, and basalt, answers are lacking or are imprecise. It is critical to avoid subsurface injection of hazardous liquid wastes when only cursory consideration has been given to these parameters.

Long-Term Reactivity

While very long-term integrity of the formation and entrapment in the formations is of primary importance, data are needed on possible long-term reactivity and kinetics for many liquid wastes in the thermal environment within the sandstone, limestone, shale, granite, basalt, etc., in which they are emplaced. These data will define which rock types are the most suitable for the long-term disposal of such wastes.

Research is also needed on the long-term chemical reactivity and kinetics of the different wastes at the bottom-hole temperatures encountered at all depths (especially greater than 10,000 feet) with the chemically different, highly concentrated brines occupying the void spaces in all deeply buried subsurface rocks.

A critical need identified by Anderson (Josephson 1982) is that of kinetics: "We hardly understand the kinetics... we need new kinetic models... we simply cannot express heterogeneous reaction rates and this is what we need to do if we are ever to predict the time it takes a potential pollutant to move a given distance."

Sedimentary Basins

As noted above, the major portion of the subsurface disposal of liquid wastes has so far occurred in sedimentary rocks, primarily limestones and sandstones. If long-term disposal and isolation from potential groundwater sources is desired, the possibility of utilizing the deeply buried crystalline (igneous) rocks that lie beneath the large, deep sedimentary basins of the United States needs to be investigated. Many such basins exist. Some of the better known examples are the Illinois, Michigan, and Denver basins. Given the proper hydrologic conditions (e.g., downward migration, high salinity, and brines compatible with the liquid to be disposed of or stagnant waters), the potential for such areas to accept liquid toxic waste for ultimate disposal has not been considered adequately. For many such basins, the subsurface water is either stagnant or moving deeper. This physical situation is one that may be well-suited for permanent disposal of liquid hazardous wastes (Bredehoeft and Maini 1981).

A major concern is the lack of knowledge concerning the flow of wastes of different chemical characteristics through microfractures and through rocks of low permeability. This knowledge is essential to make meaningful risk analyses to ensure that the disposed waste is properly isolated.

Mined-Out Areas and Solution Cavities

Under the proper circumstances, permanent disposal of hazardous liquid wastes in abandoned subsurface mined-out areas can be considered, especially in abandoned salt workings (U.S. Army Corps of Engineers 1979) either in salt domes or in bedded salt deposits. This is attractive if small volumes of organic wastes are involved. An inventory of the volume of such space in the United States, its availability and suitability (e.g., its freedom from improperly plugged holes) to store hazardous industrial wastes, and its geographic distribution are needed. One should examine whether such abandoned space can be treated properly and/or lined for use as "holding tanks."

Much more information also is needed on evaluating the potential for extremely deep burial of hazardous industrial wastes in salt dome solution cavities. In addition, detailed assessment of the integrity, long-term safety, and isolation possibilities of waste emplacement in arid zone unsaturated horizons (Winograd 1981) is also needed. It was the committee's conclusion that emplacement in salt domes or stratigraphic salt beds could be useful for certain waste types and deserves more attention than it has been given to date.

The subsurface disposal of hazardous wastes in abandoned salt mines or subsurface cavities has been advocated widely and, in some instances, practiced. The essential question is not whether salt can be used as a receptacle for the disposal of most hazardous wastes, but whether other rock types are equally or even more suitable for the disposal of specific hazardous wastes.

The factors most important in determining the best subsurface rock type and horizon for long-term containment of liquid wastes should be established. Consideration and possible use of such geologic horizons should be part of any research program to solve problems related to the long-term disposal of hazardous liquid wastes. However, the long-term safety of such regional disposal horizons (as determined by geology, specific heat, dissolution rate, hydrologic containment, brine chemistry, etc.) has not been considered adequately or evaluated properly.

Solid or Solidified Wastes

Permanent storage of solid or solidified toxic wastes can be accomplished in several ways. Among these are burial in abandoned or unused underground openings or in mined-out cavities developed specifically for a given waste. Certain conditions must be satisfied for such burial, and these will be discussed below. Among the subsurface openings that have been considered (U.S. Army Corps of Engineers 1979) or that need consideration are such cavities as abandoned salt mines and domes, old metal mines, coal mines, and deep quarries. There must exist many billions of cubic feet of such unused space in the United States. These openings are present in many different rock types and are scattered widely across the country. Both of these aspects are assets. What is needed, however, is a detailed inventory of the availability of such space and an assessment of the hazardous wastes that are amenable to burial in specific rock units. Little additional research is needed into methods of sealing off or isolating such cavities from the country rock in which they are located. The techniques appear well in hand.

It is the committee's opinion that solid wastes must be considered from four viewpoints: handling and burial as slurries, handling and burial in solid form as received, handling as independently solidified or encapsulated units, and burial after solidification and subsequent containment in barrels or some other specialized container.

Slurries

It is possible that certain hazardous wastes cannot be satisfactorily solidified or encapsulated economically. Such wastes may have to be handled in slurry form. Slurry is defined here as any solid-liquid mixture of varying solid-liquid percentages capable of being transported or handled via pipes. Such a mixture, whether the result of a given manufacturing process or deliberately made by addition of some inert material (i.e., sand, ground slag, etc.), can be disposed of in subsurface cavities.

Research is needed both on materials required for sealing off (isolating) cavities containing slurries from surrounding rock and on proper application techniques. It is anticipated that the volume of wastes falling into this category will be quite small; consequently, it is likely that relatively little research need be directed to the solution of this problem.

Solidification and Encapsulation of Wastes

The distinction is made here between solid hazardous wastes that can be buried as received and those that can be treated chemically to become a part of a solid matrix itself and solidified wastes that are enclosed or encapsulated (Lubowitz and Wiles 1979) into a solid whole by inclusion in a second solid material (e.g., silicate slag, bitumen, asphalt, concrete, and synthetic polymers). If buried as solidified masses or after containment in barrels or some other vessel subsequent to solidification, these wastes can be handled and isolated as required. Solidification of wastes prior to landfill burial or ultimate disposal in the subsurface has been accomplished by several methods (Salas 1979, Subramanian and Mahalingam 1979). A few of the final solid materials of varying solubilities that have been tested and, in some instances, used for interring hazardous wastes are asphalt and bitumen, tar and pitch, epoxy, polyolefin and other polymers, cements of various types, silicates (molten rock types and ceramics), silicates (different types of glass), and SYNROC (Ringwood 1982). Isolation from the biosphere and the subsurface environment (brines, etc.) can, for example, be obtained through use of the barrier concept being considered for high-level radioactive wastes (National Academy of Sciences 1980). The number of barriers required is determined primarily by the toxicity of the waste and the desired isolation period. In such cases, the first concern is for safety and the second for economics.

Among the barriers considered are the enclosing matrix, the container, the backfill of crushed rock (e.g., salt or gravel), bentonite or another clay, and the country or surrounding rock itself. Considerable research into the composition of various barriers has been done but much more is required. The key question involves the degree and length of isolation desired.

In all burials of hazardous wastes, the major concern is that the wastes be isolated from or contact minimized with subsurface water. A second concern is that the wastes not be returned to the ground surface and contact the biosphere. Contact with water is of concern because of fear of long-term "substance" migration.

As previously pointed out, a national inventory of the availability of subsurface space with a listing of special concerns and problems related to each site is badly needed. Concurrent with such an inventory, research should be initiated to determine the chemical compatibility of solidified toxic wastes with the different types of subsurface brines and environmental conditions present in the subsurface. It is necessary to anticipate the reactions to be expected over long periods of time, including the effects of temperature (100 to 300°C), pH, and dissolved gases. Dissolved gases can include such species as CO_2, CH_4, and especially H_2S. It is also worth considering the feasibility of converting some wastes to slurries for handling and disposal, followed by aging of the slurry and solidification in place.

Although immediate and short-term costs may be high, long-term economics may clearly favor disposal of many hazardous wastes in solidified form by burial in subsurface horizons. Continued research on both reducing the costs of and improving and developing new solidification techniques (including encapsulation) needs to be done.

Degradation and Reaction Rates

If wastes are to be rendered truly immobile by solidification processes, the permanent disposal of hazardous wastes by burial in subsurface cavities (permanent disposal) will require a better knowledge of the degradation rates of the wastes being buried, the reactions between solidified matrix and contained wastes, and any ionic exchange processes that might occur. It is necessary to know what, if any, liquid or gas bleeds from the "waste block" and what the chemical reactions are between the "bleeding" components and the country rock and subsurface brines.

Additionally, research is needed to develop further an understanding of the problems related to the barrier concept, especially to determine what minerals are best (bentonite, crushed salt, etc.) for what wastes. Similarly, research is needed to determine the best container metals for specific environments. It may be necessary to develop new alloys and materials to meet the needs of deep burial. This applies both to containing hazardous wastes in barrels and to lining underground cavities (e.g., with bentonite) prior to depositing wastes in solid or slurry form.

As a closing commentary the committee wishes to emphasize the importance of a more concerted and directed research effort to assess the feasibility and ramifications of using as burial sites for hazardous wastes the thick unsaturated zones (subsurface zones or horizons free of water) underlying much of the arid western United States (Winograd 1981). These areas can be considered a national asset in achieving a solution to the waste disposal problem. They may, in fact, be pivotal in providing a reasonable solution to the whole problem of disposal of toxic and hazardous wastes.

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