WHAT TO DO WITH HAZARDOUS WASTE

by Selim M. Senkan and Nancy W. Stauffer

Toxic and hazardous chemical wastes, the inevitable by-products of a technological society, rank as one of our most serious problems. But proper management practices can prevent them from threatening life or its environment.

FOR many decades industrialized society has produced hazardous chemical wastes. They threaten human health and the environment because they have dangerous properties; many are toxic and some can explode or undergo destructive reactions. In the 1970s a series of highly publicized incidents began linking human tragedy with hazardous wastes handled improperly in the past, either through negligence or lack of knowledge. People became terrified of waste-disposal sites, viewing them as time bombs. The fragile nature of our environment became clear, but much damage had already been done.

Meanwhile, industrial and other activities continued to produce billions of pounds of potentially hazardous wastes. Responding to growing concern, many companies adopted the safest waste-handling techniques available, and some began to invest substantial funds into improving current technologies and developing new ones. Unfortunately, some companies continued to handle their wastes irresponsibly. After all, the economic incentive is great: it costs ten to a hundred times more to use proper waste-treatment methods than simply to dump untreated wastes in unsecured landfills, rivers, lakes, and oceans. The prices charged by companies using unsafe methods did not reflect the full social cost of production, and the conscientious producers found themselves at a serious competitive disadvantage. Recognizing the economic pressures within industry and the potential dangers posed by hazardous wastes, the federal government began to take legal and political steps to ensure better waste management.

However, developing sound waste-management policies has proved controversial and complex. The Resource Conservation and Recovery Act (RCRA) of 1976 gives the U.S. Environmental Protection Agency (EPA) overall responsibility for setting hazardous-waste regulations and assigns individual states responsibility for developing specific hazardous-waste programs. Both tasks have been difficult. After considerable effort, EPA published its first set of rules and regulations in May of 1980, including criteria for identifying hazardous and toxic wastes, a list of specific and nonspecific hazardous-waste streams, and a manifest system for controlling them from production to disposal ("cradle-to-grave").

Industry immediately criticized the regulations as expensive and stifling, calling for—at a minimum—added provisions establishing "degree of hazard." (Under the current system, all substances that fit EPA's broad definition of "hazardous" are subject to the same rules.) EPA is trying to respond to industry's demand, but developing an acceptable scheme may be impossible: the agency had considerable difficulty just creating a broad definition (*see page 40*).

While EPA and industry continue their controversy, the states have problems of their own. Many states want or need regulations stricter than those set by EPA, but while they have the legal right to set stricter laws, they might find it impossible to enact them without federal backing (*see page 48*). Like environmental groups, the states are worried about the Reagan administration's steps to cut EPA's budget and ease current regulations in an attempt to improve the economy.

The Federal Perspective

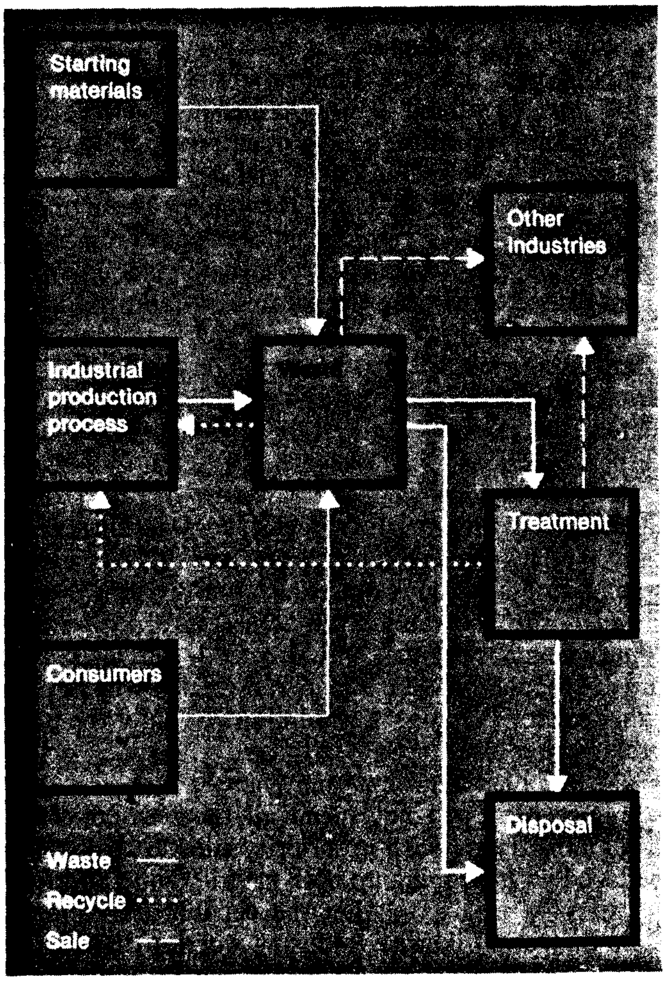
Despite those steps, the Reagan administration claims that the cleanup of hazardous spills and dumpsites is its highest priority. Such cleanup activities are covered by the Comprehensive Environmental Response Act of December 1980, which establishes a trust fund to pay for cleanup of waste sites and spills and assigns EPA responsibility for administering it. Of the $1.6 billion in this "Superfund," 87.5 percent will be collected from the chemical industry over a five-year period. Under the Superfund program, by July 1981, EPA had identified 9,300 hazardous waste sites, undertaken preliminary assessments of 5,900, completed investigations of 2,700, and begun emergency actions at 52. Both EPA and the Justice Department have been pursuing vigorous enforcement programs.

Nevertheless, some congresspeople and environmentalists are charging the administration with dragging its feet in administering the Superfund program. Many are concerned that EPA missed the June 1981 deadline for developing a National Contingency Plan, slated to be the cornerstone of the Superfund response actions. Furthermore, EPA has not completed a uniform scheme for states to rank sites they identify as threatening. And emergency actions taken thus far have focused mostly on preventing further leaching of hazardous materials from existing waste sites into groundwater; little actual hazardous-waste removal and treatment has occurred. There is also much speculation that Superfund money will not be sufficient for cleanup, with administration of the program taking most of the funds.

Environmental groups and many states fear the administration will not spend all the fees collected from industry to clean up priority sites. States could be faced with cleaning up both priority and nonpriority sites—a task exceeding the capabilities of most state budgets. Likewise, industry worries that it will end up with excessive financial responsibilities. If EPA judges a company's cleanup efforts inadequate, the agency will do the work and bill the company three times its expenses. But when a company cleans up its own sites, there is no limit on its cleanup responsibilities—no definition of what is "adequate."

The crux of the hazardous-waste regulation problem is clear: we do not have enough solid scientific information to identify with certainty the "right" level of regulation. And it is not surprising that battles are highly emotional: too much regulation can severely impair our economic well-being, while too little regulation can threaten our very lives. Nevertheless, we must not let the regulatory furor obscure one encouraging fact: while we may not fully understand all aspects of the hazardous-waste issue, we do have the basic technology to handle most waste-related problems. Many of the processes are expensive, but their costs are outweighed by the potential gains associated with saving human lives, decreasing human

To manage hazardous wastes, the general pathways of industrial waste generation, recycle, and disposal must be considered. The best solution includes reducing the initial quantity and danger of hazardous wastes, and many industries are modifying their processes to accomplish this source reduction. Wastes can also be recycled or reused; what's left must be treated and disposed of in an environmentally acceptable way.



CHARTS: OMNIGRAPHICS

suffering, and protecting our environment from toxic chemical contamination. Also, research is underway in government, industry, and academia to improve the technology, and the prospects for even more effective, less costly methods of treatment and disposal are good.

The Magnitude of the Problem

According to EPA's definition, between 10 and 17 percent of all chemical wastes are "hazardous"—some 35 to 60 million metric tons (77 to 130 billion pounds) in 1980. Although some toxic substances are now being banned, production of chemicals is increasing and new materials are being identified as hazardous, resulting in a 5 to 10 percent growth in the amount of hazardous wastes generated each year.

Essentially all industries, both manufacturing and nonmanufacturing, produce hazardous wastes in varying amounts and compositions. Most wastes come from very large generators, typically large manufacturing facilities located in the Mid-Atlantic, Southeast, Great Lakes, and Gulf Coast regions. In the nonmanufacturing sector, generators include schools, hospitals, gas stations, and repair garages.

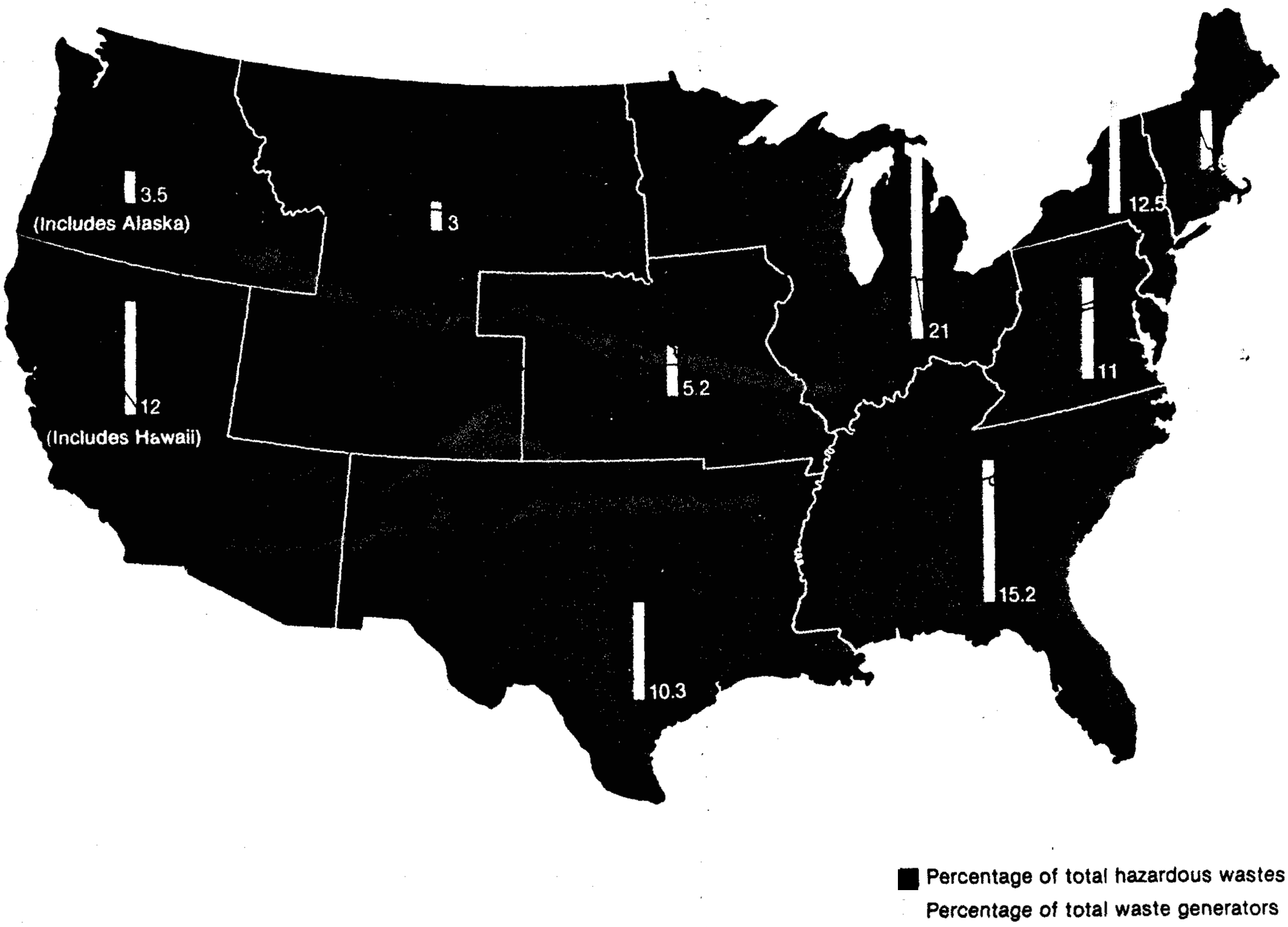
In all, there are about 760,000 individual generators of hazardous wastes. About 40,000 produce more than five metric tons of wastes per month, while 695,000 produce less than one metric ton per month. The top 5 percent of the generators are reponsible for 98 percent of the nation's wastes, while 91 percent of the generators together contribute only 1 percent of the total. However, the geographical distribution of large and small generators is not uniform nationwide (*see the figure at the right*). This regional variation is one of the factors making federal regulation of hazardous wastes difficult.

The EPA has estimated the total wastes and hazardous wastes generated by 14 specific industries (*see the figure on page 38*). Primary-metals and inorganic-chemicals industries are the biggest waste producers on the list, yet proportionally the fractions of their wastes that are hazardous are extremely low: 7.5 percent and 5 percent, respectively. Excluding pharmaceuticals, the other industries produce wastes that range from 24 percent to 100 percent hazardous. Together, the primary-metal, organic-chemicals, pesticides, explosives, electroplating, and inorganic-chemicals industries produce about 83 percent of the total hazardous wastes generated by the industries.

A complete picture of the hazardous-waste problem must include wastes produced and handled in the past. It's estimated that from 330 to 570 million metric tons of hazardous wastes were produced between 1960 and 1980. Though some of these wastes have been eliminated through proper treatment and disposal, significant quantities have been kept in over 100,000 industrial disposal sites, many still operating today. In addition to the identified sites, we must assume there are many sites that have long been closed and cannot now be accounted for. Clearly, not all industrial sites pose an immediate threat to human health, but experts estimate that between 1,200 and 34,000 sites may cause problems, such as underground water contamination, and eliminating dangers at those sites may cost more than $50 billion.

Unfortunately, precise sources, volumes, and components of the nation's hazardous wastes are not yet known and may never be public knowledge: the industrial sector is highly competitive and secretive, and

In 1980, an estimated 760,000 generators produced 35 to 60 million metric tons of hazardous waste. Most wastes come from large generators—typically large manufacturing plants in the Mid-Atlantic, Southeast, Great Lakes, and Gulf Coast regions. Proper treatment and disposal of hazardous wastes from large generators will make the greatest national impact, but in many regions small hazardous-waste generators pose serious local problems.



many companies believe information on their waste streams should remain confidential. But if we consider the enormous quantities of hazardous wastes being generated and stored, the persistence of many of the constituent compounds, and the difficulties involved in identifying their short-term and long-term toxic effects, we must conclude that our hazardous-waste problem is very serious indeed.

Waste Generation and Management

Hazardous wastes are produced by virtually all types of industries, and characteristics of the waste streams are as variable as the industries themselves. Although many cleanup and disposal options exist, no single process can be applied to all types of waste streams. Considerable knowledge and judgment are needed to select a suitable process for each specific waste or class of wastes.

To clarify the approaches to managing hazardous wastes, it is helpful to consider general pathways by which wastes are generated. There are essentially three sources of wastes (*see the figure on p. 36*). All industries require raw materials, and frequently a fraction of those materials ends up as waste streams. The process of using raw materials to form a product or perform a service also produces a substantial amount of waste. Finally, consumers create wastes by using and discarding the products.

There are several options for managing wastes, also shown in the figure:

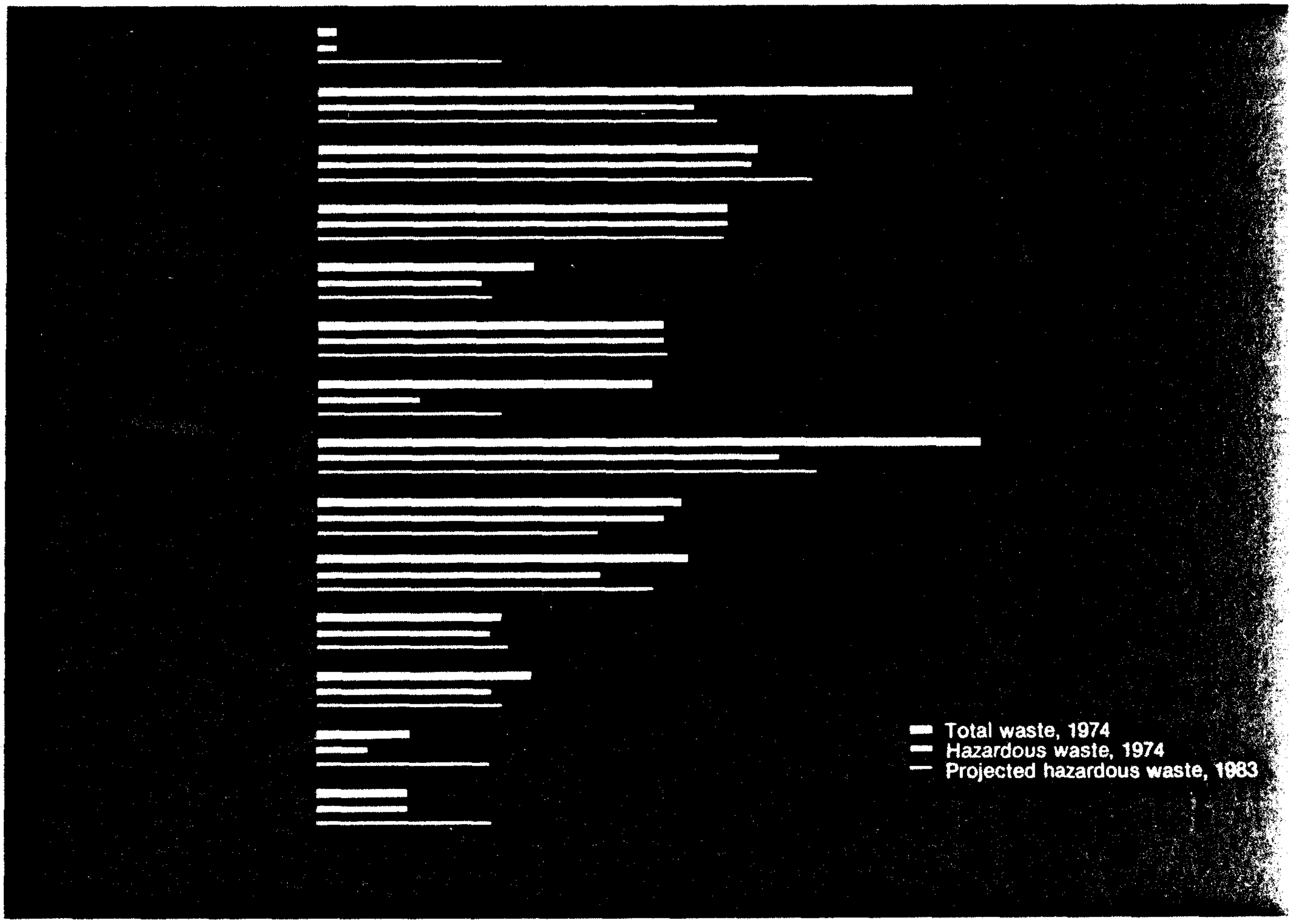
☐ They can be recycled within the industry that produced them.

☐ They can be sold to another industry.

☐ They can be treated and recycled within the same industry, sold to another industry, or disposed of.

☐ They can be disposed of without pretreatment (a practice that is illegal for hazardous wastes).

Total and hazardous wastes generated by 14 specific U.S. industries, estimated by the Environmental Protection Agency.



This analysis is valuable because it makes clear the several strategies available for reducing the hazardous-waste problem.

Source Reduction. Clearly, the ideal solution involves reducing the quantity and danger of hazardous wastes produced in the first place. Although source reduction is not always feasible, many industries are working to modify their processes to accomplish that end. Some companies are altering or pretreating their feedstocks, while others are changing processes or selected operating conditions to reduce the formation of hazardous compounds. The expenses will be partly offset by lower treatment and disposal costs and reduced potential for future problems.

Such economic incentives have recently been increased: industry must use expensive treatment and disposal practices mandated by RCRA, and must pay high prices for raw materials, particularly petroleum, petroleum-derived intermediates, and strategic minerals. Nevertheless, regulatory action may be required to ensure that all waste producers pursue source reduction. It is encouraging that industry has made significant changes, a notable example being the development of easily biodegradable pesticides to replace persistent ones such as DDT.

Waste Recycling and Reuse. Despite source reduction, however, some hazardous wastes will no doubt be produced. Before disposing of those materials, industry can explore another option: recycling and reuse. In the past, environmental regulations were minimal, and the cost of recovering materials from waste streams was greater than the cost of acquiring new materials; recycling was therefore rare. But higher costs of treatment, disposal, and raw materials are making recycling far more attractive.

Most companies are actively pursuing new ways to recover and reuse their own wastes. But given the wide variety of companies nationwide, the greatest

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opportunity for increased recycling clearly lies in industry-to-industry transfers. However, such transfers are difficult to arrange because of competition; industry places great value on secrecy, so it is difficult if not impossible for one company to know what materials are available from another.

This problem is being solved through establishment of waste clearinghouses and waste-exchange organizations that list available materials without identifying their sources. When RCRA was passed in 1976, there were 4 such waste exchanges; in 1981 there are at least 29. And many of today's exchangers are quite aggressive: while some still simply provide lists of available materials, others seek out both producers and potential consumers. There are also waste brokers who act as agents for waste-generating companies, receiving a commission for each successful sale.

One of the fastest-growing recycling markets is in chemical solvents. Recycling solvents has always been feasible; these high-value compounds can frequently be recovered by simple distillation techniques. RCRA further encouraged such recycling by making disposal of spent solvents difficult and expensive. By early 1981, solvent recycling involved some $200 million per year, and experts foresee a billion-dollar yearly market by 1986. The National Association of Solvent Recyclers, formed in Dayton, Ohio, in 1980, now has 43 members. These and other companies are making plans to construct improved facilities to handle chemical solvents. Some of the plants will recycle all the solvent, some will recycle part of the material and recover the rest as synthetic fuel oil, and others will convert all the waste to fuel.

While the trend toward recycling is clear, more can be done. Today only about 10 percent of the materials listed with waste exchanges actually changes hands; in older European organizations 30 to 40 percent is traded. Part of the problem stems from current regulations. Provisions of RCRA do not cover recycling activities comprehensively. For example, under present law some recyclers are not required to have permits for processing wastes unless they generate their own hazardous wastes. (However, recyclers may need permits for storage and transportation.) Such complications may make waste-generating companies hesitant to deal with recyclers and brokers, because if the company receiving the waste does not handle it correctly, the liability may revert to the waste generator.

The EPA is now considering revising RCRA to provide for better control over waste recyclers. However, the Chemical Manufacturers Association and a host of chemical companies are challenging EPA on the grounds that materials destined for recovery, recycling, and reuse are, by definition, not waste and thus should be exempt from hazardous-waste regulations. Although this point is valid, the likelihood that such an exemption will materialize is quite slim, as some recyclers were among the major offenders of environmental law in the past.

Meanwhile, two bills supporting recycling are being considered by Congress. One would make procedural changes in RCRA that encourage creation of pollution-control facilities, including recycling units. The other would increase the investment tax credit for companies involved in energy conservation and waste recycling. Senate hearings on the former bill were held in June 1981; hearings on the latter bill have yet to be scheduled. With such changes pending, the outlook for recycling is better than ever.

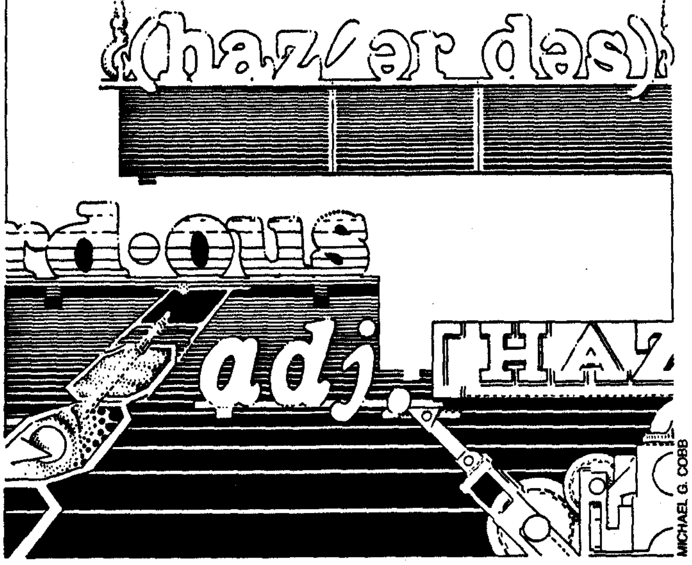
However, we must not have unrealistic expectations: according to a 1976 study by Arthur D. Little, only 3 percent of the 350 million metric tons of industrial wastes generated that year were potentially recyclable, although the fraction of hazardous wastes that is recyclable is probably higher. Changing regulations and rising prices have no doubt increased both percentages, but the fact remains that for certain types of wastes, recovery and recycling are simply not yet practical. The best we can do is to treat and dispose of such wastes in an environmentally safe way.

Classifying Hazardous Wastes

There are many waste-treatment and disposal processes, each best suited to certain types of materials. Therefore, the first step toward effective waste management is to examine an individual waste stream in enough detail to identify the appropriate processing techniques. The most practical method of classifying substances is according to their basic physical and chemical properties.

The first decision involves the state of the waste stream: is it predominantly a gas, a liquid, a solid, or a mixture? Next, the waste is classified according to its chemical constituents: are they organic or inorganic? Explosive materials should be identified, as they require special handling. Both organics and inorganics are subdivided into aqueous and nonaqueous categories, and then classified according to their concentrations of heavy metals. Heavy metals are important because their presence complicates many waste-treatment operations. Organic wastes can be further classi-

The Difficulties of Defining Hazardous Wastes



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ESTABLISHING effective and just hazardous-waste regulations is difficult, in part because it is hard to define precisely which materials should be considered hazardous. Should a chemical be classified as hazardous because at some dosage it is toxic to humans? If so, should it be regulated only at certain levels of generation?

Not surprisingly, different people offer drastically different answers to such questions. At one extreme are those who believe human activities should generate no pollutants; they advocate very strict government regulations. At the other extreme are those who believe industry can and should take responsibility for protecting the public; they are opposed to any government regulation of any industry.

A Delicate Balance

The practical optimum is somewhere between those extremes, and therein lies the problem. The best regulations would protect human health and the environment while imposing the minimum economic hardship on industry and thus our national economy. Unfortunately, we do not fully understand the possible long-term adverse health effects of many chemicals. Indeed, only recently has environmental contamination been recognized as a problem worthy of intensive scientific research. Regulators have thus been faced with the problem of imposing quantitative pollutant emission controls in the presence of little (if any) solid scientific data.

Some hazardous wastes have properties that are easy to recognize—for example, ignitability, corrosivity, reactivity, and acute toxicity—making their definition and regulation relatively uncontroversial. However, chronically toxic chemicals are harder to identify and thus are the subject of considerable controversy. Chronically toxic compounds can take 15 to 20 years or longer to produce adverse health effects. Because everyone is exposed to a wide variety of chemicals for many years, it is difficult to identify cause-and-effect relationships. Although epidemiological studies, bioassays, and other research efforts provide some insight, our understanding of the scientific principles of chronic toxicology is in its infancy and inadequate for clearing up regulatory disputes.

Defining and identifying acutely toxic chemicals can also be a problem because virtually all substances become toxic at sufficiently high doses. Some chemicals produce death in microgram doses and thus are commonly considered extremely hazardous or toxic. Others are essentially harmless, inducing a toxic response only at doses over several grams. But most chemicals fall between those two extremes, posing the question of where on such a scale we make the (perhaps arbitrary) switch from "toxic" to "safe."

There is yet another problem in deciding whether specific compounds are hazardous. Laboratory tests generally focus on a single compound, but compounds almost always exist in mixtures, and there is growing evidence of synergisms between them. Thus, the health impacts of the mixture may be totally unlike those of the individual components. For example, we may determine that a compound is harmless, but in combination with another (perhaps harmless) chemical, this compound may become highly toxic. Since we do not understand how these interactions occur, we need to examine not only an enormous number of chemicals but also all possible combinations—a formidable task. Furthermore, most standard laboratory studies use nonhuman subjects and high chemical doses, so another troublesome question is how reliably we can extrapolate the results to people. Although this is also a highly controversial area, single-cell and animal tests will be the major source of quantitative toxicity data until better means are developed.

Despite the present shortage of information, in response to public outcry, the U.S. Environmental Protection Agency (EPA) developed a system for identifying hazardous wastes through well-defined characteristics such as ignitability, corrosivity, reactivity, and acute toxicity as determined through a specific extraction and testing procedure. The EPA system also considers each chemical's chronic toxicity, changes in its health impacts at various concentrations, its potential for degrading into toxic products, its persistence in nature, and its potential for bioaccumulation. The EPA has also created a list of specific and nonspecific hazardous-waste streams.

There are several indications of the difficulty EPA had in establishing hazardous-waste regulations. First is the long time delay before any action was taken. The Resource Conservation and Recovery Act mandated that EPA establish hazardous-waste regulations in 1976, but the agency did not publish any rulings until May of 1980, primarily because of its problems in defining the legal and technical terms on which the rulings are based. Even today, those terms are not defined with sufficient scientific rigor—this situation leads to continuing conflict between industry and regulatory agencies.

As the List Changes

As an even clearer demonstration of the problems of regulating hazardous wastes, the official list of hazardous wastes is constantly changing. In May 1980 that list contained about 300 chemicals and 80 waste streams (*see the figure*). There have been almost daily additions to the list as more toxicological evidence is obtained about specific compounds or groups. Not surprisingly, many substances have also been deleted, since EPA created the list under substantial public pressure and in many cases without sound scientific data. Given that situation, the tendency was to include any waste streams that aroused the slightest suspicion. Whenever research uncovers an unnecessary item on the list, industry claims "overregulation."

Arguments among environmentalists, waste-producing industries, and regulators (who consider themselves caught in the middle) are energetic and often emotional. The difficulties of regulating hazardous wastes can be reduced only through the acquisition of better scientific data. Recognizing that fact, researchers are now creating new fields of study combining engineering, environmental chemistry, and toxicology to help define and quantify the risks associated with various types of potentially hazardous wastes. With such information we will be in a better position to attack the complex issue of determining which risks can be reduced or eliminated, and what levels of risk we may have to accept to maintain our industrialized society.—*S.M.S. and N.W.S.* □

Specific Waste Sources:	
Wastewater treatment sludge from production of chrome green pigments.	
Heavy ends from carbon tetrachloride production	
Heavy ends from vinyl chloride production	
Wastewater treatment sludge from production of chlordane	
Spent pickle liquor from steel finishing	
Nonspecific Waste Sources:	
Scrubber sludges from coke ovens and blast furnaces	
Bath sludges from electroplating operations	
Spent halogenated solvents (tetrachloroethylene, trichloroethylen chlorobenzene, etc.)	
Specific Compounds:	
4-Aminopyridine	Chlorobenzene
p-Chloroaniline	Chloroform
Ethylcyanide	DDT
Hexachloropropene	Methanol
Methylparathion	Naphthalene
Phosgene	Phenol
Asbestos	Formaldehyde
Benzene	Toluene

The Environmental Protection Agency has compiled a list of hazardous wastes and waste streams, considering such factors as acute and chronic toxicity, ignitability, corrosivity, breakdown products, and potential bioaccumulation. In May 1980, the list contained 300 chemicals and 80 waste streams; examples are shown in the table. There have been many additions and deletions as the list has developed, with changes often bringing charges of "overregulation" from some industries.

fied according to whether they are biological.

Unfortunately, most waste streams contain mixtures of all sorts of materials, and it is necessary to use several processes, either in series or in parallel. Since this practice leads to even higher treatment costs, it is likely that industries generating hazardous wastes will move in the direction of making their waste streams more uniform.

Designing Facilities

Choosing an optimal design for a waste-treatment and disposal facility is not simple, as different generators have different needs and options. There are at least three possible choices for generators of small quantities of hazardous wastes. They can install permanent, small-scale treatment facilities at plant sites and then use regional sites for ultimate disposal of treatment residues. They can use a contractor with specialized, mobile treatment units that operate at the plant site from time to time. Or they can use the services of a specialized treatment/disposal company.

The concept of a completely integrated regional facility is appealing but hard to implement (*see the figure on page 44*). Such a facility must be able to handle both large and small quantities of hazardous wastes at a reasonable cost, and must be readily accessible to a large number of generators. The siting of such a facility involves careful analysis of the geography, geology, topography, and hydrology of an area, along with social, economic, and political factors.

While integrated regional facilities are useful for small generators, companies that generate large quantities of wastes may be best served by having their own waste-treatment systems, even if there is no suitable landfill nearby for disposal of the treatment residues. Treating the wastes at the point of generation frequently reduces the amount and danger of the waste material and provides substantial reduction in transportation and related costs. Having their own treatment plants also enables companies to take greater advantage of recovery and recycling.

Treatment and Disposal Methods

There is a long list of processes for treating hazardous wastes (*see the table on page 43*). These processes are basically designed to reduce the volume of the waste, separate it into individual components that are easier to process, and/or detoxify it. Often certain processes also allow resources to be recovered. Each

Treatment processes are designed to reduce the volume of the waste, separate it into individual components that are easier to process, and detoxify it.

process ultimately produces residues that require a final disposal site, typically a secured landfill. Rather than describe each process, we will focus on a few that have a relatively broad range of applicability.

Incineration and Pyrolysis. The hazardous nature of certain wastes may be due to the structure of the molecules present rather than to the properties of the elements contained. In such cases, high-temperature treatment may simultaneously detoxify the waste and reduce its volume. The most common thermal treatment methods are incineration and pyrolysis.

Incineration involves burning wastes in the presence of sufficient oxygen with or without the use of an auxiliary fuel source. The products are generally gases (carbon dioxide, steam, hydrochloric acid, and sulfur dioxide) and ash with essentially no heating value. Pyrolysis essentially involves heating wastes in the absence of oxygen: the wastes thermally decompose to form a solid carbonaceous residue along with gaseous products. Often these two processes are combined.

The advantages of incineration and pyrolysis are substantial. These processes can in principle be applied to almost all organic wastes not severely contaminated by volatile heavy metals, and they can be used equally well on some inorganics. The facilities are capable of handling large volumes at a time, there is potential for energy and materials recovery, and the necessary equipment requires relatively little land. Finally, the processes can reduce the volume of most wastes to a minimum, reducing their danger and the costs of storing and transporting them.

However, there are several disadvantages to incineration and pyrolysis. The processes tend to be technically complicated and costly to operate—as high as $300 per cubic meter of waste. The methods may not be directly applicable to some hazardous-waste streams because of the unusual combustion characteristics of some toxic wastes, especially those containing halogenated compounds. In addition, under some circumstances the processes produce a toxic residue that requires special disposal techniques, and they frequently give off pollutants such as carbon monoxide, hydrochloric acid, chlorinated dioxins, sulfur dioxide, or soot, requiring strict operating controls and additional pollution-control equipment.

Incinerators are used both at industrial plants where wastes are generated and at specialized disposal facilities. Incineration requires the user to select a system design suited to the type of waste, and operating conditions should be fine-tuned to the particular waste being burned. Certain materials in wastes also require special handling. For instance, heavy metals such as arsenic, selenium, sodium, and mercury must be removed before incineration.

Our understanding of the subtleties of incineration and pyrolysis is limited, but advances are being made. For example, the Midwest Research Institute in Kansas City is opening a facility that will provide information on the compounds formed in an incinerator. The facility simulates actual incinerator conditions, but includes ports from which samples can be taken; the compounds in those samples can be identified and quantified. By running the system under different operating conditions, the researchers claim they can identify conditions that result in 99.99 percent destruction of the principal organic hazardous constituents—the level required by EPA.

In our laboratories in the Department of Chemical Engineering and the Energy Laboratory at M.I.T., fundamental combustion studies are in progress. We are examining the basic combustion characteristics of a variety of chlorinated hydrocarbons and their mixtures, thereby establishing a better understanding of the scientific principles involved in the incineration of toxic chemical wastes. And at the University of Dayton, researchers are examining the pyrolysis characteristics of toxic chemicals using a laboratory-scale thermal-decomposition analytical system.

Biological Methods. Biological treatment offers an effective means of handling organic and some inorganic toxic wastes. The waste stream is brought into contact with microorganisms that detoxify the waste material—decomposing organic molecules into carbon dioxide, water, or compounds with lower molecular weights. If the microorganisms are aerobes, molecular oxygen must be added to the systems; if they are anaerobes, oxygen is not necessary for them to degrade the wastes. (There are also certain microorganisms that can act either as aerobes or as anaerobes.) Of the aerobic and anaerobic processes, the former are generally faster and have wider applicability.

Principal biological treatment processes include activated sludge systems, trickling filters, aerated lagoons, anaerobic digestion systems, and composters. The first three processes can be used for aqueous waste streams with total contaminant levels under 1 percent. The activated sludge system is particularly well-developed and tested, having been used in industry for many years. Its attractive features include compactness, flexibility, and relatively rapid rates of degradation.

Major hazardous-waste treatment and disposal processes

Process	Function Performed	Type of Waste	Forms of Waste	Typical cost range (Dollars per cubic meter of waste)
Physical treatments:				
Sorption	VR,Se	1,3,4,5,6	L,G	5 - 20
Dialysis	VR,Se	1,2,3,4	L	—
Electrodialysis	VR,Se	1,2,3,4,6	L	5 - 10
Evaporation	VR,Se	1,2,5	L	2 - 5
Filtration	VR,Se	1,2,3,4,5	L,G	5 - 10
Flocculation/settling	VR,Se	1,2,3,4,5	L	1 - 5
Reverse osmosis	VR,Se	1,2,4,6	L	—
Stripping	VR,Se	1,2,3,4	L	10 - 50
Freezing/freeze drying	VR,Se,St	1,2,3,4,6	L,G	5 - 20
Distillation	VR,Se	1,2,3,4	L	25 - 100
Extraction	VR,Se	1,2,3,4	L,S	5 - 25
Magnetic separation	VR,Se	1,2	S,L/S	—
Chemical treatments:				
Ion exchange	VR,Se,De	1,2,3,4,5	L	5 - 10
Neutralization	De	1,2,3,4	L,G	2 - 10
Oxidation	De	1,2,3,4	L	50 - 150
Precipitation	VR,Se	1,2,3,4,5	L	1 - 10
Reduction	De	1,2	L	50 - 150
Incineration/pyrolysis	VR,De,Di	1,3,5,6,7,8	S,L,G	30 - 300
Catalysis	De	1,3,7,8	L,G	—
Plasma treatment	De	1,3,6	S	50 - 300
Biological treatments:				
Activated sludges	De	3	L	2 - 10
Aerated lagoons	De	3	L	1 - 5
Waste stabilization ponds	De	3	L	—
Trickling filters	De	3	L	—
Composting	De	3,4	L,S	3 - 20
Enzyme treatment	De	3	L	—
Disposal/storage:				
Deep-well injection	Di	1,2,3,4,6,7	L	1 - 5
Engineered storage	St	1,2,3,4,5,6,7,8	S,L,G	100 - 300
Land burial	Di	1,2,3,4,5,6,7,8	S,L	5 - 10
Ocean disposal	Di	1,2,3,4,7,8	S,L,G	2 - 5
Solidification/encapsulation	Se,Di	1,2,3,4,5,6,7,8	S,L,G	10 - 100

VR = volume reduction
Se = separation
De = detoxification
Di = disposal
St = storage

1 = inorganic chemical without heavy metals
2 = inorganic chemical with heavy metals
3 = organic chemical without heavy metals
4 = organic chemical with heavy metals

S = solid
L = liquid
G = gas

5 = radiological
6 = biological
7 = flammable
8 = explosive

Anaerobic digestion and composting systems can tolerate concentrations of contaminants up to 10 percent and 50 percent, respectively. Of all biodegradation systems, composting is probably the best choice for most organic waste streams, primarily because it is not as sensitive to changes in flow rates, composition, and concentrations of the wastes. Composting uses organisms that can live at relatively high temperatures (45°C and up), and those temperatures and long residence times make bioconversion thorough.

Almost all organic compounds, including halogenated hydrocarbons, are biodegradable. However, there are a few limitations. The compounds in the waste must be nontoxic to the microorganisms. The wastes also must contain some water: enzymes play a key role in the microorganisms' degradation of wastes, and enzymes require water for their activity. Soluble inorganics must be kept to a minimum as they can inhibit the enzymatic conversion process and are generally unaffected by biological treatment.

Nevertheless, biological methods are widely applicable to organic wastes, and operating costs of most methods are low. Depending on the waste stream and the process used, typical costs range from $1 to $20 per cubic meter of waste. The major drawback is that large land areas can be required to hold wastes during the long, slow biodegradation process.

Adsorption. This well-established technology removes organic as well as some inorganic contaminants from aqueous streams. The waste stream is brought into contact with porous particles that adsorb the contaminants; the contaminant-bearing particles are then removed from the system. The adsorption process is often reversible, so removed material can be recovered or treated for disposal, and the sorbent can be regenerated and recycled. The costs of such treatment are generally between $5 and $20 per cubic meter of waste treated.

The most common sorbent is carbon. Activated carbon has been used for years to treat drinking and