Chapter 7

Landfilling

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INTRODUCTION

Landfilling refers to disposing of waste on land in a series of compacted layers and covering it, usually daily, with soil or other materials such as compost. Landfilling is the primary method of MSW management in the United States today. It will continue to be needed to manage nonrecyclable, noncombustible materials, as well as residuals from recycling and incineration.

MSW landfill capacity in the United States is declining, however, because old landfills are being closed and because siting new facilities is difficult. One reason landfills are increasingly difficult to site is because of public concerns stemming from past practices, when uncontrolled "open dumping" was more common and sanitary landfills had few pollution controls. Open dumping often resulted in unsanitary conditions, methane explosions, and releases of hazardous substances to groundwater and the atmosphere, and old municipal landfills make up twenty-two percent of the sites on the Superfund National Priorities List (which was established under the Comprehensive Environmental Response, Compensation, and Liability Act, or CERCLA).

To address these concerns, Congress directed EPA, under Subtitle D of the Resource Conservation and Recovery Act (RCRA), to develop landfill criteria that included a prohibition on open dumping; EPA issued the criteria in 1979. Landfills also are now subject to stricter State regulations and the specter of financial liability under CERCLA for cleanup of contaminated sites. As a result, many new landfills, though by no means all, have pollution controls (e.g., synthetic and clay liners, leachate and gas detection and collection systems, and final cover systems) and other engineering features designed to minimize and detect releases of potentially problematic substances. Whether these technologies **are** needed for all landfills is controversial. Some observers argue that the need for these technologies depends on the site-specific conditions that lead to the production and possible release of leachate and gas. In contrast, other groups argue that landfills should be uniformly required to have these advanced features, with some allowance for variations.

This chapter examines the numbers and capacity of landfills, behavior of MSW in a landfill, the extent and causes of environmental releases, and technologies for minimizing those releases.

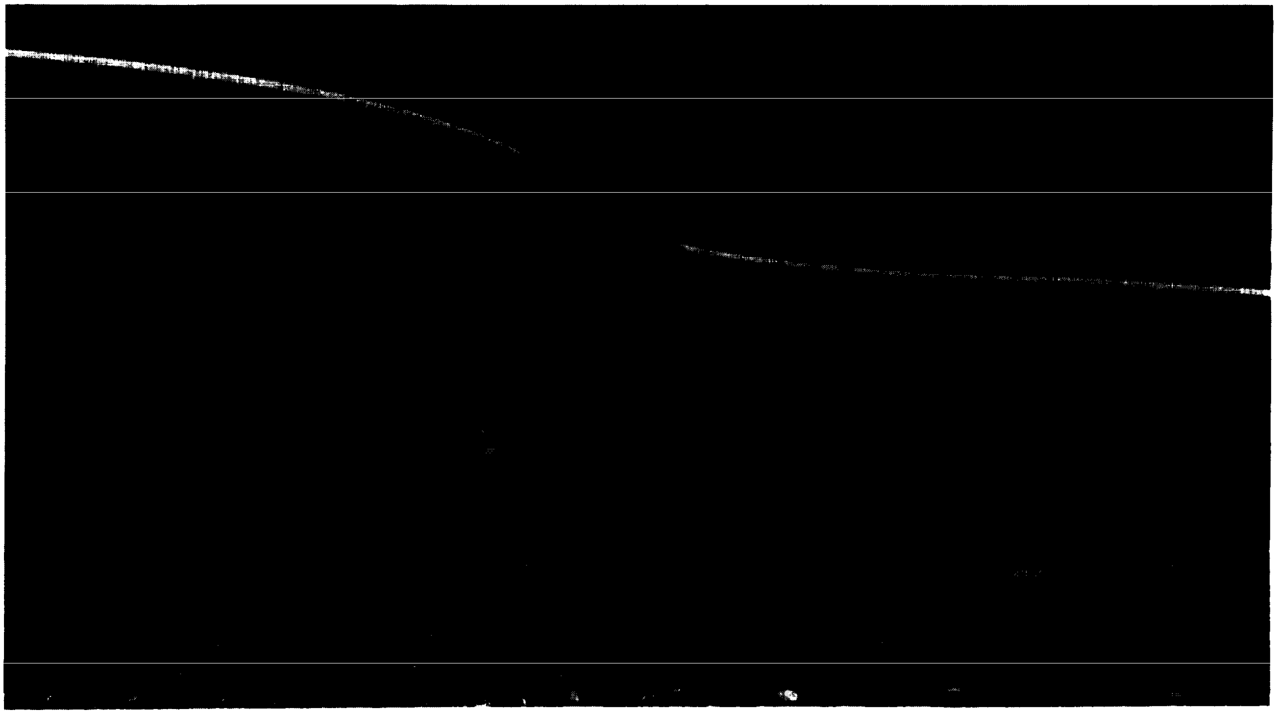
NUMBER AND CAPACITY OF MSW LANDFILLS

Overall Trends

MSW generation in the United States has increased substantially during the last two decades. EPA estimates that over 130 million tons—about 80 percent of all MSW—were landfilled in 1986 (24). The actual total may even be greater than these estimates indicate because of definition and data difficulties (ch. 3). Landfilling is the predominant form of disposal in most other countries, including many in Europe (table 7-1). Nevertheless, Japan and some European countries (e.g., Sweden, Switzerland, Denmark) rely on landfilling to a much lesser extent than the United States.

At the same time that MSW generation is increasing, parts of the United States—particularly the Northeast and the Midwest—are in the midst of a landfill capacity crisis. In one survey, EPA indicated that about one-third of all existing landfills were expected to close by 1994 (44, 77). Moreover, EPA estimated that over 80 percent of the landfills **currently operating** in 1988 will close in the next 20 years (table 7-2). Some States or regions, such as New Jersey and Long Island, are facing critical landfill capacity problems. Other States, such as Delaware and Rhode Island, have managed to develop facilities to treat most or all of their MSW.

EPA's proposed requirements for landfill operators to provide financial assurance for cleanup (see "Proposed MSW Landfill Regulations'*) could



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increase the rate at which landfills close. Once the regulations become effective, which is expected to be in 1991, any landfill that closes within 18 months after this date would not need to meet these requirements. Since the requirements could be costly to meet, this provision may be an impetus for many landfills to close before the 18-month period is over. In Wisconsin, for example, State officials estimate that up to 600 landfills, mostly small, rural ones, might close because of the regulations (19). In Nebraska, communities under 5,000 in size were previously exempted from meeting State landfill regulations (20, 54), so these types of facilities also are likely to close.

Closures of existing facilities do not necessarily predict future landfill capacity, however, because some new landfills are being sited and some existing ones are being expanded. It is particularly difficult to generalize about overall capacity because most problems and solutions occur at the city or county level and because information about capacity and numbers comes from extremely varied sources.

Capacity, as well as associated risks to human health and the environment, can be greatly affected by the practice at some landfills of accepting wastes other than MSW. Depending on the definition used, MSW accounts for an estimated 90 percent of all wastes sent to MS W landfills (77). The remainder is comprised of construction and demolition debris, nonhazardous industrial process wastes, sewage sludge, non-MSW incinerator ash, small quantity generator (SQG) hazardous waste, medical wastes, and miscellaneous wastes (77). According to an EPA survey in November 1986, about 28 percent of MSW landfills accept SQG hazardous wastes, 32 percent accept medical wastes, and about half accept sewage sludges, non-MSW incinerator ash, industrial process wastes, and asbestos-containing materials (73).

Table 7-I—Estimates of the Percentage (by weight) of Post-Recycling MSW Landfilled In the United States, Japan, and Europe[a]

Country	Percent landfilled	Year
Denmark	44	1985
France	54	1983
Greece	100	1983
Ireland	100	1985
Italy	85	1983
Japan	33	1987
Netherlands	56-61	1985
Sweden	35-49	1985,1987
Switzerland	22-25	1985
United Kingdom	90	1983
United States	90[a]	1986
West Germany	66-74	1985,1986

aThese figures refer to landfilling *after* recycling (e.g., of source-separated glass, paper, metals) has occurred. For example, the United States landfills about 80 percent of all MSW, but about 90 percent of post-recycled MSW.

SOURCES Franklin Associates, Ltd., *Characterization of Municipal Solid Waste in the United States, 1960 to 2000 (Update 1988),* final report prepared for U S Environmental Protectlon Agency (Prairie Village. KS: March 1988), A. Hershkowitz, "International Experiences in Solid Waste Management," contract prepared for U.S. Congress, Off Ice of Technology Assessment (Elmsford, NY Municipal Recycling Associates, October 1988); Institute for Local Self-Reliance (ILSR), *Garbage in Europe: Technologies, Economics, and Trends* (Washington, DC: 1988); C. Pollock, "Mining Urban Wastes: The Potential For Recycling," Worldwatch Paper 76 (Washington, DC: Worldwatch Institute, April 1987), Swedish Association of Public Cleansing and Solid Waste Management, *So/id Waste Management in Sweden* (Malmo, Sweden February 1988).

Data on Numbers and Capacity

On a national scale, EPA estimated that 6,034 active MSW landfill facilities existed in 1986 (77).[1] EPA also indicated the rate at which it expects these facilities to close during the next 20 years (table 7-2).

Additional information about trends in landfill numbers and capacity is available from: 1) data in EPA's 1986 Census (62, 73); 2) State reports; and 3) conversations with State officials. Data from these sources are not always comparable because definitions often differ.

As reported by the above sources, though, landfill capacity problems appear to be most severe in the Northeast and parts of the Midwest:

Table 7-2—Projected Number of Municipal Landfills That Will Remain in Operation Over the Next 20 Years

Year	Number of landfills
1988	5,499[a]
1993	3,332
1998	2,720
2003	1,594
2008	1,234

a1988 figures reflect projected closings of 535 landfills during 1987.

SOURCE: U.S. Environmental Protection Agency. Report *to Congress, Solid Waste Disposal in the United States, Vol. II, EPA/53;-SW-88-011* B (Washington, DC: Oct 1988),

- 8 States had less than 5 years of remaining capacity (Connecticut, Kentucky, Massachusetts, New Jersey, Ohio, Pennsylvania, Virginia, West Virginia); and
- 15 States had between 5 and 10 years (Alabama, Colorado, Florida, Illinois, Indiana, Maine, Maryland, Minnesota, Mississippi, Missouri, Montana, New Hampshire. New York, Oklahoma, Vermont).[2]

Four states (Florida, Massachusetts, New Hampshire, and New Jersey) were expected to close almost all existing landfills within the next 10 years. Because it usually takes 5 or more years to permit and develop new facilities (ch. 8), any area with less than 10 years of expected landfill life can be considered to have capacity problems.

In New Jersey, for example, 7 of 10 major landfills that were open in early 1987 were expected to close by the end of 1989. New Jersey law prevents counties without landfill capacity from transporting MSW in-state to counties with remaining capacity; instead, counties lacking capacity must make other arrangements, such as transporting MSW out-of-state (67). As a result, the State as a whole has essentially no remaining capacity.

Even in the densely populated Northeast, however, it is difficult to generalize about capacity. For example, between 1980 and 1984 the Delaware Solid Waste Authority located three new landfills and expanded the State's available capacity to an

[1] EPA defined a facility as an MSW landfill if it received at least 50 percent household and/or commercial waste, was not a hazardous waste landfill, and had at least onc active landfill unit (i.e., a disposal area within the facility that had the same liner type throughout). The average facility had 1.09 active units, 0.52 closed units, and 0.64 planned units. An earlier survey reported over 9,()(X) landfills, but that estimate included nonmunicipal landfills (39, 71).

[2] Rhode Island also was included in the latter category, but other data indicate that the State has an estimated 15 years of remaining capacity (63).

estimated 25 to 30 years (81). Rhode Island has an estimated 15 years of capacity, largely because of the Central Landfill (operated by the Rhode Island Solid Waste Management Corporation) that accepts 90 percent of the State's solid waste (63). Even New York had an estimated 9 years of remaining capacity as of 1987 (46).

In the Southwest, States such as Arizona and New Mexico do not appear to have an overall capacity crisis. possibly because of lower population densities and greater land availability (1, 65). In addition, groundwater aquifers in the Southwest tend to be located far below the surface where they are less likely to be contaminated by leachate from MSW landfills.

Great variation in capacity exists within States. Rural areas, for example, often do not have the same capacity problems as do urban areas. Within Illinois, the northwestern part of the State and the Chicago area face the most severe problems, while rural southern Illinois does not face capacity problems (79). Rural areas in Florida do not lack landfill capacity, but urban areas such as Pinellas County (St. Petersburg) and Dade County (Miami) are facing capacity problems (58).

Even these general rural and urban trends are variable. Some rural areas do face landfill shortages, and not all urban areas are unable to solve their capacity problems. In Ohio, landfill capacity in the more urban north was estimated as of 1988 to be between 8 and 21 years, while the rural southeast had only *3.5 years (48).* Some large cities have succeeded in increasing their landfill capacity. Phoenix opened a new landfill that is expected to provide 50 years capacity (l). These facilities are not always near the cities, however. For example, in 1990 Portland will begin sending MSW to a new landfill in eastern Oregon that could meet the city's landfill needs for up to ***20 years (34).***

Data on Closings and Openings

Limited data are available on MSW landfill closings and openings. EPA estimated that 14,000 MSW landfills have closed around the country since 1978,70 percent of those operating at the time (78). The number of closings, however, does not necessarily reflect net changes in available landfill capacity. For example, Pennsylvania lost 13 MSW landfills between July 1986 and November 1987. However, one new landfill was opened and two others were expanded, and statewide capacity increased from 4.2 years in May 1987 to 5.5 years by November 1987 (51). Unfortunately, most States collect data on numbers of closings, rather than capacity.

Many estimates about landfill numbers assume that current disposal rates will continue and that no new landfills will be sited in the future. It is true that new landfills are difficult to site. EPA estimated that only 10 percent of MSW landfills were under 5 years old, indicating that few had opened recently (77). However, in some cases the new facilities are larger than previous facilities, again illustrating the limitations of data based only on crude numbers.

Landfills are being sited or expanded in some States, even if the number of new sitings is declining. Delaware and Pennsylvania, as noted above, have sited new landfills and expanded old ones. In Missouri, four new landfills were permitted and five received permits to expand between July 1986 and late 1987 (17). In California, 4 new landfills were sited and 12 old ones were expanded between 1983 and 1988 (21). In Ohio, 2 new landfills were sited and 12 old ones expanded from 1985 through 1987 (48).

For some States (e.g., Missouri, California, and Pennsylvania), these developments can translate into a net increase in capacity. In addition, if new landfills are larger than the ones that close, then fewer new landfills would be required to replace lost capacity. This was the case in Missouri, where 90 percent of its increase was due to one new landfill in St. Louis county, and in Pennsylvania, where one new landfill accounted for 75 percent of the capacity increase.

Interstate Transportation of MSW

Proposals to use disposal sites in other States are frequent and often focus on areas that are either rural or that have existing disposal facilities. Although some States have tried to ban importation of MSW, such efforts frequently run afoul of the Interstate Commerce Clause (ch. 8).

Interstate transportation of MSW appears to have increased, particularly, but not only, in the Northeast. Little concrete information on interstate transportation is available, however. Anecdotal information obtained from State reports and conversations with State officials indicates that shipment of MSW to other States occurs from many areas, including, for example, Missouri, Ohio, Illinois, New York, New Jersey, and Wisconsin (17, 48,60,67). Missour[i] was estimated to transport one- third of its MSW out-of-state, In New Jersey, about 55 to 60 percent of the MSW produced in the State was exported out-of-state in 1988, primarily to Pennsylvania, but also to Ohio, West Virginia, Connecticut, New York, and Kentucky (67).

One factor that can influence interstate transportation is competition among landfill operators and haulers. In general, waste will flow in the direction of lower costs. For example, landfill capacity is adequate in Wisconsin, but even so some MSW is transported along the Milwaukee-Chicago corridor, possibly because it is less costly for haulers to transport MSW over longer distances to their own landfills than to dispose of MSW in a competitor's landfill (60).

DECOMPOSITION OF MSW IN LANDFILLS

About three-fourths of MS W by weight is organic waste (e.g., paper, yard waste, and food waste) and about one-fourth is inorganic (e.g., metals and glass) (ch. 3). Organic wastes are biodegradable and can decompose under proper landfill conditions to produce carbon dioxide, methane, organic acids, ammonia, water, and other chemicals. In contrast, inorganic wastes are not biodegradable and essentially remain unchanged over time.

Decomposition refers to the breakdown of organic materials into different compounds as a result of microbial activity. When organic wastes are put in a landfill, some **aerobic** decomposition occurs initially as aerobic bacteria (i.e., bacteria that function in the presence of oxygen) begin to break down the waste. They also quickly consume the available oxygen (64). **Anaerobic** decomposition (i.e., decomposition caused by bacteria that function without oxygen) then begins and is the dominant mode of decomposition (27).

Aerobic and anaerobic decomposition generate different byproducts. Aerobic bacteria break down the waste materials into organic acids and other chemicals, and the bacteria themselves produce carbon dioxide as a byproduct of their metabolism (64). Anaerobic bacteria, however, produce methane as a result of their metabolic activity (i.e., methanogenesis).

Decomposition can continue for many years, as long as some organic material is available for bacterial activity. The rate depends on many factors, including moisture content, pH. temperature, degree of compaction, and MSW age, composition, and size. When degradation occurs, the volume of the original MSW is reduced. in effect providing additional landfill capacity (see ''Recycling Landfill Space" below). Decomposition also can cause subsidence of landfill caps and greater penetration by rain in some cases.

There is evidence, however, that decomposition rates of organic materials in landfills are so slow that the space-saving benefits may not be important (57, 85). In particular, decomposition under relatively dry conditions stops and materials can remain unaltered for decades (80). At some landfills, organic materials such as paper and food waste have not decomposed since their disposal 10 to 20 years ago. This is not necessarily surprising, since archaeologists have long known that perishable materials can last for centuries under the right conditions (85).

When decomposition does occur, the fate of the different byproducts depends on a number of factors. Liquids that percolate through the landfill (e.g., from rainfall, moisture in the waste itself, or the byproducts) can carry some chemicals through the soil and toward groundwater. This mixture is known as *leachate. The* organic acids formed during aerobic decomposition can increase the mobility, volubility, and sometimes the potential toxicity of metals in the leachate. In contrast, evidence suggests that under anaerobic conditions, metals are less soluble and instead may precipitate out as, for example, metallic sulfides (27,28).

The quantity of leachate generated depends on factors such as rainfall, temperature, humidity, surface runoff, and subsurface water migration, all of which affect the rate of anaerobic bacterial activity (27). The presence of leachate is the impetus for various pollution controls at landfills (e.g., liners and leachate collection systems) because decomposition of the organic materials without collection and control of the byproducts is undesirable.

In most cases, the carbon dioxide and methane generated by bacteria are eventually emitted to the atmosphere. These gases were previously considered relatively benign (except for the explosive threat of methane), but they now are considered as prime actors in the global warming phenomenon (87). All methods of dealing with organic wastes produce carbon dioxide, though. and landfills in the United States probably contribute a negligible amount of global carbon dioxide emissions. They may contribute between 2 and 6 percent of global methane emissions, however (see ''Atmospheric Emissions" below). While the methane can be recovered for energy production. it often is not produced at a sufficiently high rate to make recovery economical. One idea to make recovery more viable and reduce atmospheric emissions is to enhance the rate of methane production (see 'Enhancing Decomposition Rates' ').

Recycling Landfill Space

"Recycling" landfills-reusing the same landfill space after a period of decomposition-has been suggested as a means of extending landfill lifetimes, allowing the repair of liners and leachate collection systems, and recovering materials of value (36, 80). One recycling operation in Collier County, Florida, already mines an MSW landfill and processes materials at a centralized facility (25). Screening is used to remove fine soil and humus and to recover ferrous metals.

The Delaware Solid Waste Authority plans to excavate—when degradation is essentially over, as measured by a decrease in methane production—an 8-acre cell containing about 140,000 tons of MSW deposited between 1980 and 1982. The excavated material will be screened for ferrous scrap, plastics, wood, textiles, aluminum, glass, and other materials; some of these could be burned (to exploit their Btu value), while others possibly could be recycled. The Authority intends to rebuild the liners and leachate collection systems so that the area can be reused, and to use the screened dirt as daily cover material.

Biodegradable Plastics

Biodegradable plastics are being promoted as a solution to litter problems and, to some extent, to landfill shortages. The reduction in volume associated with degradation into smaller pieces and dust-sized particles could be desirable, depending on its timing and impact on landfill subsidence and whether the extra capacity created is used to advantage. However, the types of products that could be made with biodegradable plastics comprise a relatively small portion of the MSW that enters landfills.

In addition, much is unknown about the performance, timing, and rate of degradation of biodegradable plastics (ch. 5).[3] Little is known about additives in plastic products; for example, depending on conditions, metal additives could be released in soluble forms and become part of leachate. In contrast, nondegradable plastics are basically inert when landfilled and probably are not significant contributors of byproducts.

Research is needed on subjects such as the conditions under which different components degrade, how rapidly they degrade, whether degradable plastics would have much effect on landfill capacity, and whether they would cause any environmental problems.

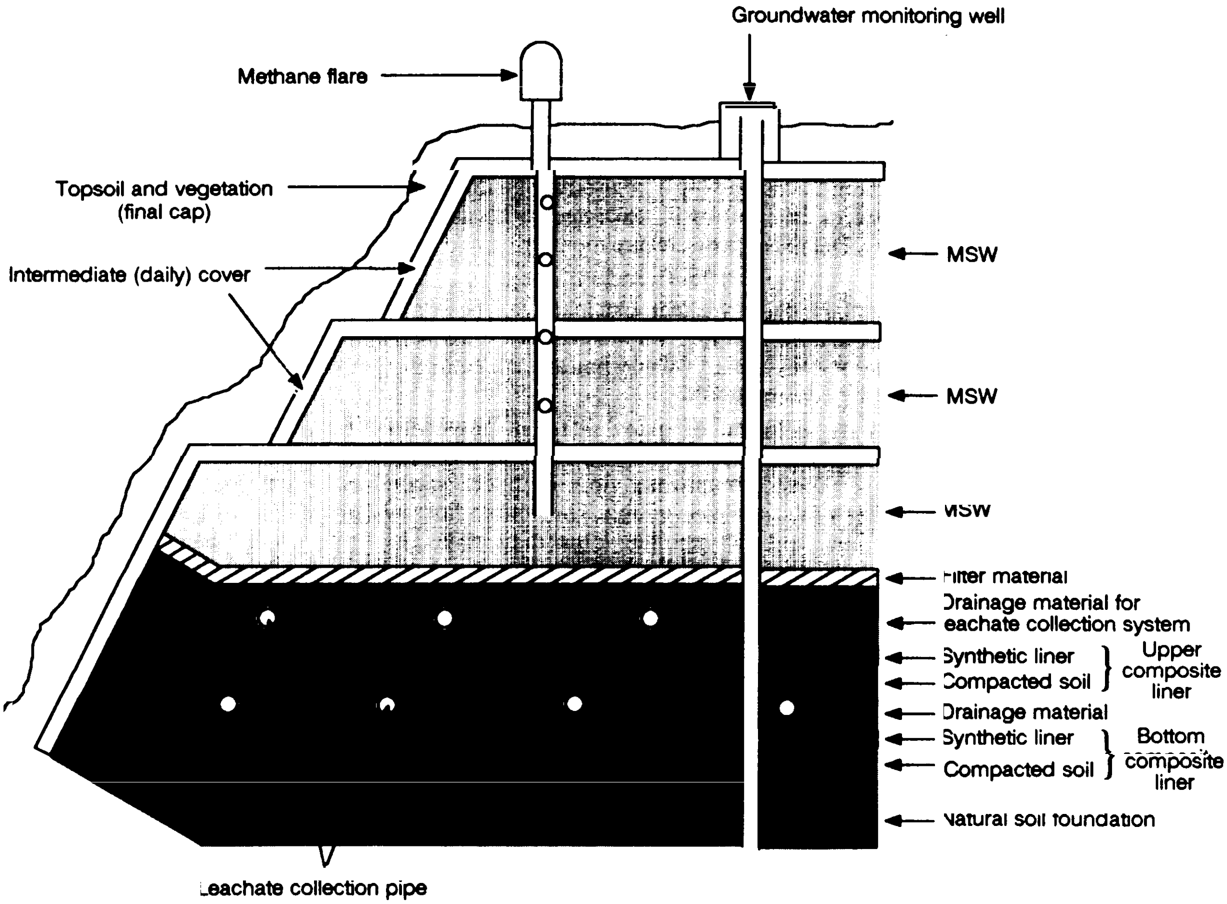
LANDFILLS AS SYSTEMS

Whether a landfill will eventually cause environmental problems depends on a host of factors—including the nature of the MSW, the rate of decomposition, site-specific hydrogeology, rainfall. distance to aquifers, types of liners and covers, runoff controls, and ability to collect leachate and gas. For example, some landfills that caused problems in the past clearly were sited inappropriately.

Many different engineering components or controls can be included in a landfill design, such as liners, monitoring systems, leachatc collection systems, and gas venting or collection systems (figure 7-1; box 7-A describes a landfill in Japan that has many of these features). The necessity of various engineering controls can vary given the hydrogeological and other conditions at a site.

[3] Photodegradable plastics would not degrade in landfills because they would be buried and not exposed to light.

Figure 7-1—Diagram of Configuration of Selected Engineering Features at MSW Landfills



SOURCE: Office of Technology Assessment, 1989, after 52 *Federal Register 20226, May 29, 1887.*

Thus, to provide sufficient environmental protection a landfill must be designed as an engineered system and located where it will be least likely to cause contamination. For example, landfills should not be sited in areas with permeable soils, shallow groundwater, or wetlands. This approach enhances the prospects of collecting contaminants before they migrate to the surrounding environment.

This section discusses engineering control features from a technical standpoint. They are discussed separately below, but in practice they must be considered as integrated elements in a single system. The section also summarizes available information on the numbers of landfills that actually exhibit these features and discusses some additional design concepts that merit additional research.[4] A later section discusses EPA's proposed regulations for landfill design and operation.

Engineering Controls

Liners and Covers

Liners are installed along the bottom and sometimes the sides of a landfill to reduce the migration of leachate to groundwater beneath the site, as well as laterally. In addition, a ''cover'" or ''cover system' can be placed over a landfill once it has closed to prevent the introduction of water into the landfill (and thus reduce leaching).

[4] The information on landfill features is drawn primarily from EPA's survey of landfill operators and owners (73). EPA combined data on the 70 percent of existing landfills that opened before 1980 and the 30 percent that opened since then.

Box 7-A—Japan's Santama Landfill

Santama landfill, located in Tokyo prefecture, is an example of a modem landfill. It came on line in 1984, and although it is not representative of most Japanese landfills, it is likely to be representative of many future designs.

The landfill is a joint venture among 25 municipalities and 2 towns. Funds for operating the facility come from taxing the contributing municipalities and charging a tipping fee twice a year. The site was identified in 1981, and although some public opposition was encountered, negotiations lead to an agreement that the facility would have advanced pollution controls. About 22 hectares will be used for landfilling, with a surrounding undeveloped green zone of 14 hectares. At the end of its useful life, expected to be about 13 years, the site will be capped and transformed into a sports facility. Details of post-closure monitoring and leachate collection and treatment plans are not known to OTA.

One unique aspect of the Santama facility is that, like many Japanese landfills, it does not accept organic wastes (paper, food, yard wastes). Instead, these wastes are collected by the municipalities and sent to incinerators. It also does not accept industrial waste. It does accept fly and bottom ash from the MSW incinerators (mostly untreated but about 10 percent processed by cementation).

Another unique aspect is its inclusion of many different engineering features: computerized weigh-in, record-keeping system for each truck, truck washing system, intricate liner system and ‘‘sandwich” process, leachate collection and drainage pipes, groundwater flow channels, secondary wastewater treatment plant for leachate, groundwater monitoring wells, and gas venting. The bottom liner system consists of 1 meter of thick clay covered by a synthetic rubber liner and then another 1 meter of clay. The filling of the landfill is based on a ‘‘sandwich process’ ‘-each 2-meter layer of MSW is covered with a 1 meter thick clay lining. The wastewater treatment facility provides activated sludge secondary treatment for the leachate. It removes an average of 92 percent of the biochemical oxygen demand (BOD), bringing post-treatment levels down to 8 to 10 ppm. The leachate is then disinfected with chlorine and sent to a sewage treatment plant in Tokyo. BOD is tested weekly at an on-site laboratory; cyanide, PCBs, nitrates, phosphorus, and seven metals are tested monthly.

The design is not without some problems and controversies. The landfill is located along a small stream, which dictates the need for a disaster prevention flood control system. One reviewer also suggests that the sandwich process may waste space and inhibit internal drainage (8). Data are not available on leachate volume and characteristics or on hydrological balance, so it is difficult to evaluate the effect of this feature.

About two-thirds of all landfills have some type of soil (including clay) beneath them, but the soil at these landfills was not necessarily engineered (i.e., compacted or remolded) to a particular design (table 7-3). Only 1 percent of landfills are estimated to have synthetic liners; the use of synthetic liners is expected to increase, but only to about 6 percent at planned landfills. Many other types of liners have also been used, including admix compositions (e.g., paving asphalt concrete), sprayed-liners (e.g., liquid rubber), and soil sealants (30).

One difference between clay and synthetic liners is permeability, the rate at which water and chemicals move through a liner. The permeability of clay liners to **water** ranges between 10^{-6} to 10^{-7} cm/see, depending on clay content, compaction, and treatment (e.g., addition of lime). Synthetic liners are less permeable to water, with a range between 10^{-5} and 10^{-6} cm/sec. It is not clear whether one type is more or less permeable to organic chemicals (see “Synthetic Liners” below). Clay is more absorptive of chemicals (i.e., once a pollutant moves into clay, it tends to stay there) (30).

Both types of liners are subject to problems that can cause leachate to move through the liner more rapidly. Synthetic liners can sometimes be punctured or tom (e.g., in installation or in actual operation), while clay liners can crack. However, the frequency with which these problems occur is unknown.

Whether these differences and problems are significant depends on many factors, in particular the rate at which leachate is generated and how efficiently it is collected. A liner system cannot be judged in isolation; the leachate collection system and other design features must also be considered.

Table 7-3-Presence of Soil or Synthetic Membrane Liners at Closed, Active, and Planned MSW Landfill Units[a]

Type of liner	Percentage of landfill units with given type			Percentage used in combination with another type at active units
	Closed	Active	Planned	
In-situ soil	34	28	30	9
Engineered soil	35	39	36	15
Synthetic membrane	<1	1	6	<1
Other	8	7	8	2
None or unknown	39	40	35	—

aTotals add to more than 100 percent because some units have more than one type.

SOURCE: Adapted from U.S. Environmental Protection Agency, Survey of *State and Territorial Subtitle D Municipal Landfill Facilities,* draft final report. prepared by Westat, Inc., Oct. 13, 1987.

Synthetic Liners--Synthetic liners are thin sheets (i.e., 0.3 to 0.6 cm thick) composed of materials such as rubber, polyvinyl chloride. or various polyethylene. Most synthetic liners are considered impermeable to water, especially when compared with natural soil liners.

The characteristics of a liner affect how it will react to different chemicals. For example, liners made of materials such as high-density polyethylene (HDPE) and vulcanized rubber have molecular arrangements that are crosslinked, an arrangement that resists swelling and dissolution by solvents of similar polarity (29).[5]

Some laboratory experiments suggest that volatile organic chemicals (e.g., trichloroethylene or TCE, toluene, and xylene) can migrate rapidly through synthetic liners (31). The amounts and directions of migration varied depending on characteristics of the chemicals (e.g., relative volubility), the liner (e.g., polymer content, thickness), temperature, and concentration of the chemicals on either side of the liner (31). In different tests conducted by EPA, most synthetic liners were eventually destroyed when exposed to methylene chloride in full strength concentrations (14, 68).

It is not known whether these results are representative of actual landfill conditions. In the laboratory experiments reported by Haxo and Lahey (31), the concentrations of organic chemicals in the solutions were relatively high, for example 1,100 ppm for TCE. In a landfill, synthetic liners probably encounter more dilute solutions in most cases. For example, although TCE is common in leachate, its average concentration in several MSW leachate samples was generally less than 200 ppm (table 7-4); another study indicated an average of 38 ppm (but with a range of 1 to 1,460 ppm) (41).

Thus laboratory experiments with immersed liners involve TCE concentrations that may not represent field conditions, although they are within the upper limit of concentrations detected in some field samples. They do indicate, however, that additional research is needed on the frequency with which synthetic liners are exposed to high concentrations of volatile organic chemicals and on long-term performance of the liners under these conditions.

Seams for Flexible Membrane Liners-An important aspect of flexible membrane liners is the process by which the seams of the different liner segments are joined. Segments of a liner can be joined together in the factory by using solvent adhesives or dielectric methods, or in the field using various welding methods.

EPA has tested seam strength under conditions designed to simulate chemical and physical environments that might be encountered at hazardous waste facilities (43). Two types of strength generally are evaluated: peel strength (i.e., the ability of the seam to resist peeling apart of two liner segments) and shear strength (i.e., the ability of the liner material to resist lateral separation). Results indicate that shear and peel strength are not correlated, with peel strength being related to the strength of the bond and shear strength being related to properties of the liner material. The method used to create the seams causes differences in peel and shear strength. EPA concluded that existing data and manufacturers' recommendations on the chemical compatibility of

[5]Nonpolar molecules do not have a significant electrical charge.

Table 7-4–Median Concentrations of Substances Found in MSW Landfill Leachate, in Comparison With Existing Exposure Standards[a]

Substance[b]	Median concentration (ppm)	Exposure standards Type[a]	Exposure standards Value (ppm)
Inorganics:			
Antimony (11)	**4.52**	T	0.01
Arsenic (72)	**0.042**	N	**0.05**
Barium (60)	**0.853**	N	**1.0**
Beryllium (6)	0.006	T	0.2
Cadmium (46)	0.022	N	0.01
Chromium (total) (97)	0.175	N	0.05
Copper (68)	0.168		0.012
		W	0.018
Cyanide (21)	0.063		0.7
Iron (120)	221	W	1,000
Lead (73)	0.162	N	0.05
Manganese (103)	9.59	w	0.05
Mercury (19)	0.002	N	0.002
Nickel (98)	0.326	T	0.07
Nitrate (38)	1.88	w	10
Selenium (18)	0.012	N	0.01
Silver (19)	**0.021**	N	0.05
Thallium (11)	**0.175**	w	0.04
Zinc (114)	8.32	w	0.110
Organics			
Acrolein (1)	~~~	**W**	**21**
Benzene (35)		**T**	**5**
Bromomethane (1)	170	**T**	10
Carbon tetrachloride (2)	202	**T**	5
Chlorobenzene (12)	128	**T**	1,000
Chloroform (8)	195	**C**	5.7
bis (Chloromethyl) ether (1)	**250**	**C**	**0.0037**
p-Cresol (10)	2,394	**T**	**2,000**
2,4-D (7)	129	**T**	100
4,4-DDT (16)	0.103	**C**	0.1
Di-n-butyl phthalate (5)	**70.2**	**T**	**4,000**
1,2-Dichlorobenzene (8)	11.8	**W**	**763**
1,4-Dichlorobenzene (12)	13.2	**T**	**75**

Substance[b]	Median concentration (ppm)	Exposure standards Type[a]	Exposure standards Value (ppm)
Dichlorodifluoromethane (6)	237	T	**7,000**
1,1-Dichloroethane (34)	1,715		**7**
		N	**0.58**
1,2-Dichloroethane (6)	1,841	T	**5**
1,2-Dichloropropane (12)	66.7	w	**5,700**
1,3-Dichloropropane (2)		c	**0.19**
Diethyl phthalate (27)	118		**30,000**
2,4-Dimethyl phenol (2)		W	**2,120**
Dimethyl phthalate (2)	42.5	w	**313,000**
Endrin (3)	16.8	T	**0.2**
Ethyl benzene (41)	274	w	**1,400**
bis (2-Ethylhexyl) phthalate (10)	184	**T**	
Isophorone (19)	1,168	**W**	**5,200**
Lindane (2)	0.020	**T**	**4**
Methylene chloride (68)	5,352	**C**	**4.7**
Methyl ethyl ketone (24)	4,151	**W**	**2,000**
Naphthalene (23)	32.4	**W**	**620**
Nitrobenzene (3)	54.7	**T**	**20**
4-Nitrophenol (1)	17	**W**	**150**
Pentachlorophenol (3)	173	**T**	**1,000**
Phenol (45)	2,456	**T**	**1,000**
1,1,2,2-Tetrachloroethane (1)	210	**C**	1.75
Tetrachloroethylene (18)	132	**C**	6.9
Toluene (69)	1,016	**T**	10,000
Toxaphene (1)	1	**N**	5
1,1,1-Trichloroethane (20)	887	**N**	**200**
		T	**3,000**
1,1,2-Trichloroethane (4)	378	**C**	**6.1**
Trichloroethylene (28)	187	**N**	**5**
		T	**3.2**
Trichlorofluoromethane (10)	56.1	**T**	10,000
1,2,3-Trichloropropane (1)	230	**T**	**20**
Vinyl chloride (10)	36.1	**N**	**2**

aTypes of exposure standards:
C. EPA Human Health Criteria, based on carcenogenicity
N= National Interim Primary or Secondary Drinking Water Standard
T= EPA Human Health Criteria, based on systemic toxicity
W= Water Quality Criteria
bNumber of samples in parentheses.

SOURCE: After U.S. Environmental Protection Agency, Office of Solid Waste, *Summary of Data on Municipal Solid Waste Landfill Leachate Characteristics, Criteria for Municipal Solid Waste Landfills (40 CFR Pert 258), EPA/530-SW-88-038 (Washington, DC: July 1988).*

liner materials provide an initial basis for evaluating expected liner performance in given chemical environments (43). However, EPA also concluded that tests of less than 6 months may be inadequate to determine the performance of some flexible membrane liners and that the 120-day immersion period specified in one standard test (known as EPA Method 9090) may need review to ensure that it is long enough to determine chemical compatibility,

Natural Soil--soil, especially different types of clay, is commonly used to underlie MSW landfills (table 7-3). In some cases the materials are simply used in-situ. In other cases they are brought together and engineered (i.e., compacted or remolded) to increase strength and reduce permeability. As noted above, clay liners are more permeable to water than are synthetic liners. Engineered soil, however, is less permeable than uncompacted soil (52 *Federal Register 12568.* April 17, 1987).

The permeability of natural soil liners to organic chemicals such as solvents is variable and depends on many factors, including characteristics and concentrations of the chemicals, contents and degree of compaction of the clay, and type of engineering. The fate of chemicals also depends on whether they are adsorbed onto soil particles. EPA noted, in a proposed rulemaking for hazardous waste management systems, that compacted clay liners can adsorb much of the leachate, reducing the amount that reaches leachate collection systems (52 *Federal Register 20224,* May 29, 1987). Other researchers, however, contend that little is known about adsorptive capacity for chemicals such as solvents (8).

Soil liners also can become dessicated for various reasons. For example, some solvents that are insoluble in water (e.g., xylene and carbon tetrachloride) may cause water to migrate out of the soil. When dessication occurs, the soil may shrink. Subsequent cracking and channeling of the soil may form pathways through which liquids can flow (59).

Composite Liners—A composite liner is composed of an engineered soil layer overlain by a synthetic flexible membrane liner. This combination is uncommon (table 7-3). Such liners could provide higher protection than individual liners because each liner component has different resistance properties.

Cover Types-During the operating life of a landfill, cover is usually applied on a daily basis to control disease vectors and vermin, prevent odors and fires, and discourage scavenging (74). In general, about 6 inches of compacted earth is used. Currently, 45 States require that cover be applied daily. EPA's proposed landfill regulations also would require the application of daily cover (53 *Federal Register 33314,* Aug. 30, 1988). The type of soil used for daily cover does not appear to be critical (74); clay, silt, or a combination of the two with sand or gravel is generally considered adequate.

To close a landfill, a final cover usually is placed on top to reduce infiltration of water. The design of the cover considers various factors such as soil type, degree of compaction, surface slope, drainage, and water balance (77). For example, the top of the landfill can be sloped to increase runoff and reduce infiltration (64). The type of soil used also matters, because highly organic soils (e.g., peat) do not compact easily. EPA estimated that most active and planned units have or will have some type of earth cover (77); only 2 percent have or will have a synthetic membrane cover.

Leachate Collection and Removal Systems

Leachate collection and removal systems use pipes to collect the leachate that settles on top of a liner and prevent it from migrating into groundwater. A typical system consists of a series of perforated collection pipes (usually 4 to 6 inch PVC), drainage layers and blankets, header pipes, and sumps. The pipes are placed above the liner in drainage layers filled with sand or gravel (76). In landfills with double liners, the pipes are placed both above the top liner and between the top and bottom liners. In general, liners are designed with a slope so that leachate drains into a central collection point.

The efficiency of leachate collection systems depends on the rate of leachate generation, spacing of collection pipes, slope of liners, liner permeabilities, and presence of drainage blankets. EPA has used models to estimate leachate collection efficiencies. At rates of leachate generation considered typical of landfills (i.e., 10 to 100 gallons per acre per day), for example, EPA estimated that systems associated with composite liners would exhibit collection efficiencies approaching 100 percent, while systems associated with clay liners would exhibit much lower efficiencies (52 *Federal Register 12571,* April 17, 1987).

Only 11 percent of existing landfills have any type of leachate collection system (77) and available data do not allow a determination of how much leachate is actually subject to collection. In addition, the presence of a leachate collection system is not necessarily sufficient to prevent groundwater contamination. EPA has identified MSW landfills equipped with leachate collection systems that failed to prevent such contamination because of inadequate design and/or construction (76).

Once leachate is collected. it can be managed by recirculating it in the landfill, transporting it to a municipal sewage treatment plant, discharging it to a treatment plant through a sewer, and treating it on-site with biological treatment processes (77). Leachate recirculation is used at about 3 percent of MS W landfills. Other types of leachate management methods are used less frequently. According to EPA, the discharge of leachate to surface water is expected to decline in the future, while the use of recirculation and transportation to treatment plants is expected to increase.

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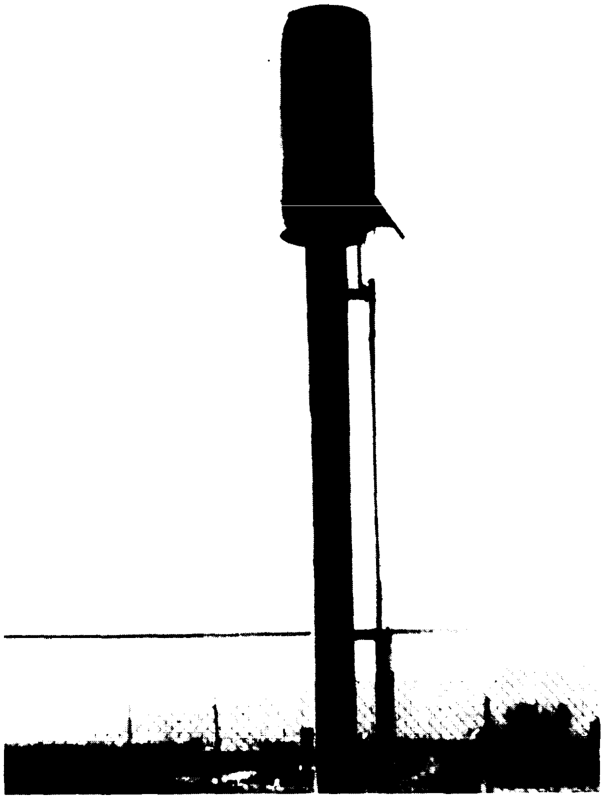


Photo credit: Office of Technology Assessment

Methane is of concern because of its explosive nature and potential to affect global temperatures. It can be collected for energy recovery, allowed to escape into the atmosphere through vents, or, as shown here, "flared" or burned as it is emitted from collection pipes.

Methane Production, Collection, and Use

Landfill gas is composed primarily of equal parts methane and carbon dioxide, with trace organic chemicals (e.g., benzene, trichloroethylene, vinyl chloride, methylene chloride) also present. Methane production begins once conditions in a landfill become anaerobic. Rates of methane production depend on moisture content of the landfill; concentrations of nutrients and bacteria; pH, age and volume of the degrading material; and the presence or absence of sewage sludge.

Methane can be collected and processed for energy recovery, allowed to escape into the atmosphere through vents, or "flared*' (i.e., burned) as it is emitted from collection pipes. Several methods can be used to collect or vent methane: 1) a permeable trench can be installed at the landfill's edge to provide a pathway to vent gases; 2) a gravel trench with a semi-permeable liner can be built running from the top to the bottom of the landfill to provide a pathway for venting; 3) a system combining pipes with a gravel trench can be built; and 4) an active pumping system can be used to draw gas out of the landfill through wells. These systems are operated only in portions of landfills that have been closed temporarily or permanently with a cap (22), although they can be installed as the landfill is built and then later connected.

The recovery efficiency of individual collection systems varies, depending on the type and spacing of the recovery system and the type of landfill covering (i.e., its permeability to gas). According to EPA, active pumping systems are the most effective means for collecting landfill gas, while permeable trenches are the least effective (74). in active systems, perforated collection pipes are placed at depths usually of 30 to 100 feet. Compressors are used to create a vacuum within the pipes and draw the gas out of the landfill; an excessive vacuum, however, can draw atmospheric air into the landfill, resulting in an aerobic environment that changes the bacterial mix and leads to production of carbon dioxide rather than methane.

More than 1,500 MSW landfills deal with methane by venting, flaring, or collection and recovery. If methane emissions were collected completely and processed for energy recovery, they could account for up to **5** percent of all natural gas consumption or 1 percent of all energy demand in the United States (74). However, only about 123 landfills actually collect methane to recover energy (77). The collected gas can be purified to increase its Btu content (to values of 500 to 1,000 Btu per standard cubic foot) and then be used in boilers, space heaters, and turbines. Purification involves using chemical and physical processes (e.g., dehydration by triethylene glycol process, molecular sieves, and refrigeration) to remove particulate matter, water, carbon dioxide, and most trace elements (64, 74).

Ambient Environmental Monitoring

Most MSW landfills do not have equipment to monitor air, surface water, or groundwater for various pollutants (77). As of November 1986, only about 35 percent monitored groundwater, 15 percent monitored surface water, 7 percent monitored methane gas, and 3 percent monitored other air emissions. Among facilities that monitored groundwater, an average of 2.1 upgradient and 3.8 downgradient wells existed. Wells were sampled approximately three times annually, with about two samples taken per sampling period. On average these facilities had been monitoring groundwater for 5 years (73).

Ownership Status

EPA estimated as of 1986 that most MSW landfills (approximately 86 percent) were publicly owned: 29 percent by counties, 28 percent by cities, 3 percent by the Federal Government, 1 percent by State governments, and 25 percent by other governmental entities (77). The remaining 14 percent were privately owned. The majority of publicly owned facilities are small (i.e., receive less than 30 tons per day), while privately owned facilities are generally larger. One representative of private operators estimated that about 50 percent of total landfill capacity may be privately owned (55).

Data from the mid-1980s show that privately owned MSW landfills were designed more frequently with leachate collection systems than were publicly owned landfills (62 percent v. 35 percent for county-owned and 35 percent for city-owned). Privately owned landfills are also more likely to conduct groundwater monitoring (30 percent v. about 15 percent for county- and city-owned), and surface water monitoring (31 percent v. 24 percent for county and 13 percent for city) (44). It is not clear, however, whether this trend is the result of ownership or simply a response to more stringent State regulations that have been promulgated in recent years and that are applicable to all new landfills, regardless of ownership status.

Other System Designs

At least two different concepts regarding the design of landfills merit additional research. One concept involves enhancing the decomposition process by recycling leachate back into the landfill. The other involves confining waste in mounds that are built above the normal ground level.

Enhancing Decomposition Rates

Some researchers suggest that the decomposition process could be enhanced by collecting leachate and recycling it back into the organic material, an idea that has been examined in laboratory situations (28, 51, 80). Recycling leachate in some manner is used at a few MSW landfills today (see ‘‘bachate Collection and Removal Systems” above).

One study at a Pennsylvania landfill concluded that recycling leachate resulted in more rapid decomposition, enhanced methane production, and increased stabilization (77). The Delaware Solid Waste Authority recently initiated a study to examine this idea on a larger scale under field conditions. It set up two 1 -acre landfills cells for household MSW only; leachate is being collected and removed for external disposal from one cell, and recycled in the other cell. Decomposition rates will be measured after 5 years.

Experimental data indicate several potential benefits: 1) the time needed to decompose organic materials might be reduced from around 15 years to only a few years; 2) methane production could be maximized, making recovery more viable; 3) reusable space would become available more rapidly; 4) collected leachate would not have to be treated at wastewater treatment plants; and 5) metals might precipitate out within the landfill instead of being carried by leachate into groundwater.

However, the researchers also have noted several problems: 1) uncertainties exist about the ultimate reactivity or fate of chemical compounds created during the process; 2) regulatory proposals by EPA would ban addition of any liquids to landfills; and 3) these designs would require careful management (e.g., small landfill cells, proper design and location of leachate collection systems, and controlled rates of leachate recycling) to minimize potential off-site migration. In addition, if problems occur with the liner or leachate collection system, the chance of off-site migration would increase. For example, small tears in the liner can occur during construction or daily operation. EPA has noted that the increased volume of leachate may clog the leachate collection system (77). These potential problems suggest that enhanced decomposition be used only at sites that are not located near groundwater.

Above-Grade Containment Mounds

In general, MSW is now placed below ground level at landfills. One idea developed for hazardous waste treatment is to confine waste above-ground under a waterproof cover system to reduce leachate generation and make leachate collection easier (9,10). The design includes: 1) an above-ground storage mound, sloped to support the weight of the waste and the cover; 2) a liner system across the base to retard entry of water and subsequent percolation of leachate; 3) a drainage system consisting of stable aggregates and collection pipes installed over the lower liner; 4) a leachate collection system that is drained freely by gravity, with drainage exiting the mound above ground; and 5) a cover system consisting of a layer with gas collection equipment, a composite liner, a drainage layer, a topsoil layer, and permanent vegetative cover.

The possible advantages are that leachate would be removed immediately by gravitational drainage, sloped construction would reduce pending of leachate on the liners, and repair may be easier. For example, if leakage became a problem because of a faulty cover system, it would become apparent soon after the fault develops, whereas leaking covers at below-ground landfills only become apparent as a result of groundwater contamination. Disadvantages include the potential for erosion of the topsoil layer and high costs (e.g., for excavating and transporting soil to the site to build the mound).

A few MSW landfills already incorporate parts of this design. For example, the Delaware Solid Waste Authority has one above-grade section with a 4-foot separation between the seasonally high groundwater level and the bottom of the liner (80). It is designed with two synthetic liners sandwiching a drainage layer and leachate collection. Another facility in Wisconsin has similar features (8). However, these have not been constructed with gravity-operated drains, so they do not incorporate all of the concept's features.

HEALTH AND ENVIRONMENTAL EFFECTS

This section reviews landfills on the Superfund National Priorities List, and discusses releases of toxic constituents and subsequent contamination of groundwater, surface water, and air. The information is derived in part from reviews conducted as EPA has worked to develop revised regulations under Subtitle D (72, 77).

Landfills on the Superfund List

According to EPA, 70 percent of existing MSW landfills began operation before 1980. Many of these older facilities were not designed with control features such as leachate collection systems or liners, and many accepted hazardous wastes. Moreover, many operating landfills continue to accept hazardous wastes. Small quantity generator wastes are exempted from the RCRA requirement to be managed at hazardous waste treatment facilities, and "household hazardous wastes" also are not subject to such regulation (ch. 3).

As a result, some older landfills accepted substantial amounts of hazardous waste. Some of these have been placed on the Superfund National Priorities List (NPL) due to their potential impacts on human health and the environment. In May 1986, 184 sites (22 percent) of the 850 sites proposed for the NPL were municipal landfills (77). One review of these sites indicated that only two of them did not involve co-disposal of MSW and hazardous wastes (41). Other observers, however, contend that MSW by itself, without any hazardous wastes, is sufficient to cause the types of problems associated with the municipal landfills on the NPL (see "Sources of Contamination" below).

The general lack of engineering controls at most existing landfills, combined with the fact that many landfills have accepted or continue to accept hazardous wastes or industrial nonhazardous wastes, suggests that additional municipal landfills may eventually require remedial action.

Releases of Potentially Toxic Substances

Releases of potentially toxic substances from MSW landfills occur primarily through three pathways: migration of leachate to groundwater, migration of leachate and runoff to surface water, and emissions of volatile gases to the atmosphere (figure *7-2).* In addition, releases can occur through explosions caused by the buildup of explosive gases (e.g., methane). Current understanding of these release processes is incomplete. However, enough monitoring of MSW landfills has occurred to allow some conclusions to be drawn regarding the types of substances released to these environments and their subsequent impacts.

Violations of State environmental protection standards by MSW landfills have occurred at a number of sites—EPA reports almost 2,300 violations for groundwater, surface water, air, and subsurface methane (77). Most violations are detected through monitoring. However, since few MSW landfills conduct monitoring, these figures clearly represent a conservative estimate of actual violations. Although violations do not necessarily mean that impacts on human health or the environment have occurred, they do indicate a greater possibility of impacts now or in the future.

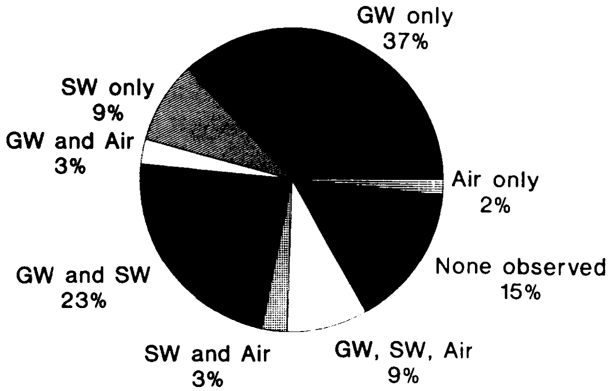
Groundwater Contamination

It is impossible to determine the actual risks posed by leachate from most landfills because groundwater monitoring data are rare. Only 25 percent of all MSW landfills monitored groundwater as of 1986 (77). This lack of monitoring is alarming because downgradient drinking water wells exist within 1 mile of an estimated 46 percent of all MSW landfills. Even given the relative lack of monitoring, over 100 potentially harmful substances have been identified in MSW landfill leachate (77).

Other data indicating that landfills can be a threat to groundwater quality come from case studies conducted by EPA at 163 landfills (primarily non-NPL landfills) (77). EPA identified 135 of these landfills that constitute a threat to human health or the environment because of their potential for groundwater contamination. Moreover, of the 184 MSW landfills on the NPL. 132 have had impacts on groundwater and 68 were listed solely because of groundwater contamination.

The extent to which substances of concern have *migrated toward* or into groundwater, and the range of potential risks associated with them, are critical unanswered issues. To estimate human health risks

Figure 7-2—Observed Releases From NPL Landfills to Water and Air



SOURCE: U.S. Environmental Protection Agency, Report to Congress. Solid *Waste Disposal in the United States, Vol. //, EPA/530.sw-88-011B* **(Washington, DC: Oct. 1988).**

posed by MSW landfills, EPA uses a model to predict the release, transport, fate, and impacts of eight pollutants (including vinyl chloride, tetrachloroethane, and methylene chloride) found in landfill leachate. Important variables that influence the magnitude of risks include distance to the nearest downgradient well, infiltration rate, landfil1 size, and aquifer characteristics (77). The model estimates, for example, that 5.5 percent of existing MSW landfills pose a lifetime cancer risk of $1O^{-4}$ to $1O^{-5}$ (i.e., one person out of every 10,000 to 100,000 people) and that 11.6 percent pose a risk of 10^{-5} to 10^{-7} (i.e., one person out of every 100,000 to 10 million people).

This model, however, has been criticized-both for underestimating risks and overestimating risks. One critic, for example, felt that using nationwide averages for some parameters masks important site-specific variability and leads to possible underestimates of risk (16). In contrast, another critic felt that the model used unreliable data that should not be extrapolated to national estimates because potential risks probably were overestimated (81). As of July 1989, EPA was revising its proposed landfill regulations in response to these types of public comments.

Microorganisms that can potentially spread disease also are present in landfills and have *been* detected in leachate and in the air (e.g., on dust particles) at landfills (49). They can originate from a number of sources, such as animal feces, human feces in diapers, sewage sludge, and even from materials such as glass, metal, plastic, paper, and yard wastes. Concentrations of pathogenic bacteria (e.g., fecal streptococci) vary substantially with time but tend to decrease rapidly after 3 to 6 months of operation, because they are destroyed by chemicals in the leachate (49). Viruses have not been found in leachate. Although only a few studies have been conducted, they have shown no adverse effects associated with microorganisms in MSW at landfills.[6]

Surface Water Contamination

Surface water contamination is related, at least in part, to the fact that few MSW landfills employ controls designed to prevent leachate and runoff from migrating out of the facility. Such contamination, for example, is known to have occurred at 73 (45 percent) of the 163 non-NPL landfills and at 79 (43 percent) of the 184 NPL landfills (77). The overall extent of surface water contamination associated with MSW landfills is impossible to determine, however, because of the general lack of monitoring.

The effect of leachate on organisms that live in surface water depends on the concentration of chemicals in the leachate and on the sensitivity of the organisms to those concentrations. Laboratory bioassays indicated that the toxicity of MSW leachate to rainbow trout living in surface water depended on where the leachate came from and how it was treated (12). Leachate taken directly from landfills was about 10 times more toxic than diluted leachate taken from drainage ditches surrounding landfills, although diluted leachate still caused some mortality. In contrast, leachate treated with physical or chemical methods was considered nontoxic. The experiments indicated that leachate toxicity was greater at low pH values but that it declined with time (also see ref. 35).

Ten cases of ecological damage (e.g., reduced diversity of bottom-dwelling aquatic communities) have been investigated that were related to contamination of surface water (77). Since ecological effects are rarely investigated, the extent of such damage probably is much greater than currently reported.

Atmospheric Emissions

MSW landfills generate several gases that pose risks to human health and the environment. The primary gases are methane and carbon dioxide, but numerous organic chemicals in gaseous forms are emitted as well (table 7-5). Of the 184 NPL landfills. less than 2 percent are listed for air emissions alone, but air emissions contributed to the decision to list the site in 17 percent of the cases (figure 7-2).

Methane emissions are of concern because of their explosive nature. EPA examined 29 cases in which damages occurred because of methane migration from landfills. In 23 of the cases, methane was detected away from the landfill at concentrations above the lower explosive level (77).[7] Explosions and fires occurred at 21 of the surveyed sites, resulting in a loss of life on five occasions.

More recently, methane emissions have received attention because of their potential to affect global temperatures. Current estimates of methane emissions from MSW landfills and other sources vary considerably and are highly uncertain. One study examined sources of atmospheric methane and estimated that the anaerobic decay of MSW in landfills around the world contributed between 30 million and 70 million tons annually (5). This could constitute about 5 to 20 percent of all methane released (13). The United States has been estimated to account for about one-third of biodegradable carbon content in the world (5); if this ratio is applicable to the amount of degradable MSW, then MSW landfills in the United States could contribute about 2 to 6 percent of global methane emissions (based on data in ref. 6). Moreover, since methane traps about 25 times more infrared energy than does carbon dioxide (56), from a climate perspective it

[6]According t. the American Paper Institute (2), there is no cv idence that disposable diapers add infectious material to landfill leachates or that handling such diapers is linked with viral diseases.

[7]Methane is explosive when its Concentration is between 5 and 15 percent, by volume, in air at normal temperatures. Two Federal regulatory standards exist: an allowable concentration of 5 percent or less at a property boundary, and an allowable concentration of 1.25 percent or less at buildings both on and off the site (40 CFR 257.3-8(a)).

Table 7-5-Concentrations of Gaseous Constituents From MSW Landfills

Constituent	Range of concentration (ppm)	Median
Benzene	0-32	0.3
Carbon dioxide	342,000-470,000	350,000
Carbon tetrachloride	0.011	
1,2-Dichloroethane	19-59	
Ethyl benzene	0-91	1.5
Heptane	0-11	0.45
Hexane	0-31	0.8
Isopentane	0.05-4.5	2.0
Methane	440,000-587,000	500,000
Methyl-cyclohexane	0.017-19	3.6
Methyl-cyclopentane	0-12	2.8
Methylene chloride	0-118	0.83
Nonane	0-24	0.54
Perchloroethylene	0-186	0.03
Toluene	0-357	6.8
1,1,1-Trichloroethane	0-3.6	0.03
Trichloroethylene	0-44	0.12
Trichloromethane	0.61	
Vinyl chloride	0-1o	2.2
Xylene	0-111	0.1
m-Xylene	1.7-76	4.1
0-Xvlene	0-19	1.8

SOURCES: U.S. Environmental Protection Agency, *Report to Congress: Solid Waste Disposal in the United States, Vol. II, EPA/530-SW-88-O11B* **(Washington, DC: October 1988); J. Wood and M. Porter, "Hazardous Pollutants in Class II Landfills,''J .Air Pollutio Control 37(5)609-615, May 1987.**

maybe more desirable to flare methane and convert it to carbon dioxide, rather than merely vent its

Emissions of potentially carcinogenic organic chemicals (e.g., vinyl chloride and benzene) also have been detected at landfills. Evidence of this has been found in southern California at sites that do not accept non-MSW wastes (86), as well as at landfills in other States (e.g., Wisconsin and New Jersey) (42). EPA estimated that about 200,000 metric tons of non-methane volatile organic chemicals (VOCs) are emitted from landfills each year (53 *Federal Register 33338,* Aug. 30, 1988). However, EPA's estimates of VOC emissions have been criticized because there is no standard method for sampling air emissions, particularly VOCs, from landfills (84). The critique suggested that standard procedures need to be developed for collection of air samples, sample containment and analysis, and quality control. In one study in the San Francisco Bay area, VOCs were present in the gas at 47 of 60 landfills (66), There was only minimal evidence of migration of the VOCs off-site into the ambient air, but problems in sampling procedures made it difficult to evaluate the ambient air data.

VOC emissions can affect ozone concentrations because many of these emissions are ozone precursors (26). It is unknown, however, to what extent emissions from landfills contribute to regional non-attainment of National Ambient Air Quality Standards for ozone.

In addition, mercury also has the potential to volatilize into the atmosphere. One Swedish study found that emissions of mercury from four landfills were one to two times higher than background levels (4). However, all four landfills had accepted large quantities of non-MSW, so it is difficult to use this data to evaluate the importance of mercury emissions from MSW landfills.

[8]Several legislative initiatives have tried to address this. One Senate bill proposed in 1988, fOr t? xample, would have: 1) required Subtitle D facilities to be designed and operated 10 minimize methane emissions; 2) prohibited, as of Jan. 1, 1994, mass releases of methane (e.g., by venting wells); and 3) required EPA to determine the contribution of methane to global warming, the sources and sinks of' methane, and methods of controlling methane emissions.

Sources of Contamination: MSW or Industrial Waste?

A well designed, constructed, and operated landfill might exhibit high rates of leachate and gas generation because it usually would be designed to decompose degradable MSW. However, such a landfill also should be designed to be highly efficient in collecting that leachate and gas. A landfill that exhibits these features and is sited properly thus should not be a major source of contamination of groundwater, surface water, or the air.

However, some old MSW landfills have been identified as sources of such contamination, indicating that they were not well designed or operated; as stated earlier, 184 such sites now are included on the NPL. The most common chemicals found at these landfills include halogenated and aromatic organic chemicals and metals (77). Approximately 72 percent of the landfills were associated with releases into groundwater, 44 percent experienced surface water contamination, and 17 percent experienced air emission problems (figure 7-2). At sites with surface water contamination, liquid waste was present at approximately 70 sites, sewage sludge at 45 sites, and pesticides at approximately 10 sites (77).

EPA considers industrial wastes disposed of at the 184 NPL landfills to be the most significant source of contamination, followed by sewage sludge and household hazardous wastes. One analysis of the landfills, for example, found that industrial wastes were co-disposed with MSW in all but two cases (41, 61). This finding has been used to support the contention that MSW landfills are not significant sources of releases of hazardous substances unless they have been used for disposal of industrial wastes.

However, there are other possible explanations. It is possible that MSW landfills that were not known to receive hazardous wastes were not allowed to be listed on the NPL, even if they had associated contamination problems. In particular, an EPA policy memo stated that MSW landfills without a clear record of accepting hazardous waste would not be listed on the NPL (37). This policy was later changed to allow the listing of MSW facilities that did not have a clear record of receiving hazardous waste (38), but whether such landfills will actually be listed is unknown.

Some researchers also suggest that substantial releases of hazardous substances will occur from MSW landfills even where no regulated hazardous wastes have been accepted (11, 83). Webster, in particular, hypothesizes that natural anaerobic processes in MSW landfills can convert nonhazardous waste (e.g., lignin in paper) into hazardous substances such as benzene and toluene (83). These compounds, which also are used to make ingredients in some common household products, are present in gas emissions from MSW landfills (table 7-5; also see ref. 35).

If correct, this hypothesis would have significant implications. If anaerobic processes do generate hazardous substances from MSW, then MSW landfills would not necessarily be safe repositories for MSW, particularly if the waste contains organic matter. Moreover, if these processes result in the formation and release of hazardous substances at levels comparable to industrial hazardous waste landfills, then it might not be appropriate to continue to allow MSW landfills to operate under less stringent standards than those imposed on Subtitle C landfills. In addition, if MSW could generate substantial amounts of hazardous substances, current Superfund apportionment policy, which is based on volume and toxicity, might force **municipal** Principal Responsible Parties to contribute a greater share to cleanup costs of sites where co-disposal of municipal and industrial waste has occurred. These costs could be enormous.

As might be expected, this hypothesis is controversial. Two independent reviews criticized both major premises, that organic substances found in MSW are degraded anaerobically into more toxic substances, and that this generation overshadows the contribution of toxic substances from industrial wastes (41 .47). One critic believes that insufficient data were presented to support the premises and that lignin breaks down very slowly and is most effectively attacked by aerobic bacteria, rather than anaerobic bacteria (47). One study estimated that the total cancer risks from all chemicals in MSW leachate were one to two orders of magnitude lower than from chemicals in industrial leachate (11) (table 7-6); if true in general, these data would undermine the hypothesis.

Table 7-6-Estimated Cumulative Carcinogenic Potency for Organic Chemicals in MSW and Industrial Landfills

	Estimated carcinogenic potency ($x10^{-6}$)			
	All chemicals		Suspect carcinogens	
Type and name of landfill	Median	Mean	Median	Mean
Municipal:				
Lyon	303	1,270	296	1,260
Meeker	23	260	4	30
Rochester	210	1,150	112	573
Industrial:				
Love Canal	1,020	3,940	117	234
Kin-Buc	38,500	13,700	38,300	137,000
Mixed waste:				
La Bounty	1,160	22,900	110	689

SOURCE: K. Brown and K. Donnelly, "An Estimation of the Risk Associated With the Organic Constituents of Hazardous and Municipal Waste Landfill Leachates," *Hazardous Waste and Hazardous Materials* 5(1):1-30, 1988.

A review conducted for the National Solid Waste Management Association (NSWMA) pointed out contradictions between Webster's data and EPA's data on generation rates, with EPA's rates being substantially lower (41). The NSWMA review acknowledges that "microbiological degradation of MSW landfill contents does produce chemicals that are different than those originally present, " but it also contends that concentrations of chemicals are almost always higher in leachates from industrial hazardous waste landfills than from MSW or mixed landfills. The central theme of the NSWMA report is that while the degradation of MSW may produce measurable quantities of hazardous substances, these quantities are small in comparison with those released from the disposal of industrial hazardous wastes in MSW landfills.

REGULATION OF MUNICIPAL LANDFILLS

Federal regulation of MSW landfills increased in 1979 with the promulgation of criteria for open dumps. These criteria, however, did not have a substantial impact on practices at MSW landfills. This prompted EPA to propose additional regulations in 1988 governing the design and operation of MSW landfills. Both the 1979 criteria and the 1988 proposal are discussed below.

Effect of 1979 Federal Criteria

The 1979 **criteria** for new and existing MSW landfills (listed in 40 CFR 257) were intended to provide greater protection from the adverse effects of landfills, but the criteria have had little impact. For example, the percentage of landfills that use engineering and/or design controls to prevent migration of leachate increased only slightly since 1979. Prior to 1980, only 11 percent of all landfills that began operation in the 1970s had leachate collection systems, while 18 percent of those that started after 1980 reported using such systems. Similarly, 67 percent of all landfills operating prior to 1980 had liners, while 75 percent that started after 1980 had liners. Moreover, the criteria have had almost no effect on the siting of new landfills in hydrologically sensitive areas (e.g., karst terrain or below the seasonal high water table) (77).[9]

Proposed MSW Landfill Regulations

In August 1988, EPA proposed new criteria to govern the design and operation of new and existing MSW landfills, as required by Section 4010 of RCRA (53 *Federal Register 33313,* Aug. 30, 1988). The proposed regulations include: location restrictions; facility design restrictions based on performance goals; operating criteria; groundwater monitoring requirements; corrective action requirements for groundwater contamination; financial assurance requirements for closure, post-closure,

[9]**Karst terrain** refers to **an** irregular limestone region with underground streams **and** caverns.

and known releases; closure standards; and post-closure standards. [10]

The proposed regulations reflect EPA's desire to reduce the costs to municipalities of meeting these requirements and to give States as much flexibility in implementing them as possible. EPA had several choices about the types of standards to propose:

- ''performance' standards based on risk assessments, which would probably lead to high variability in landfill designs;
- ''uniform' standards based on technical design considerations, with some allowance for variations, which would lead to little variability in designs; and
- ''categorical standards based on technical design considerations, with designs for different categories of site-specific conditions, which would lead to an intermediate level of variability.

EPA chose to propose risk-based performance standards for design (by outlining the range of risks allowed) and for closure procedures (by describing in narrative terms what is required). States would operate a permitting and regulatory program based on these standards.

The **1988** proposals received substantial public comments, including many criticisms of the risk-based performance approach. The Environmental Defense Fund, for example, called for uniform landfill standards (e.g., double liners, with an upper synthetic liner and a lower composite liner; double leachate collection systems; final cover of synthetic material), with a limited variance available if alternative design and operating practices at the site would prevent migration into groundwater or surface water at least as effectively as the uniform design standard (16). In contrast, the Association for State and Territorial Solid Waste Management Officials and the National Solid Waste Management Association called for a categorical approach that allows States and operators to choose designs based on site-specific conditions (e.g., rainfall and hydrogeology) (15). Other commenters have suggested that the regulations should not allow landfills to be located in areas such as flood plains or wetlands (8). EPA currently is revising the proposed regulations in light of the public comments it received.

Application to Existing Landfills

The proposed regulations would regulate new and existing facilities differently. Facilities in existence when the regulations become effective would not be required to retrofit with liners, leachate collection systems, or other control features. Existing facilities would be required to provide financial assurance and perform closure, post-closure, and corrective actions. Until the regulations become effective, however, there would be considerable opportunity for existing landfills to close and avoid these potentially costly requirements.

The proposed regulations are designed to apply to all landfills that are in existence 18 months after the final rule has been promulgated and to all landfills constructed after that date. Facilities closed at the time the regulations become effective, however, would not be covered. Instead, EPA would encourage "each state to develop a long term regulatory strategy to deal with these closed facilities. ' Consequently, there **could be substantial incentive for many existing facilities, particularly those approaching the end of their lifespan, to close and avoid potentially expensive responsibilities such as corrective action and closure procedures.**

EPA's proposed regulations acknowledge that these closed facilities represent potential threats to human health and the environment and states that they ''may be addressed under EPA's Superfund Program or by RCRA enforcement provisions for imminent hazards. '

Even for facilities that close after the 18-month period, the proposed criteria set forth no minimum technical standards regarding how a landfill should be closed. Instead, landfill owners or operators are required to close "each landfill unit in a manner that minimizes the post-closure formation and release of leachate and explosive gases to air, groundwater or surface water to the extent necessary to protect human health and the environment. " The lack of minimum technical requirements in the closure proposal would leave States with broad discretion in approving closure plans, while providing them with

[10] In general, the new EPA criteria would be equally applicable to both publicly and privately owned MSW landfills, although financial obligations would differ (see ''Financial Assurance' below).

little guidance on what actions constitute adequate closure.

Risk-Based Design Criteria

EPA's proposed regulations do not necessarily require new landfills to install liners or leachate collection systems. Instead, the proposal would require each State to choose a' 'risk goal' based on the cancer risk associated with consuming contaminated groundwater, and then specify design standards intended to achieve that goal as each State sees fit. The range of acceptable lifetime risks set by EPA is 10^{-4} to 10^{-7} (i.e., one out of every 10,000 to 10 million people). If a State chose a high risk goal (i.e., to allow a relatively high risk of 10^{-4}), then it is possible that no liner or leachate collection system would be required.

According to the proposal, a State could choose a risk goal that applies to all landfills in the State or it could set risk goals on a site-specific basis, as long as the level of protection chosen by the State is within the range of allowable risks in the proposed regulations. That is, a State could choose to regulate each aquifer differently, in terms of allowable cancer risk, so long as the cancer risk from consuming contaminated drinking water is between 10^{-4} and 10^{-7}. The States also would have to solve the difficult task of determining which technical requirements will meet those standards; the proposed criteria did not indicate how design features such as liners, leachate collection systems, covers, and groundwater monitoring systems should be selected once a State determines the acceptable risk level.

This approach raises some important potential problems. For instance, the Nation lacks a consistent risk assessment methodology for States to use in evaluating landfills; there are also inherent uncertainties in risk assessments. In addition, it is debatable whether all States have the ability to quantitatively evaluate different control technologies in the context of potential risk reduction. There currently are no models or analytical methods for quantitatively evaluating which combinations of control technologies, under conditions of varying leachate quality and exposure pathways, will meet which standards. The availability of trained state employees capable of evaluating these models also is uncertain, and some critics question whether the models themselves adequately mimic real conditions *(7).*

Ultimately, then, EPA's proposal as currently formulated could lead to an extremely diverse level of environmental protection provided at MSW landfills, even within an individual State. In addition, under these regulations it is likely that most planned landfills will lack features such as synthetic liners and groundwater monitoring systems (77).

Liner Specifications-The choice of landfill liners is not specified in the proposed regulations. This is significant because a number of different synthetic and natural liner materials can be used, each susceptible to different physical and chemical stresses. Because the requirement to install a liner would rest with the State and its determination of which control technologies are necessary to meet the specific risk goal at the point of compliance (POC), the determination of adequate liner types would also be made by the State. However, given the uncertainties associated with risk assessments and the added complication of trying to predict risk reductions associated with the installation of different liner types, another approach would be to specify approved liner types or systems to ensure a minimum level of protection nationwide.

Groundwater Monitoring-The proposed regulations are based in part on the notion that aquifers of lower resource **value** deserve less protection than those of higher resource value. This is consistent with EPA's Ground Water Protection Strategy, which calls for a sliding scale of protection for aquifers depending on their current status of contamination and use. Specifically, the proposed regulations would allow States to consider the "existing quality of the groundwater" in setting requirements for design of landfills. States also would have the flexibility to set alternative POCs beyond the landfill boundary where "the aquifer is of low quality and has little or no potential for future use." This would cause "contaminant concentrations to diminish (due to degradation, dispersion, and attenuation) over distance and, thus, potentially decrease the stringency of design criteria needed to meet the design goal. ' The use of alternative POCs would allow the costs of control systems to be mitigated by taking advantage of the dilution available in the aquifer.

The regulations also would set up a two-phase groundwater monitoring system. The first phase would monitor a limited number of substances, and if contamination was detected, the second phase would monitor for more substances. The frequency for initial groundwater monitoring would be set by the States depending on groundwater flow and the value of the resource.

An important feature of the proposed regulations is the availability of a waiver from groundwater monitoring when a facility can demonstrate that ''there is no potential for migration of hazardous constituents from the landfill unit to the uppermost aquifer during the active life, closure, or post-closure periods. ' The intent of this provision is twofold: to ease the financial burdens on MSW landfill operators and to provide an incentive to site landfills in hydrogeologically preferred areas. However, use of this waiver probably would mean that States would have to rely on the uncertain predictive ability of current leachate migration models; where those models underpredict leaching of hazardous constituents, unmonitored releases to groundwater could occur.

These proposed provisions have been criticized by many observers. The groundwater monitoring requirements, and the requirement that States develop trigger levels, have been criticized as being too flexible and likely to lead to variable State standards **(18). The** Environmental Defense Fund, for example, considered the alternative POC provision to be a violation of RCRA (16). In contrast. the Small Business Administration felt the POC should be greater than proposed. Some groups also have objected to the requirements because they would be too costly and stringent, especially for small, municipally owned landfills.

Financial Assurance

The proposed regulations include a requirement for owners or operators of MSW landfills to demonstrate that they are capable of financing closure, post- closure care, and corrective action for known releases. The financial assurance criteria would **not** apply to landfills owned and operated by the States or the Federal Government, but they would still apply to local governments. This could impose large cleanup costs that would have to be borne entirely by local governments. This issue is discussed in more detail in chapter 1 (see option 2 under "Landfilling") and chapter 8.

Corrective Action for Air and Surface Water Emissions

The proposed regulations state that about 200,000 metric tons of non-methane volatile organic chemicals are emitted to the air from MSW landfills every year. As a result, the proposal states EPA's future intent to regulate these releases under other statutes—specifically, Clean Air Act Section 111 (b) (for new landfills) and Section 11 l(d) (for existing landfills). Consequently, EPA would exclude these releases from the corrective action requirements in the landfill regulations. Whether future Clean Air Act regulations would require some corrective action for releases of VOCs is unclear, however. Similarly, the proposed landfill regulations include requirements to prevent the discharge of pollutants to surface waters, but would exclude releases to surface waters (as well as soil contamination) from the corrective action requirements.

CHAPTER 7 REFERENCES

1. Abbott, B., Arizona Department of Environmental Quality, personal communication, May 1988.
2. American Paper Institute, "Data on Disposable Diapers, Total U.S. and State of Washington" (New York, NY: January 1988).
3. BASF Corp., ''CONTREP Base Sealing System," brochure on file at OTA (Mannheim, West Germany: 1988).
4. Bergvall, G., Karlsson, R., and Wall in, S., ''Measurement of Mercury Vapor Emissions From Swedish Waste Landfills, " in ISWA *88: Proceedings of the Fifth International Solid Waste Conference, Volume 2 (San* Diego, CA: Academic Press Limited, 1988), pp. 55-60.
5. Bingemer, H., and Crutzen, P., "The Production of Methane From Solid Wastes, " *J. Geophysical Research* 92(D2): *2181-2187,* February 1987.
6. Belle, H. J., Seiler, W., and Bolin, B., "Other Greenhouse Gases and Aerosols: Assessing Their Role for Atmospheric Radiative Transfer, " *The Greenhouse Effect, Climate Change and Ecosystems,* B. Bolin et al. (eds.) (New York, NY: John Wiley & Sons, 1988), pp. 157-203.

7. Brown, K. W., "Letter to RCRA Docket Info Center (0S-305), U.S. EPA, " Nov. 21, 1988.
8. Brown, K. W., Texas A&M University, personal communication, Feb. 13, 1989.
9. Brown, K. W., and Anderson, D. C., ''Aboveground Disposal, ' *Standard Handbook of Hazardous Waste Treatment and Disposal*, H.M. Freeman (cd.) (New York, NY: McGraw-Hill, NY: 1988), pp. *10.85*-10.91.
10. Brown, K. W., and Anderson, D. C., "Above Grade Storage of Waste, " paper presented at *National Conference and Exhibition on Hazardous Waste and Environmental Emergencies* (Houston, TX: Mar, 12-14, 1984).
11. Brown, K., and Donnelly, K., "An Estimation of the Risk Associated With the Organic Constituents of Hazardous and Municipal Waste Landfill Leachates, ' *Hazardous Wrote and Hazardous Materials* 5(1):1-30, *1988.*
12. Cameron, R. D., and Koch, F. A., "Toxicity of Landfill Leachates, " *Journal Water Pollution Control Federation* 52(4):760-769, April 1980.
13. Chandler, W. U., Barns, D. W., and Edmonds, J. A., "Atmospheric Methane Emissions: A Summary of Sources and Policy Issues, " draft contract prepared for U.S. Congress, Office of Technology Assessment (Washington, DC: Battelle, Pacific Northwest Laboratories, Dec. 21, 1988).
14. Curran, M. A., and Frobel, R. K., "Strength and Durability of Flexible Membrane Liner Seams After Short-term Exposure to Selected Chemical Solutions, ' *Lund Disposal of Hazardous Waste, Proceedings of Eleventh Annual Research Symposium, EPA/600/9-85/013* (Cincinatti, OH: 1985), pp. 307-312.
15. Darcey, S., "New Draft of Subtitle D Regs Increases States' Discretion, ' *World Wastes*, pp. 24-26, March 1988.
16. Environmental Defense Fund, "Comments of the Environmental Defense Fund on the Solid Waste Disposal Facility Criteria, " Docket No. F-88 -CMLP-FFFFF (Washington, DC: Nov. 30, 1988).
17. EnvironmentaJ Improvement and Energy Resources Authority, *Statewide Resource Recovery Feasibility and Planning Study*, Missouri Department of Natural Resources (Jefferson City, MO: December *1987).*
18. Environment Reporter, "EPA Gets 250 Comments on Landfill Proposal; Design, Ground Water, Financial Sections Hit, " *Env. Reporter 19(33): 1654-1656,* Dec. *16, 1988.*
19. *Environment* Reporter, ''Up *to 600* Wisconsin Rural Landfills Expected To Close Because of EPA Rule, " *Env. Reporter* 19(48):2551-2552, Mar. 31, 1989.
20. Environment Reporter, ''Unlicensed Garbage Dumps Tested To Check Effects on Ground Water, ' *Env. Reporter* 19(48):2556-2557, Mar. 31, 1989.
21. Eowan, G., California Waste Management Board, personal communication, May 1988.
22. Flanagan, K., '*Methane Recovery Does More Than Provide Energy, " *Solid Waste and Power 2(4):30-33,* August 1988.
23. Florida Department of Environmental Regulation, "Report on the Potential for Solid Waste Management Grants," May 1986.
24. Franklin Associates, Ltd., *Characterization of Municipal Solid Waste in the United States,* 1960 *to* 2000 *(Update 1988)*, final report prepared for U.S. Environmental Protection Agency (Prairie Village, KS: March 1988).
25. Gershman, Brickner & Bratton, Inc., *Performance, Constraints, and Costs of MSW Management Technologies*, contract report prepared for U.S. Congress, Office of Technology Assessment (Falls Church, VA: Sept. 26, 1988).
26. Haagen-Smit, A. J., Bradley, C, E., and Fox, M. M., "Ozone Formation in Photochemical Oxidation of Organic Substances, " *Indust. Eng. Chem.* 45:2086, *1953.*
27. Harper, S. R., and Pohland, F. G., "Design and Management Strategies for Minimizing Environmental Impact at Municipal Solid Waste Landfill Sites," paper presented at *1988 Joint CSCE-ASCE National Conference on Environmental Engineering* (Vancouver: July 13-15, 1988).
28. Harper, S.R., and Pohland, F. G., "Landfills: Lessening Environmental Impacts, ' *Civil Engineering* 58(1 1):66-69, November 1988.
29. Haxo, H., ' 'Durability of Liner Materials for Hazardous Waste Disposal Facilities" (Oakland, CA: Matrecon, Inc., 1981).
30. Haxo, H., "Effects on Liner Materials of Long-term Exposure in Waste Environments," Lund *Disposal of Hazardous Waste, EPA-600/9-82-002* (Cincinnati, OH: U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, 1982), pp. 191-211.
31. Haxo, H. E., Jr., and Lahey, T. P., "Transport of Dissolved Organics From Dilute Aqueous Solutions Through Flexible Membrane Liners, " *Hazardous Waste and Hazardous Materials* 5(4):275-294, 1988.
32. Hershkowitz, A., ''International Experiences in Solid Waste Management, ' contract prepared for U.S. Congress, Office of Technology Assessment (Elmsford, NY: Municipal Recycling Associates, October 1988).
33. Institute for Local Self-Reliance, *Garbage in Europe: Technologies, Economics, and Trends* (Wash-

ington, DC: 1988).

34. Johnson, B., "Portland: First in the West To Send Waste Long Distance." *World Wastes 31(10):21-32,* October 1988.

35. Kinman, R.N., and Nutini, D. L., "Household Hazardous Waste in the Sanitary Landfill, " *Chemical TIMES & TRENDS* 11:23-29 and 39-40, July 1988.

36. Knapp, D., and Sutton, C., *On the Recycling of Landfills* (Berkeley, CA: Materials World Publishing, 1981).

37. Longest, H., "Listing Municipal Landfills on the NPL,'' U.S. Environmental Protection Agency memorandum, Oct. 24, 1986.

38. Longest, H., "Listing Municipal Landfills on the NPL,'' U.S. Environmental Protection Agency memorandum, Aug. 21, 1987.

39. Maples, A., U.S. Environmental Protection Agency, personal communication, April 1988.

40. Mendieta, H., Texas Department of Health, personal communication, May 1988.

41, Meta Systems, Inc., "MunicipalSolid Waste Landfilling: A Review of Environmental Effects' (Cambridge, MA: Oct. *4, 1988).*

42. Minott, D., "Comparative Health Risk Assessment of Energy-Recovery and Landfill Facilities, ' presented at the *Conference on Solid Waste Management and Materials Policy (New* York, NY: January 1988).

43. Morrison, W. R., and Parkhill, L. D., *Evaluation of Flexible Membrane Liner Seams After Chemical Exposure and Simulated Weathering, U.S.* EPA Hazardous Waste Engineering Research Laboratory, EPA/600/S2-87/015 (Cincinnati, OH: April 1987).

44. National Solid Waste Management Association, "Landfill Capacity in the U. S.: How Much Do We Really Have" (Washington, DC: Oct. 18,1988).

45. New Jersey Department of Environmental Protection, *Solid Waste Management Plan, Draft Update: /985-2000* (Trenton, NJ: July 15, 1985).

46. New York State Legislative Commission on Solid Waste Management, ''Where Will the Garbage Go?' (Albany, NY: January 1987).

47. Noble, J., Tufts University, personal communication, Oct. 18, 1988.

48. Ohio Environmental Protection Agency, *Available Capacity for Solid Waste in Ohio,* Division of Solid and Hazardous Waste Management, Annual Report (Columbus, OH: July 1988).

49. Pahren, H., "Microorganisms in Municipal Solid Waste and Public Health Implications, " *CRC Critical Reviews of Environmental Control* 17(3): *187-228, 1987.*

50. Pennsylvania Department of Environmental Resources, "Permitted and Operating MSW Landfills and Incinerators in Pennsylvania" (Harrisburg, PA: July 1986).

51. Pennsylvania Department of Environmental Resources, "Status of Existing and Proposed Facilities for the Processing and Disposal of Municipal Solid Waste in Pennsylvania" (Harrisburg, PA: November 1987).

52. Pohland, F.G., and Harper, S. R., "Critical Review and Summary of Leachate and Gas Production From Landfills, ' U.S. EPA, Hazardous Waste Engineering Research Laboratory, EPA/600/S2-86-073 (Cincinnati, OH: March 1987),

53. Pollock, C., "Mining Urban Wastes: The Potential For Recycling,'' Worldwatch Paper 76 (Washington, DC: Worldwatch Institute, April 1987).

54. Prindiville, S., "Testimony of Sheila M. Prindiville, Director, Solid Waste Program, National Solid Waste Management Association, before House Energy and Commerce Committee, Subcommittee on Transportation, Tourism and Hazardous Materials," June 5, 1987,

55. Prindiville, S., National Solid Waste Management Association, personal communication, November 1988.

56. Ramanathan, V., Cicerone, R. J., Singh, H. B., and Kiehl, J.T., "Trace Gas Trends and Their Potential Role in Climate Change, " *J. of Geophysical Research* 90:5547-5566, *1985.*

57. Rathje, W. L., Hughes, W. W., Archer, G., and Wilson, D. C., "Source Reduction and Landfill Myths, " paper presented at *ASTSWMO National Solid Waste Forum on Integrated Municipal Waste Management* (Lake Buena Vista, FL: July 17-20, 1988).

58. Reese, J., Florida Department of Solid Waste, Bureau of Waste Planning and Regulation, personal communication, April 1988.

59. Reeves, D., "The Performance of Clay Liners for Hazardous Waste Landfills, " Environmental Defense Fund In-House Report (Washington, DC: 1982).

60. Reindl, J., Wisconsin Department of Natural Resources, personal communication, May 1988.

61. Repa, E., ''Lessons Learned From Past Disposal Practices, " *Waste Age 19(5): 86-90,* May 1988.

62. Repa, E., "Landfill Capacity: How Much Really Remains" (Washington, DC: NSWMA, Oct. 1988).

63. Rhode Island Solid Waste Management Corp., *Statewide Resource Recovery System Development Plan* (Providence, RI: June 1987).

64. Robinson, W., *The Solid Waste Handbook (New* York, NY: John Wiley & Sons, 1987).

65. Silva, D., Science & Engineering Associates, Inc., personal communication, March 1988.

66. Siu, W., Levaggi, D. A., and Brennan, T.F., "Solid Waste Assessment Test Results From Landfills in the San Francisco Bay Area, " paper 89-155.2 presented at 82nd *Annual Meeting and Exhibition, Air & Waste Management Association* (Anaheim, CA: June 25-30, 1989).
67. Sondermeyer, G., New Jersey Department of Environmental Protection, personal communication, March 1988.
68. Sprague, R. T., and Boschuk, J., "Installation of HDPE Liners During Winter Months, " Paper presented at *International Conference on Geomembranes* (Denver, CO: 1986).
69. Swedish Association of Public Cleansing and Solid Waste Management, *Solid Waste Management in Sweden* (Malmo, Sweden: February 1988).
70. Swindler, M., Indiana Department of Environmental Management, Office of Solid and Hazardous Waste Management, personal communication, April 1988;
71. U.S. Environmental Protection Agency, *Census of State and Territorial Subtitle D Non-Hazardous Waste Programs, EPA/530-SW-86-039* (Washington, DC: October 1986).
72. U.S. Environmental Protection Agency, *Subtitle D Study, Phase 1 Report,* Office of Solid Waste and Emergency Response, EPA/530-SW-86-054 (Washington, DC: October 1986).
73. U.S. Environmental Protection Agency, *Survey of State and Territorial Subtitle D Municipal Landfill Facilities.* draft final report, prepared by Westat, Inc., Oct. 13, 1987.
74. U.S. Environmental Protection Agency, Office of Solid Waste, *Operating Criteria (Subpart C), ' 'Criteria for Municipal Solid Waste Landfills'' (40 CFR Part 258), EPA/530-SW-88-037* (Washington, DC: July *1988).*
75. U.S. Environmental Protection Agency, Office of Solid Waste, *Summary of Data on Municipal Solid Waste Landfill Leachate Characteristics, ' 'Criteria for Municipal Solid Waste Landfills" (40 CFR Part 258), EPA/530-SW-88-038* (Washington, DC: July 1988).
76. U.S. Environmental Protection Agency, Office of Solid Waste, *Design Criteria (Subpart D), ' 'Criteria for Municipal Solid Waste Landfills'' (40 CFR Part 258), EPA/530-SW-88-042* (Washington, DC: July 1988).
77. U.S. Environmental Protection Agency, *Report to Congress: Solid Waste Disposal in the United States, Vol. II,* EPA/530-SW-88-01 1B (Washington, DC: October 1988).
78. U.S. Environmental Protection Agency, Office of Solid Waste, *The Solid Waste Dilemma: An Agenda for Action, EPA/530-SW-89-019* (Washington, DC: February 1989).
79. University of Illinois, ''IEPA Report on Disposal Capacity, " *Solid Waste Management Newsletter* 3(3):1, March 1989.
80. Vasuki, N. C., "Why Not Recycle the Landfill!" *Waste Age,* pp. 165-70, November 1988.
81. Vasuki, N. C., Delaware Solid Waste Authority, personal communication, Feb. 16, 1989.
82. Vonasek, J., "An Investigation of Solid Waste Management Methods, Formats and Charges in Florida, " prepared for Government Refuse Collection and Disposal Association Mandatory Collection Committee (Tallahassee, FL: David M. Griffith & Associates, Ltd., Apr. 6, 1988).
83. Webster, I., "Municipal Solid Waste Landfills: Toxic Chemical Releases and the Role of Industrial Wastes in Those Releases, " unpublished manuscript (Brea, CA: Unocal Corp., 1988).
84. Weston, R. F., Inc., "Air Sampling and Analysis of Organic and Inorganic Constituents at Various Solid Waste Facilities, " report prepared for Delaware Solid Waste Authority (West Chester, PA: 1988 draft).
85. Wilson, D. C., "Ancient Trash, Modern Solid Wastes: An Archaeologist's Perspective on Reuse, Recycling, Waste, and Landfill Degradation, " paper presented at *National Solid Waste Management Symposium* (Prescott, AZ: Apr. 10, 1989).
86. Wood, J., and Porter, M., "Hazardous Pollutants in Class II Landfills," *J. Air Pollution Control 37(5):609-615,* May 1987.
87. Woodwell, G. M., *The Role of Terrestrial Vegetation in the Global Carbon Cycle (New* York, NY: John Wiley & Sons, 1984).