October 1992 • NREL/TP-431-4988H

Data Summary of Municipal Solid Waste Management Alternatives

Volume VIII: Appendix F—Landfills

SRI International
Menlo Park, California

National Renewable Energy Laboratory
A Division of Midwest Research Institute
Operated for the U.S. Department of Energy
Under Contract No. DE-AC02-83CH10093

NOTICE

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Microfiche A01
Printed Copy A05

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issue of the following publications which are generally available in most libraries: *Energy Research Abstracts (ERA)*; *Government Reports Announcements* and Index (*GRA* and I); *Scientific and Technical Abstract Reports (STAR)*; and publication NTIS-PR-360 available from NTIS at the above address.

NREL/TP-431-4988H • UC Category 249 • DE92016433

Data Summary of Municipal Solid Waste Management Alternatives

Volume VIII: Appendix F—Landfills

SRI International
Menlo Park, California

NREL Technical Monitors: Bimleshwar Gupta
Philip Shepherd

National Renewable Energy Laboratory
(formerly the Solar Energy Research Institute)
1617 Cole Boulevard
Golden, Colorado 80401-3393
A Division of Midwest Research Institute
Operated for the U.S. Department of Energy
under Contract No. DE-AC02-83CH10093

Prepared under subcontract no: RF-1-1103

October 1992

Report Organization

This report, *Data Summary of Municipal Solid Waste Management Alternatives*, comprises 12 separately bound volumes. Volume I contains the report text. Volume II contains supporting exhibits. Volumes III through X are appendices, each addressing a specific MSW management technology. Volumes XI and XII contain project bibliographies. The document control page at the back of this volume contains contacts for obtaining copies of the other volumes.

Volume	Contents	Document Number
I	Report Text	TP-431-4988A
II	Exhibits	TP-431-4988B
III	Appendix A Mass Burn Technologies	TP-431-4988C
IV	Appendix B RDF Technologies	TP-431-4988D
V	Appendix C Fluidized-Bed Combustion	TP-431-4988E
VI	Appendix D Pyrolysis and Gasification of MSW	TP-431-4988F
VII	Appendix E Material Recovery/Material Recycling Technologies	TP-431-4988G
VIII	Appendix F Landfills	TP-431-4988H
IX	Appendix G Composting	TP-431-4988I
X	Appendix H Anaerobic Digestion of MSW	TP-431-4988J
XI	Alphabetically Indexed Bibliography	TP-431-4988K
XII	Numerically Indexed Bibliography	TP-431-4988L

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont)

LIST OF TABLES

LIST OF ILLUSTRATIONS

APPENDIX F. LANDFILLS

While the preceeding appendices have focused on thermochemical approaches to managing municipal solid waste (MSW), this appendix and those that follow on composting and anaerobic digestion address more of the bioconversion process technologies. Landfilling is the historical baseline MSW management option central to every community's solid waste management plan. It generally encompasses shredfills, balefills, landfill gas recovery, and landfill mining.

While landfilling is virtually universal in use, it continues to undergo intense scrutiny by the public and regulators alike. Most recently, the U.S. Environmental Protection Agency (EPA) issued its final rule on criteria for designing, operating, monitoring, and closing municipal solid waste landfills. While the Federal government has established nationwide standards and will assist the States in planning and developing their own practices, the States and local governments will carry out the actual planning and direct implementation. The States will also be authorized to devise programs to deal with their specific conditions and needs.

While the main body of this appendix and corresponding research was originally prepared in July of 1991, references to the new RCRA Subtitle D, Part 258 EPA regulations have been included in this resubmission (908). By virtue of timing, this appendix is, necessarily, a "transition" document, combining basic landfill design and operation information as well as reference to new regulatory requirements. Given the speed with which landfill practices are and will be changing, the reader is encouraged to refer to Part 258 for additional details. As States set additional requirements and schedules and owners and operators of MSW landfills seek to comply, additional guidance and technical information, including case studies, will likely become available in the literature.

In addition to the final Part 258 rule for the control of emissions from RCRA Subtitle D landfills, new source performance standards (NSPS) have been proposed for MSW landfills whose construction, modification, or reconstruction begins after a standard is proposed (909). This action addresses air emissions from MSW landfills which contribute to ambient ozone problems, air toxic concerns, and potential explosion hazards. Such an NSPS would require MSW landfill sources to control emissions, particularly nonmethane organic compounds (NMOCs), to the level achievable by "best demonstrated technology" (BDT) considering both costs and any nonair quality health and environmental impacts and energy requirements. While reference is made to the proposed standards and guidelines throughout this report (Appendix F), the proposed rule should be consulted for further details (909).

F.1 OVERVIEW

Following World War II, concern over air pollution caused landfilling to displace incineration as the preferred method for the disposal of municipal solid waste (507). However, the early landfills were in reality nothing more than open dumps. The concept of sanitary landfilling was developed in the early 1970s, and, to this day, has remained the most popular method for municipal solid waste (MSW) disposal in the U.S. As shown in Table F-1, as of 1990, approximately 80% of the MSW generated in the United States was disposed of in landfills (465, 507).

Landfilling's popularity can be credited to its low cost and general availability. In the early 1970s, about 15,000 authorized MSW landfills existed in the U.S. This number, however, has been steadily declining. As of 1990, 6,326 active MSW landfills existed in the United States (667). It is projected, that by 1994, only about 3,332 authorized MSW landfills will exist (659); and by 2000, the number of authorized MSW landfills may drop to less than 1,000 (391). This dramatic decline can be attributed to three factors: 1) older landfills are reaching the end of their expected lives; 2) environmental regulations are being strengthened; and 3) siting new landfills is increasingly difficult, mainly because of public opposition (372).

Certain regions of the country such as the Northeast have experienced more severe landfill shortages than other regions and have compensated by developing alternative disposal options such as recycling and incineration. For other regions with sufficient land area, landfilling remains the predominant disposal method (465). Nonetheless, a minimum landfill capacity will always be needed in any particular region to receive the residue from other disposal options such as recycling and incineration, and to receive the non-combustible, non-recyclable portion of MSW (372).

Regulations regarding the design and operation of landfills vary from state to state; however, in general, a state-of-the-art landfill contains the following components (48):

- Liner system
- Leachate collection system
- Leachate treatment system
- Cap system
- Gas recovery and energy production systems

TABLE F-1. U.S. LANDFILL STATISTICS, 1990 (667)

State	Total MSW, TPY	% Land-Filled	No.	Cost, $/Ton	Remaining Capacity, Years
Alabama (d)	4,400,000	93	107	5.25	<4
Alaska (b)	511,000	85	740	up to 120	20
Arizona	3,100,000	95	92	up to 22	n/a
Arkansas (b)	2,000,000	92	73	15 - 20	7
California (f)	50,000,000	87	330	10 - 28	n/a
Colorado (d)	2,000,000	80	140	up to 22	20
Connecticut	2,900,000	41	60	60 - 100	n/a
Delaware (c)	875,000	37	3	35 - 45	20+
District of Columbia	755,000	63	1	42	4
Florida	18,300,000	64	170	5 - 60	<5
Georgia	4,400,000	85-90	180	10 - 27	3-4
Hawaii (f)	1,200,000	83	17	17 - 54	5
Idaho (f)	850,000	95	85	up to 10	10
Illinois (f)	13,100,000	92	117	12 - 38	8
Indianna	5,500,000	75	83	12	7
Iowa (d)	2,300,000	88-91	82	up to 30	10
Kansas (a)	1,600,000	95	130	4 - 14	15 - 20
Kentucky (d)	4,600,000	87-94	75	10 - 28	3
Louisiana (f)	3,500,000	97	32	15 - 30	10+
Maine	922,000	38	185	40 - 75	n/a
Maryland (f)	7,200,000	73	42	up to 85	7
Massachusetts (e)	10,000,000	37	150	45 - 65	3 - 5
Michigan	11,700,000	96	71	n/a	n/a
Minnesota (a)	4,200,000	53	51	35	5 10
Mississippi (f)	1,800,000	96	85	16 - 25	<4
Missouri (b)	6,000,000	90	84	13	9
Montana (e)	600,000	90	90	5 - 15	n/a
Nebraska	1,100,000	88-90	40	4 - 13	8 - 10
Nevada	1,000,000	95	100	up to 10	20
New Hampshire (d)	1,000,000	68	51	18 - 60	n/a
New Jersey (b)	14,000,000	52	31	50 - 150	n/a
New Mexico	1,200,000	99	130	n/a	2 - 5
New York (f)	22,000,000	70	233	n/a	9
North Carolina (d)	6,000,000	94	125	10 - 25	n/a
North Dakota	450,000	97	47	15	20+
Ohio (a)	14,000,000	81	88	20+	8 - 10
Oklahoma	3,600,000	85	147	8 - 15	15
Oregon (d)	2,200,000	65-70	94	26 - 50	20+
Pennsylvania	9,200,000	88-90	48	n/a	5+
Rhode Island (d)	1,000,000	82	1	13 - 59	4
South Carolina (e)	2,500,000	86	76	5 - 10	10
South Dakota	500,000	99	36	3 - 4	10 - 15
Tennessee (d)	5,400,000	94	96	up to 26	n/a

TABLE F-1. U.S. LANDFILL STATISTICS (Cont)

State	Total MSW, TPY	Land- Filled	No.	Cost, $/Ton	Remaining Capacity, Years
Texas	18,000,000	91	934	12	15
Utah	1,100,000	78	50	up to 22	20
Vermont	350,000	67-70	60	20 - 67	3
Virginia (a)	9,000,000	80	291	20	n/a
West Virginia	1,700,000	90-95	44	15 - 30	5
Wisconsin (a)	7,000,000	96	180	n/a	n/a
Wyoming (b)	300,000	97	100	up to 10	20+
Totals	292,513,000	80	6,326		

----

n/a = Not Available
(a) = Includes some industrial waste
(b) = Includes demolition waste
(c) = Includes some sewage sludge and industrial waste
(d) = Includes some demolition and industrial waste
(e) = Includes some sewage sludge and demolition waste
(f) = Includes demolition wastem some industrial waste and sewage sludge

- o Landscaping
- o Security systems
- o Plan to return the facility acreage to the community
- o Groundwater monitoring wells

In 1988, the U.S. EPA proposed revisions to the Resource Conservation and Recovery Act (RCRA), Subtitle D regulations. After extensive public comment and review, EPA issued a final rule on 9 October 1991, with an effective date of 9 October 1993 (909).

The new regulations add a Part 258 to RCRA Subtitle D specifically for municipal solid waste landfills (MSWLFs), including those that co-dispose of sewage sludge with household waste. The new Part 258 proposes minimum criteria for MSWLF's primarily in the form of performance standards. Using performance standards as opposed to design standards, EPA is allowing states the flexibility to determine whether or not specific sites and specific design features will perform to the minimum performance standards such that human health and the environment are protected.

Part 258 requires that owners and operators of MSWLFs comply with the rule provided the facility was receiving MSW on 9 October 1991. If the facility has or will terminate operations between this date and 9 October 1993, only the final cover requirements of Part 258 apply. If an owner/operator receives waste on or after 9 October 1993, all of Part 258 applies except the ground water monitoring provisions in subpart E (phased in over a 5-year period), and the financial responsibility provisions of subpart G (effective April 9, 1994).

The operational requirements for all owners/operators, on and after the effective date of the rule are to:

- o Exclude the receipt of hazardous waste
- o Provide daily cover
- o Control on-site disease vectors
- o Provide routine methane monitoring
- o Eliminate most open burning
- o Control public access

- Construct run-on and run-off controls
- Control discharges to surface water
- Cease disposal of most liquid wastes
- Keep records that demonstrate compliance

An overview of some of the key provisions are presented in Table F-2.

Under the authority of the Clean Air Act, the EPA has recently proposed regulations for air pollutant emissions from both new and existing municipal solid waste landfills (909). These regulations will regulate the combustion of methane from landfills as well as the reduction of nonmethane organic compounds (NMOCs) through the use of a gas collection system and an add-on control device. A designated facility under the proposed guidelines is each existing MSW landfill that has accepted waste since 8 November 1987, or that has capacity available for future use.

The proposed standards for new MSW landfills (909) are based on best demonstrated technology (BDT) that will reduce emissions from new MSW landfills emitting 150 Mg/yr (167 tpy) of NMOC's or more. BDT is defined as a well-designed and well-operated gas collection system, and a control device capable of reducing NMOCs in the collected gas by 98 weight-percent. New landfills emitting less than 150 Mg/yr (167 tpy) of NMOCs are not defined under BDT. Therefore, these smaller facilities are exempt from the proposed rule.

Proposed guidelines for existing MSW landfills follow the same requirements identified for new MSW landfills. A well-designed and well-operated collection system is defined as one capable of handling the maximum gas generation rate, capture gas from all parts of the landfill, have a design capable of monitoring gas generation and flexible to adjust and expand as needed. The BDT control device applicable to all affected and designated facilities is an open flare that will reduce NMOC emissions by 98 weight-percent. Other control devices have been defined by EPA for use in meeting this standard. They can be grouped into two broad categories, including enclosed combustion devices and purification systems. Examples of enclosed combustion devices include boilers, gas turbines, I.C. engines, and incinerators. Purification techniques serve to upgrade landfill gas to pipeline quality natural gas.

TABLE F-2. KEY FEATURES OF FINAL RCRA SUBTITLE D, PART 258 -- CRITERIA FOR MUNICIPAL SOLID WASTE LANDFILLS (908, 719, 717)

SUBPART A--GENERAL

Objective: Establish minimum national criteria for municipal solid waste landfills (MSWLFs), including MSWLFs used for sludge disposal and disposal of nonhazardous municipal waste combustor (MWC) ash.

Implementation: Approved States will have flexibility in implementing these criteria.

Application: Only final cover requirements for facilities that stop receiving waste between October 9, 1991 and October 9, 1993; all requirements for facilities receiving waste on or after October 9, 1993. Exceptions -- ground water monitoring and financial requirements extended.

SUBPART B--LOCATION RESTRICTIONS

Location of Existing MSWLF Units: Specifies minimum distance to airports (258.10), not to be located on 100-year floodplain (258.11), and effectively barred from wetlands (258.12).

Location of New Units and Lateral Expansion: In addition to stated restriction regarding proximity to airports, floodplains and wetlands, specifies minimum distance to faults (258.13), banned from seismic impact zone (258.14) and must demonstrate ability to withstand hazards of unstable land areas (258.15).

SUBPART C--OPERATING CRITERIA

Procedures for Excluding the Receipt of Hazardous Waste (258.20): Implement program to detect hazardous wastes, perform random inspection of loads, maintain inspection records and train personnel.

Cover Material Requirements (258.21): Provide daily cover of at least six inches of earthen materials.

Disease Vector Control (258.22): Prevent or control spread of disease.

Explosive Gases Control (258.23): Perform quarterly monitoring to ensure MSWLF methane concentration does not exceed 25 percent of the lower explosive limit in structures and at MSWLF boundary.

Air Criteria (258.24): Open burning generally prohibited and compliance required with relevant SIP provisions.

Access Requirements (258.25): Control public access to avoid unlawful dumping or tampering.

Run-on/Run-off Control Systems (258.26): Control flow from active portion of MSWLF. Run-off governed by surface water requirements (258.27).

Surface Water Requirements (258.27): Operate in compliance with National Pollutant Discharge Elimination System (NPDES) and Clean Water Act (CWA) requirements.

Liquids Restrictions (258.28): Disposal of bulk or containerized liquid waste prohibited EXCEPT household wastes (not including septic) AND leachate or gas condensate from MSWLF with composite liner and leachate collection.

TABLE F-2. KEY FEATURES OF FINAL RCRA SUBTITLE D, PART 258 – CRITERIA FOR MUNICIPAL SOLID WASTE LANDFILLS (Cont)

SUBPART C – OPERATING CRITERIA (Cont)

Recordkeeping Requirements (258.29): Maintain records such as: inspection records, training procedures, notifications, gas monitoring results, ground-water and corrective action findings or records, closure/post-closure plan, cost estimates.

SUBPART D–DESIGN CRITERIA (258.40)

Design Options: Select either site-specific design that meets the performance standard stated in the rule and approved by Director of an approved State, OR composite liner design.

Performance Standard Design: Not to exceed the maximum concentration limits (MCLs) for Table 1 constituents (p. 51022) in the uppermost aquifer at the relevant point of compliance, which is not to be more than 150 meters from the MSWLF boundary.

Composite Liner Design: System will consist of two components: upper component to have minimum 30-mil flexible membrane liner (FML); and lower component to have minimum two-foot layer of compacted soil with a hydraulic conductivity of no more than 1×10^{-7} cm/sec. [If HDPE material is used, FML must be 60 mil thick].

SUBPART E–GROUND-WATER MONITORING AND CORRECTIVE ACTION

Ground-Water Monitoring Systems (258.51): Well placement must characterize background ground-water not affected by leakage AND water quality passing the relevant point of compliance. Monitoring well casing must be screened and perforated, packed with gravel and sand, and have an annular space above sampling depth that is sealed to prevent contamination.

Ground-Water Sampling and Analysis Requirements (258.53): S&A program will: cover procedures to collect, analyze and quality assure samples; measure ground water levels; establish background ground-water quality; and employ approved statistical methods to determine the number of samples.

Detection Monitoring Program (258.54): Conduct semiannual detection monitoring during the active life of the facility for the 15 organic and 47 inorganic constituents listed in Appendix I to this rule (p. 51033).

Assessment Monitoring Program (258.55): Required whenever a statistically significant increase over background occurs for one or more of the Appendix I constituents. Any exceedance triggers requirement for sampling for all Appendix II constituents (p. 51034). Detection of any Appendix II constituents requires additional sampling to establish background levels. Establish ground-water protection standards for all detected constituents from assessment monitoring data.

Assessment of Corrective Measures (258.56): Whenever any Appendix II constituent exceeds the ground water protection standards defined in 258.55, correction action must be initiated.

Selection of Remedy (258.57): Remedies must be: protective of human health and environment; attain ground-water protection standards (258.55); control releases of Appendix II constituents to the maximum extent practicable; and comply with all standards for management of wastes (258.58(d)) under RCRA.

TABLE F-2. KEY FEATURES OF FINAL RCRA SUBTITLE D, PART 258 -- CRITERIA FOR MUNICIPAL SOLID WASTE LANDFILLS (Cont)

SUBPART E -- GROUND-WATER MONITORING AND CORRECTIVE ACTION (Cont)

Implementation of the Corrective Action Program (258.58): Establish and implement a corrective action program that: meets the requirements of 258.55, states the effectiveness of the selected remedy, and demonstrates compliance with established ground-water protection standards, all on a schedule acceptable to and certified by the State.

SUBPART F--CLOSURE AND POST-CLOSURE CARE

Closure Criteria (258.60): A final cover must be comprised of an erosion layer underlain by an infiltration layer that is a minimum of 18 inches of earthen material with a permeability equal to or less than the permeability of any bottom liner system or natural soils, OR a permeability no greater than 1×10^{-5} cm/sec, whichever is less. The erosion layer must consist of a minimum of 6 inches of earthen material that is capable of sustaining native plant growth.

Post-Closure Care Requirements (258.61): Required for a period of 30 years, post-closure care consists of: maintaining the integrity and effectiveness of the final cover; maintaining and operating the leachate collection system; monitoring ground water; and maintaining and operating the gas monitoring system.

SUBPART G--FINANCIAL ASSURANCE CRITERIA

Applicability of Effective Date (258.70): Effective April 9, 1994.

Financial Assurance for Closure (258.71): Must have an up-to-date estimate for closing the largest area of all MSWLF units ever requiring a final cover at any time during the active life when the extent and manner of its operation would make closure most expensive. Must establish financial assurance for closure (258.74).

Financial Assurance for Post-Closure Care (258.72) and Corrective Action (258.73): Similar requirements exist for the post-closure care period and for any corrective actions that may have been required.

Allowable Mechanisms (258.74): As prescribed by this rule, financial assurance for closure, post-closure and corrective action may be accomplished by any one or a combination of: trust fund, surety bond guaranteeing payment or performance, letter of credit, insurance, or State-approved mechanism.

The proposed standards and guidelines would also require the periodic calculation of the annual NMOC emission rate at each affected or designated facility with a maximum design capacity of 100,000 Mg (110,000 tons) or more. For each facility where the calculated emission rate equals or exceeds the regulatory cutoff of 150 Mg/yr (167 tpy) of NMOCs, the proposed standards will require the installation of a well-designed gas collection system and one of several control devices to either recover or destroy the emissions.

F.2 TECHNOLOGY DESCRIPTION

Three methods of landfilling are presently in use: the area, trench, and ramp methods (126). The site contours determine the method used for a particular site. The area method is used to fill an open recessed area; the ramp method is used on a sloping site; and the trench method is used on a flat or gently sloping site where the land is excavated systematically in trenches and filled with waste. Each method requires the use of daily cover material. A typical waste to soil (cover) ratio is 4:1. Daily cover improves the landfill aesthetics, discourages scavenging by birds, pests, and humans, and helps to control fires and odors.

MSW undergoes two changes in a landfill: compaction and degradation. MSW as-delivered has a bulk density of 450 to 600 pounds per cubic yard (lb/cy); landfill equipment can increase the density to 800 to 1,400 lb/cy (126). Settlement of the landfill is a function of the degree of compaction delivered by the compaction equipment. A 15 percent settlement is typical with good compaction, and a 25 percent settlement is typical with poor compaction (126).

Degradation of the organic portion of the MSW takes place in five phases. During the first two phases, oxygen is consumed by aerobic bacteria. When the oxygen is depleted, faculative and anaerobic microorganisms take over. Phase three is the first of the three anaerobic stages and is characterized by a low pH (4-5), a high volatile acid production, a high Chemical Oxygen Demand (COD), high conductivity, and low methane production. In phase four, the second of the three anaerobic stages, methane producing bacteria predominate. They degrade volatile acids to methane and carbon dioxide, causing a rise in pH, a decrease in COD, and a reduction in conductivity. The methane to carbon dioxide ratio is approximately 50/50, depending on the activity of the methane-producing bacteria in relation to other microbial forms, and also on the nature of the organic matter in the MSW (126). Methane gas produced in a landfill can be collected, processed, and converted to energy. The final fifth phase results in the stabilization of the landfill.

Since a landfill is constantly evolving, the five phases are not distinct and may occur simultaneously throughout the landfill. All phases will occur if sufficient organic material and moisture is available, and if the bacteria are not inhibited by any chemical source (323). The five phases are typically referred to as a combined singular process.

F.2.1 Landfill Leachate

F.2.1.1 Leachate Generation

Leachate is generated by precipitation or groundwater percolating through the landfill mass and by the draining of fluids contained in the MSW. The quantity of leachate is much higher while the landfill is open, but it is ultimately controlled to some extent after the installation of the low permeability landfill cap. Leachate cannot be completely eliminated because water cannot be totally prevented from entering the landfill mass. Cracks can develop from freeze-thaw and wet-dry cycles, or from subsidence and differential settling (585). As water flows downward through the landfill mass, it reacts both chemically and physically with the waste. Contaminants from the waste and the reactions occurring in the waste mass will wash out of the mass with the water. If a liner system is not provided to direct the leachate into a collection system, the leachate can possibly enter the groundwater. The contaminants and concentrations typically found in landfill leachate are discussed in Section F.4, Environmental Releases.

F.2.1.2 Leachate Management

The following are the available leachate management options:

- o Discharge to a sewer, no pretreatment
- o Discharge to a sewer, with pretreatment
- o Treatment and land disposal
- o Treatment and discharge to surface water body
- o Recirculation

Table F-3 shows the status of U.S. landfill leachate management practices as of 1988.

TABLE F-3. U.S. LANDFILL LEACHATE MANAGEMENT STATUS - 1988
[(698) cited in (323)]

Practice	Number of Landfills Closed	Active	Planned
Recirculate by Spraying	40	158	185
Recirculate by Injection	10	36	16
Recirculate by Other Means	11	34	22
Land Spreading	15	84	60
Truck to public WWTP	48	76	245
Sewer Discharge to public WWTP	53	118	135
Other/unknown Off-Site Treatment	5	21	23
On-site Biological Treatment	41	102	108
On-site Chemical/Physical Treatment	34	61	60

Note: Some facilities use more than one practice.

F.2.1.3 Leachate Treatment and Disposal

The ultimate disposal location for landfill leachate is either a sewer, a surface water body, or the land. The preferred method of leachate disposal is discharge to the municipal sewer system since this relieves the landfill operator of the responsibility of leachate treatment (271). However, because of the high strength and variable nature of leachate, pretreatment may be required. Land disposal or discharge to a surface water course will require treatment or consideration for treatment prior to discharge, as described below.

According to the new Subtitle D, Part 258.27 regulations, MSWLFs may not cause a discharge of pollutants into waters or wetlands that violates any requirements of the Clean Water Act (CWA), the National Pollutant Discharge Elimination System (NPDES), or an area-wide or State-wide water quality management plan, approved under the CWA.

The provisions of Part 258.28 state that leachate derived from an MSWLF unit may be returned to the MSWLF provided that the new or existing MSWLF, or lateral expansion, is designed with a composite liner and leachate collections system as described under Section 258.40(a)(2).

Leachate treatment typically consists of biological and/or physical treatment. A sample leachate treatment system flow diagram is presented in Figure F-1. The system can be located on or off site at a dedicated facility or at a public wastewater treatment plant. The high strength and variable nature of MSW landfill leachate makes treatment difficult. Robinson and Marris [(699) as cited in (271)] concluded the following regarding leachate treatment:

1. The composition of leachate changes over the life of the site and therefore treatment methods that are appropriate initially may not be satisfactory later. In general, leachate from newly deposited waste is more amenable to biological treatment than are leachates from more established fill areas.

2. Generally, the leachates are deficient in phosphorus and possibly nitrogen; and therefore, without nutrient addition, biological treatment may be inhibited.

3. Anaerobic biological treatment can significantly reduce concentrations of contaminants, but the performance of the systems severely declines when temperatures fall below 20 degrees C (68 degrees F).

4. Physical chemical processes have not been shown to remove soluble organic matter efficiently from the leachates. Physical/chemical techniques may, however, be necessary to remove toxic concentrations of specific chemicals.

5. Pilot-scale experiments have indicated that recirculation of leachate through the landfill has advantages in terms of both leachate control and accelerated stabilization of solid waste.

F.2.2 Liner Systems

Protection of groundwater supplies is a vital issue since more than half of all Americans rely on underground water supplies for their drinking water (384). The best available method of protecting such water bodies from leachate contamination is to collect and treat the leachate before it can contaminate the groundwater. Liner systems are used to provide an impermeable barrier between the landfill (and its leachate) and the groundwater. When leachate meets the sloped liner system, it flows laterally to a collection pipe laid at the low point of the landfill base. The piping slopes to storage tanks which drain or are pumped to a treatment system. As of 1986, only 15% of the municipal landfills were equipped with a liner system [(688) cited in (397)]. Degradation of the groundwater at 146 municipal landfills has been documented by the EPA, affecting 35 drinking water supplies [(689) as cited in (465)].

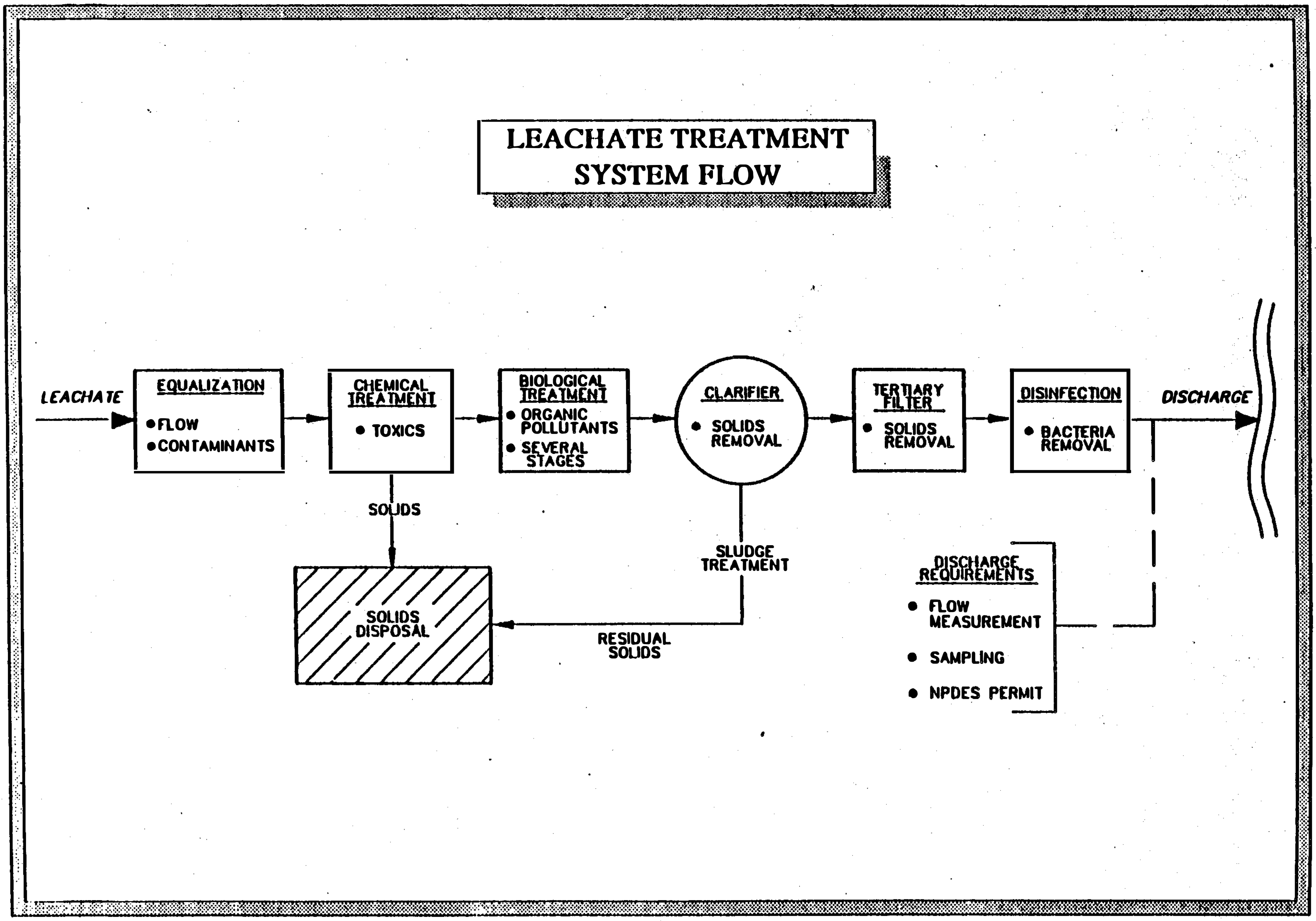


Figure F-1. Leachate Treatment System Flow (586)

F.2.2.1 Design Criteria for New MSWLF Units and Lateral Expansions

Before discussing the designs, advantages and disadvantages of various liner systems in use today, this section presents an overview of the "performance-based" requirements of the new RCRA Subtitle D landfill design criteria (908). According to Part 258.40, new MSWLF units and lateral expansions must have one of the following designs:

- o Design that meets performance standard and approved by an approved State, or
- o Composite liner and leachate collection system

In the first approach, the design must meet with appropriate State approval. The performance based design must ensure that the maximum concentration limits (MCLs) presented in Table F-4 will not be exceeded in the uppermost aquifer at the relevant point of compliance, i.e., not more than 150 meters from the waste management unit boundary. The factors to be used in the approval of the design and the relevant point of compliance are articulated in Part 258.40 of the regulation.

TABLE F-4. MAXIMUM CONCENTRATION LIMITS (908)

Chemical	MCL (mg/l)
Arsenic	0.05
Barium	1.0
Benzene	0.005
Cadmium	0.01
Carbon tetrachloride	0.005
Chromium (hexavalent)	0.05
2,4-Dichlorophenoxy acetic acid	0.1
1,4-Dichlorobenzene	0.075
1,2-Dichloroethane	0.005
1,1-Dichloroethylene	0.007
Endrin	0.0002
Fluoride	4
Lindane	0.004
Lead	0.05
Mercury	0.002
Methoxychlor	0.1
Nitrate	10
Selenium	0.01
Silver	0.05
Toxaphene	0.005
1,1,1-Trichloroethane	0.2
Trichloroethylene	0.005
2,4,5-Trichlorophenoxy acetic acid	0.01
Vinyl Chloride	0.002

A composite liner design consists of two components. The upper component consists of a 30-mil minimum thickness flexible membrane liner (FML). The lower component consists of at least a two-foot layer of compacted soil, whose hydraulic conductivity does not exceed 1 x 10^{-7} cm/sec. When high density polyethylene (HDPE) is used, the FML components must be at least 60 mil thick. The FML must be in direct and uniform contact with the compacted layer.

Both design approaches are illustrated in Figure F-2.

F.2.2.2 Liner Systems Currently In Use

Liners have been constructed of soil (typically clay), admixtures such as asphalt concrete, soil cement, soil asphalt, or bentonite clay, synthetic membranes, sprayed on coatings, soil sealants, or chemical absorptive liners [(690) as cited in (271)]. Composites of two or more liner systems have also been used. Figure F-3 shows six typical liner design alternatives. Liner materials must withstand chemical attack and structural loadings during installation and during the landfilling operations.

Soil liners containing clay are used in many landfills because of the low hydraulic conductivity of clay. Clay liners are constructed in compacted layers or lifts. The total liner thickness can be 5 feet or more, depending on the specific site conditions. Soils containing greater than 25 percent clay typically have a permeability in the range of 10^{-8} cm/sec to 10^{-5} cm/sec (271). Daniels and Brown [(691) as cited in (465)] found that field permeabilities were closer to 10^{-5} cm/sec because of faulty construction techniques such as too few lifts, low moisture during compaction, too little clay content, insufficient compaction, freezing, and poor construction quality control.

Admixtures are formed in place often using the natural soil at the base of the landfill. They have been successfully used in impoundments (271).

Synthetic membranes are manufactured in rolls 48 inches to 96 inches wide and 0.020 inch to 0.120 inch thick. The seams are sealed in the field. To protect against deterioration by ozone attack, the liner is usually covered by soil after installation. Liners are available in several polymers, each with unique advantages and disadvantages. Table F-5 presents the advantages and disadvantages of four synthetic liners.

Sprayed on liners, soil sealants, and chemically absorptive liners have been used on a limited basis on impoundments, and have been tested for use on landfills (271).

New MSWLF units and lateral expansions must have one of the following designs:

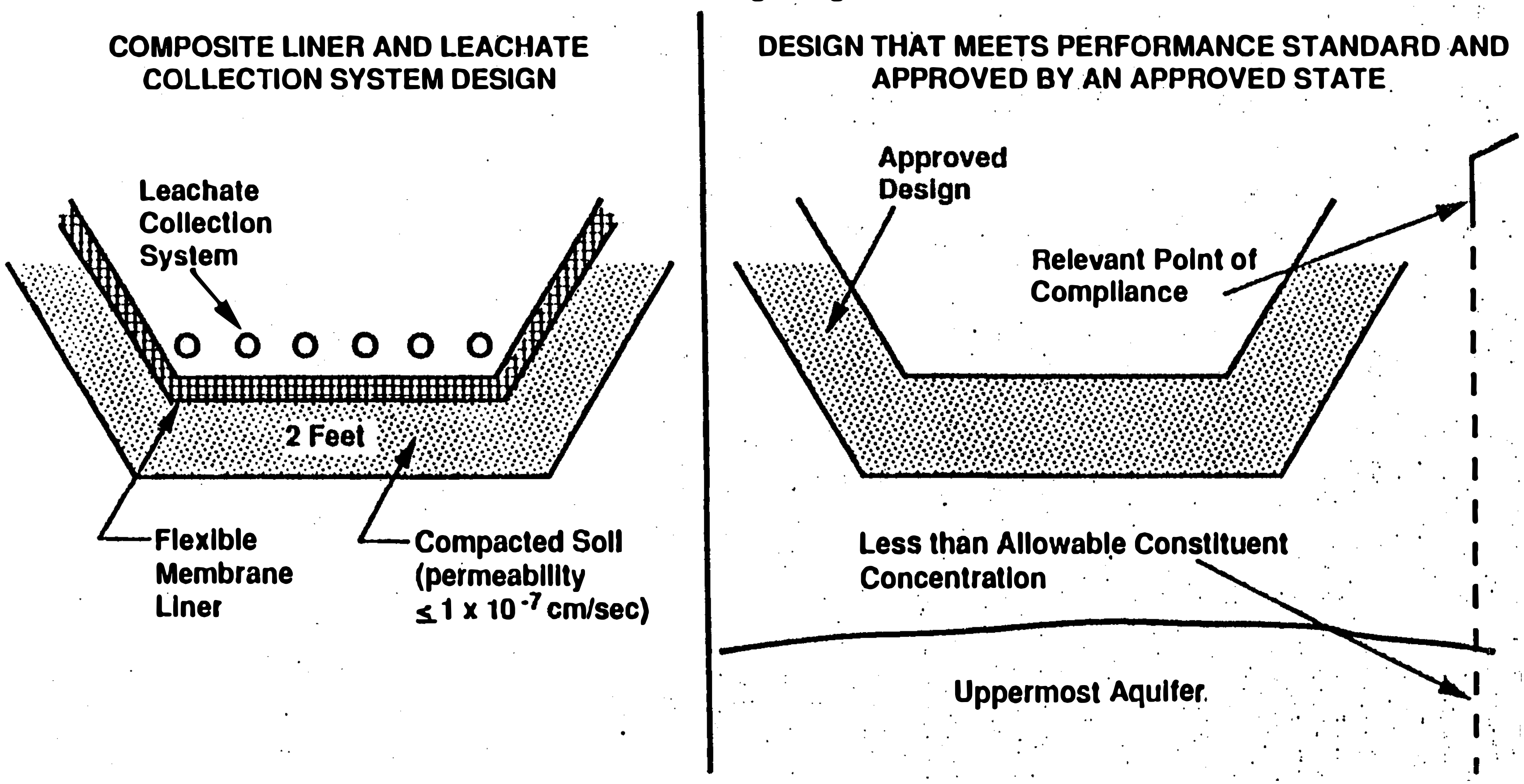


Figure F-2. New MSWLF Design Criteria

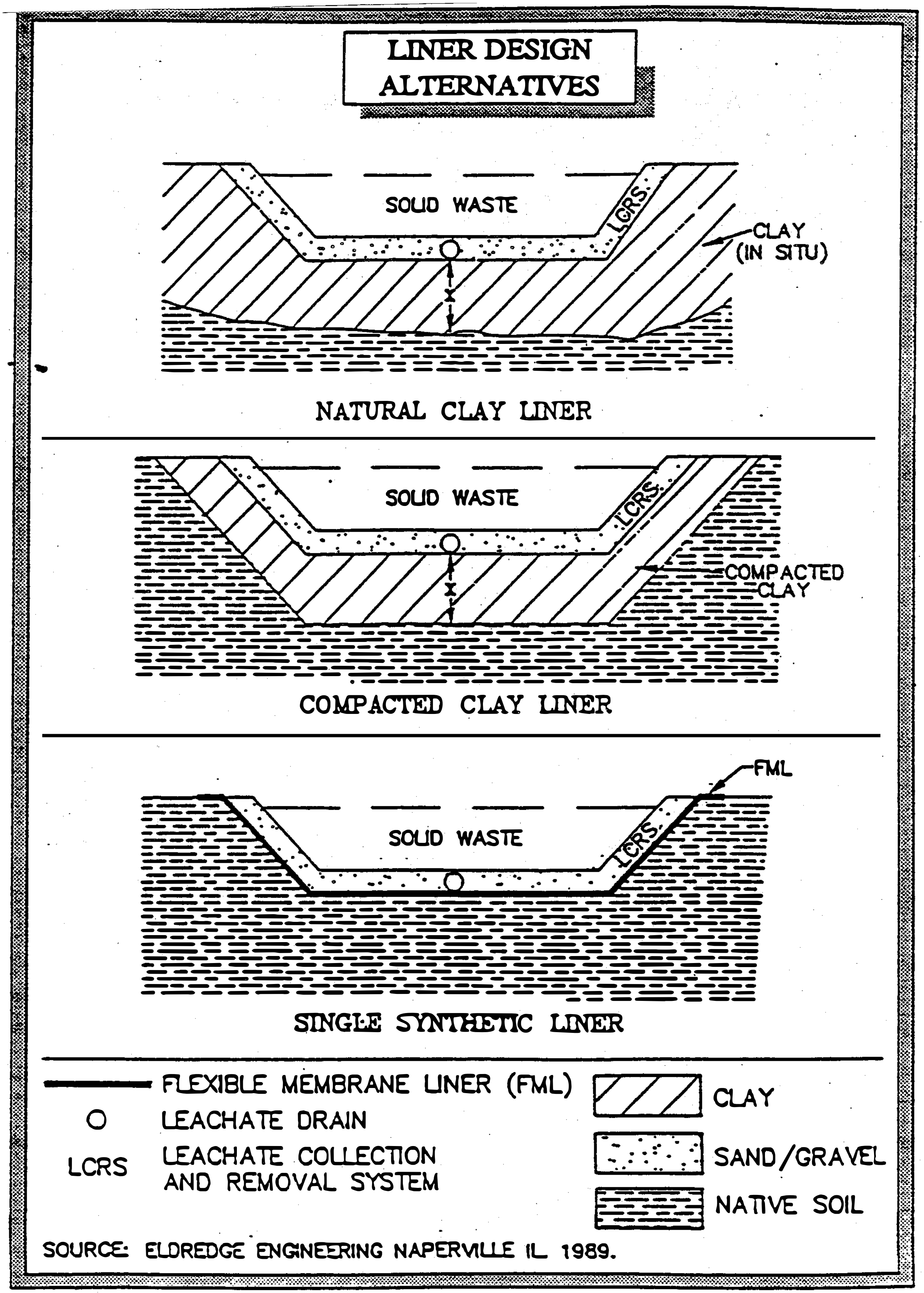


Figure F-3. Liner Design Alternatives (586)

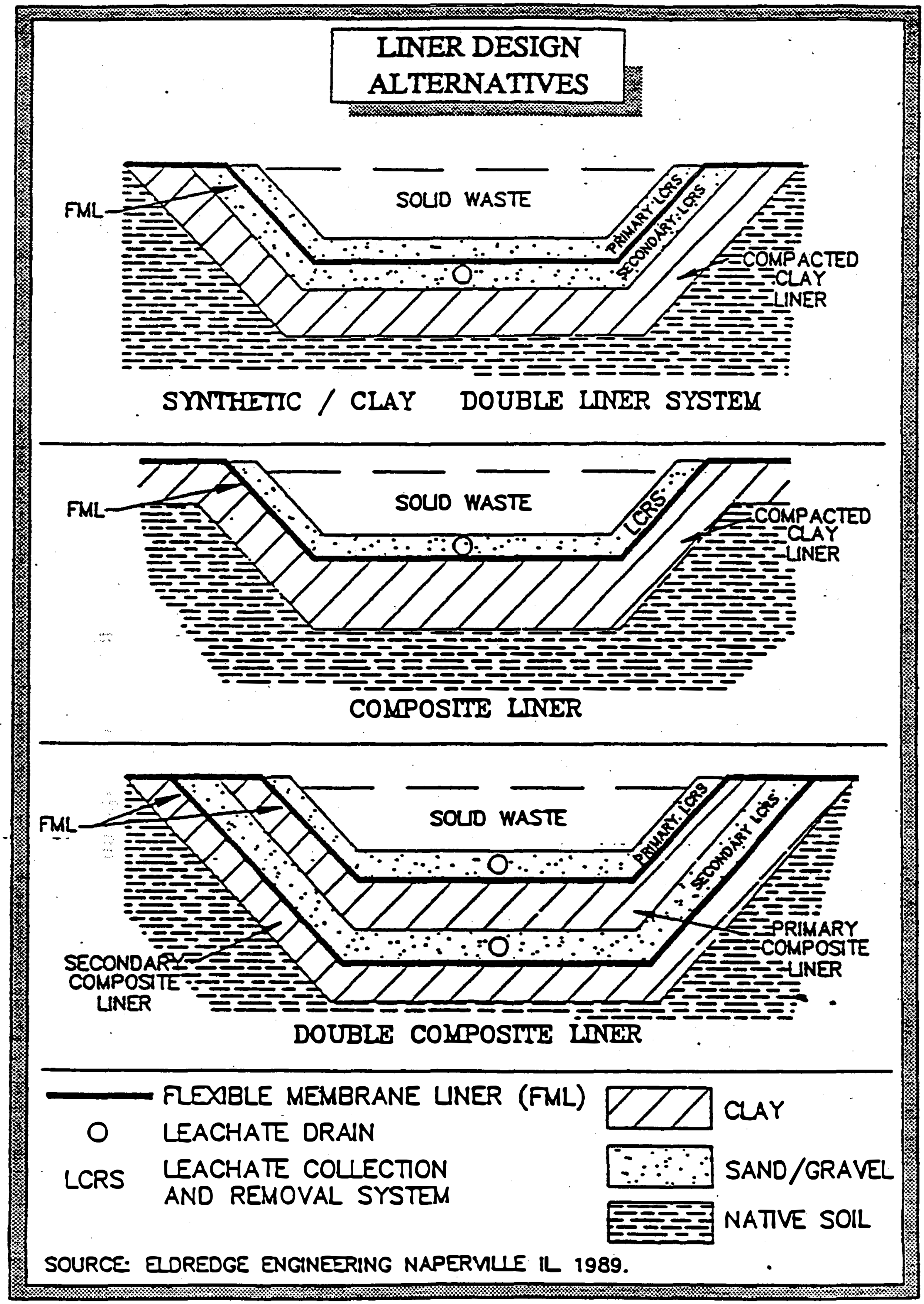


Figure F-3. Liner Design Alternatives (Cont)

TABLE F-5.

ADVANTAGES AND DISADVANTAGES OF SELECTED SYNTHETIC LINERS (586)

Chlorinated Polyethylene

Advantages	-	Good tensile strength
	-	Good elongation strength
	-	Resistant to many inorganics
Disadvantages	-	Will swell in presence of aromatic hydrocarbons and oils
	-	High elongation
	-	Poor memory

Chlorinated Polyethylene

Advantages	-	Good resistance to ozone, heat acids and alkalis
	-	Easy to seam
Disadvantages	-	Poor resistance to oil

Polyvinyl Chloride

Advantages	-	Good resistance to inorganics
	-	Good tensile, elongation, puncture, and abrasion-resistant properties
	-	Wide ranges of physical properties
	-	Easy to seam
Disadvantages	-	Attached by many organics, including hydrocarbons, solvents and oils
	-	Not recommended for exposure to weathering and ultraviolet light conditions

High Density Polyethylene

Advantages	-	Good chemical resistance to oils and chemicals
	-	Resistant to weathering
	-	Available in 20 to 150 mils thicknesses
	-	Resistance to high temperature
Disadvantages	-	Thicker sheets require more field seams
		Subject to stress cracking
		Subject to puncture at lower thicknesses
		Poor tear propagation

Even with a liner system, containment of water within a landfill can be difficult. No one liner is chemically resistant to every imaginable component of MSW, and thus does not provide a completely safe system. Recent research on stress cracking of liner systems has questioned the true chemical resistance of liners previously thought to be chemically resistant (123). Both clay and synthetic liners can suffer a loss of compressive strength over time. Organic acids formed during decomposition can cause dessication of the clay, resulting in shrinkage cracks. All liners can be damaged by physical stresses from the waste burden.

F.2.3 Groundwater Monitoring Wells

Ground water monitoring wells serve as indicators as to whether or not landfill leachate is contaminating the ground water. Figure F-4 shows a typical ground-water monitoring well. The minimum requirements for monitoring wells, referenced in the Subtitle D, Part 258.51(c) regulations, state that they must be cased in a manner to maintain the integrity of the well bore hole (908). The casing must be screened or perforated and packed with gravel or sand, as necessary to enable collection of samples. Further, the annular space, i.e., between the bore hole and well casing, above the sampling depth must be sealed to prevent contamination of samples and ground water.

Ground water monitoring systems can be simple or elaborate, depending on the specific site conditions. An example of a typical minimum ground water monitoring layout, currently in use, is illustrated in Figure F-5 (908). As previously stated, the new Part 258 regulations regarding landfills specify the general performance requirements for ground water monitoring systems that must be approved by individual States.

Section 258.51 requires that a "sufficient number of wells, [be] installed at appropriate [upgradient and downgradient] locations and depths to yield ground water samples from the uppermost aquifer." In addition to characterizing the background water that has not been potentially affected by leakage of a unit, the quality of water passing the relevant point of compliance or the waste management unit boundary must be sampled (reference Figure F-2). The Director of an approved State has latitude to modify well placement in the case of obstacles that prevent sampling at the point of relevant compliance. Further, multi-unit ground water monitoring systems may be approved instead of separate ground water monitoring systems for each MSWLF unit, when the facility has several units.

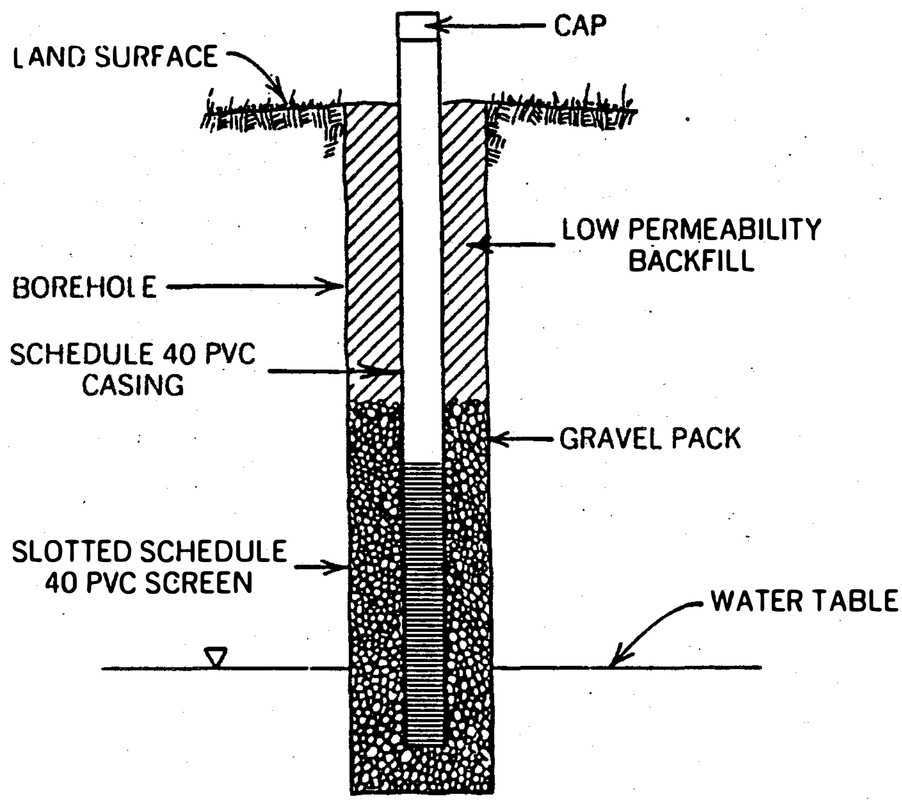


Figure F-4. Typical Monitoring Well Screened Over a Large Vertical Interval

(271)

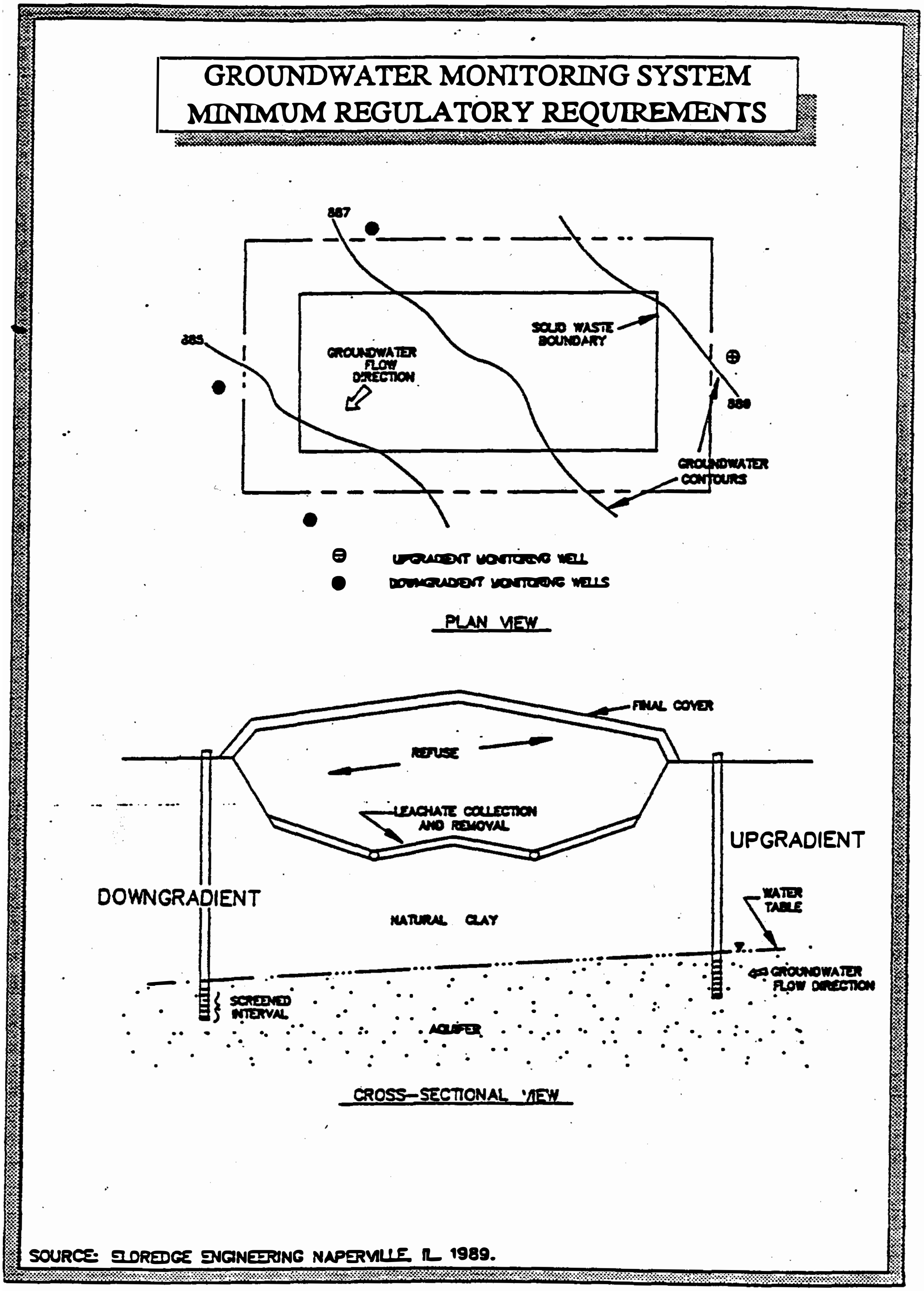


Figure F-5. Groundwater Monitoring System Minimum Regulatory Requirements

(507)

Related to the actual design and installation of ground water monitoring systems, are several sections of the regulations covering sample taking procedures, analysis and corrective action. These sections are identified below:

- <u>Ground Water Sampling and Analysis Requirements (Section 258.53)</u> -- Including: procedures for sample collection, sample preservation and shipment, analytical procedures, chain of custody control and QA/QC control; establishment of background ground water quality; and establishment of sample number and frequency based on statistical procedures identified.

- <u>Detection Monitoring Programs (Section 258.54)</u> -- Establish, at a minimum, a detection monitoring program that will monitor for the constituents listed in Appendix I (Federal Register, Vol. 56, No. 196, October 9, 1991, page 51032) which includes 47 volatile organics and 15 inorganic constituents.

- <u>Assessment Monitoring Program (Section 258.55)</u> -- Required whenever a statistically significant increase over background has been detected for one or more of the constituents listed in the Appendix I. When triggered, the owner/operator must sample and analyze the ground water for all constituents identified in Appendix II (Federal Register, vol. 56, No. 196, October 9, 1991, pages 51033-51039).

- <u>Assessment of Corrective Measures (Section 258.56)</u> -- Required within 90 days of detecting a statistically significant exceedance of an Appendix II constituent, as described in Section 258.55.

- <u>Selection of Remedy (Section 258.57)</u> -- Based on the results of the corrective measures assessment, the owner or operator must select a suitable remedy, as defined in this section, and notify the State Director of the selection. A schedule for implementation of remedy is also established.

- <u>Implementation of Corrective Action Program (Section 258.58)</u> -- A program to assess the efficacy of the remedy selected with respect to stated goals of this Section.

F.2.4 Landfill Caps

The landfill cap serves to prevent to the best degree possible, the entry of water into the landfill mass, to slow the release of landfill gases, and to provide a growing medium for the vegetative cover. Figure F-6 presents a "composite" profile of all of the possible layers that have been used in the design of landfill caps. Cap designs vary widely with a combination of layers to handle site-specific conditions.

Subpart F--Closure and Post-Closure Care, Section 258.60 of the regulations (908) requires owners and operators of all MSWLF units to install a final cover system that is designed to minimize filtration and erosion. The final cover system system is to be comprised of an erosion layer underlain by an infiltration layer. The infiltration layer must be comprised of a minimum of 18 inches of earthen material that has a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present, or a permeability no greater than 1×10^{-5} cm/sec, whichever is less. Further, the erosion layer must consist of a minimum of 6 inches of earthen material that is capable of sustaining native plant growth.

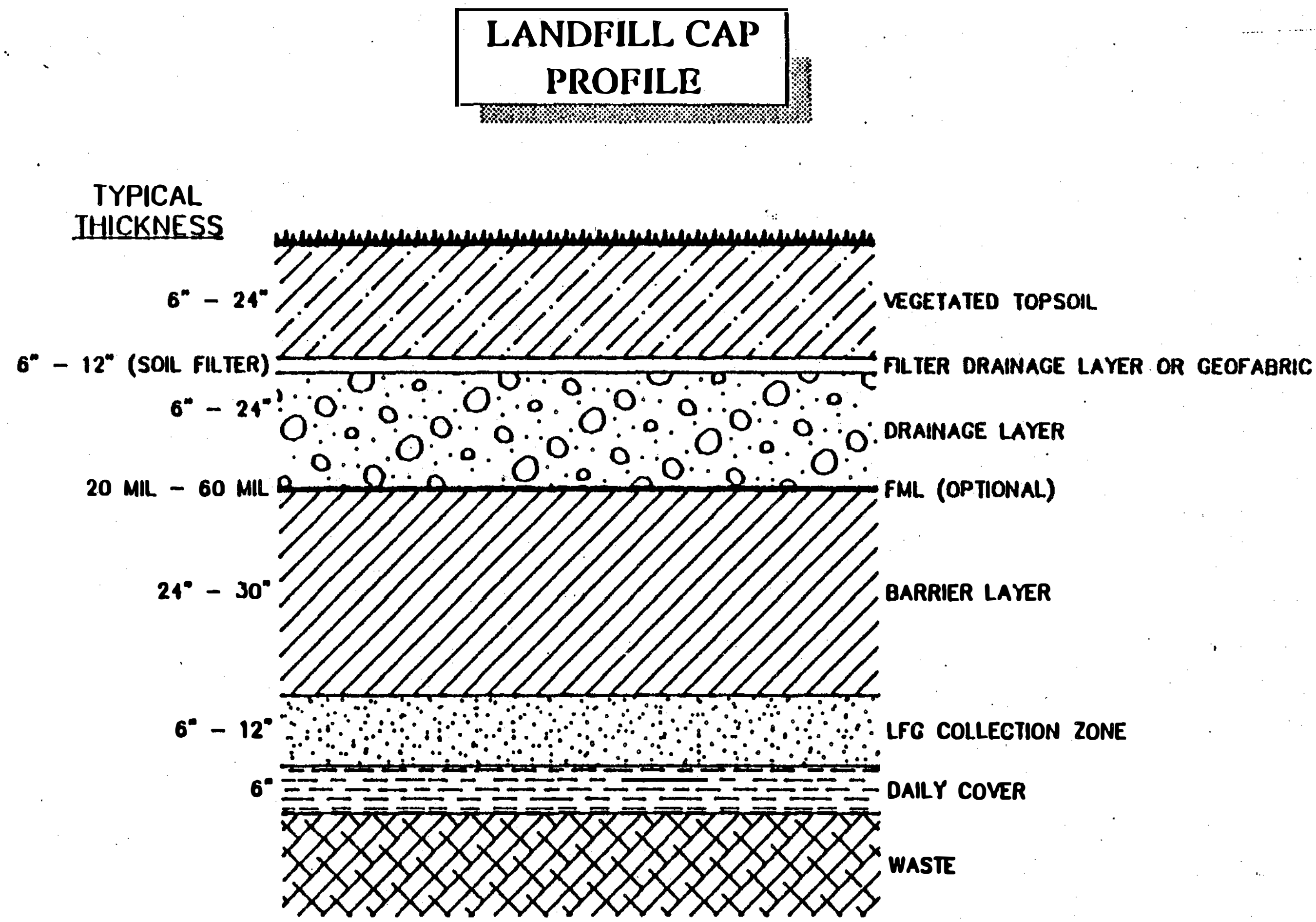
F.2.5 Landfill Gas

F.2.5.1 Gas Production

Landfill gas is produced by bacteria as a by-product of the anaerobic decomposition of organic matter. It typically consists of about 55 percent methane, 44 percent carbon dioxide, and 1 percent trace contaminants (232). Methane and the trace contaminants, however, remain in the gaseous phase and require special consideration.

Methane is flammable and explosive at concentrations of 5 to 15 percent in air (232). Gas movement within the landfill is governed by diffusion and convection. Landfill gas has been known to migrate off-site and into the basements of adjacent homes. Four explosions have occurred near the Port Washington, New York landfill and one at the Babylon, New York landfill when landfill gas entered the basement of homes and ignited (232). Gas migration up to 400 meters has been measured (457). On-site gas explosions and fires have also occurred. The U.S. EPA has recorded at least 10 deaths or serious injuries as a result of landfill gas explosions [(701) as cited in (409)]. Deaths by asphyxiation have also occurred when landfill gas has migrated into confined spaces habitated or frequented by people (457). Uncontrolled landfill gas can cause vegetative damage. As landfill gas migrates, it displaces oxygen in the soil. If this occurs in the plant root zone, the vegetation can be destroyed (457).

Figure F-6



NOTE: EXAMPLE ILLUSTRATES THE NUMBER OF LAYERS AVAILABLE FOR LANDFILL CAP DESIGN. NOT ALL LAYERS ARE NECESSARY FOR EACH APPLICATION.

Figure F-6. Landfill Cap Profile (586)

A wide range of landfill gas production rates have been reported in the literature. Wolfe and Maxwell (411) report that tests conducted by Waste Management of North America have shown generation rates ranging from 0.05 to 0.23 cubic feet/pound/year (100 to 460 standard cubic feet/ton/year), DeBaere et al (290) estimate gas production to be 6 to 40 liters/kg/year (192 to 1,283 standard cubic feet/ton/year). Morelli (584) states that the production rates range from 16 to 2,200 cubic feet/ton/year, and that the most commonly reported values are from 50 to 500 cubic feet/ton/year.

It takes one to two years for a landfill to start producing gas in a sufficient quantity. The amount produced is reduced each year as the organic material is decomposed. One estimate of the annual decrease in gas production is 2.5% (222). A typical landfill will produce about 6,000 to 12,000 standard cubic feet (scf) of gas for every ton of waste (411).

F.2.5.2 Gas Management

Landfill gas must be controlled to prevent gas migration, with attendant impacts on health and the environment, and the accumulation of gas pockets within the landfill, which pose serious safety hazards. Also, the actual gas recovery rates from existing MSW landfills is highly variable (411,290), further suggesting the need for standards and guidelines for design and performance.

EPA's proposed standards of performance for MSW landfills dated May 30, 1991 covers performance testing and monitoring and best demonstrated technology requirements for new and existing MSW landfills. The technology of landfill gas extraction and control continues to evolve with new and more sophisticated methods of optimizing gas extraction being developed by both landfill owners and developers. Some of the key provisions of MSW landfill gas extraction regulations are summarized below.

Two types of systems are available for controlling gas movement in landfills: passive and active systems (271, 909). Passive systems consist primarily of a number of gas extraction wells, some of which may be connected to a flare. Often, passive wells vent gases uncontrolled to atmosphere, serving primarily to prevent gas migration and reduce fire and explosion hazard. In theory, a passive system could be as effective as an active system if each well or trench were equipped with an effective control device, and if the well or trench spacing were adequate to effectively collect gas from all areas of the landfill. Due to their shorter radius of influence, however, an effective passive system would require a larger number of wells resulting in higher costs for passive over active systems treating comparable volumes of gas (909).

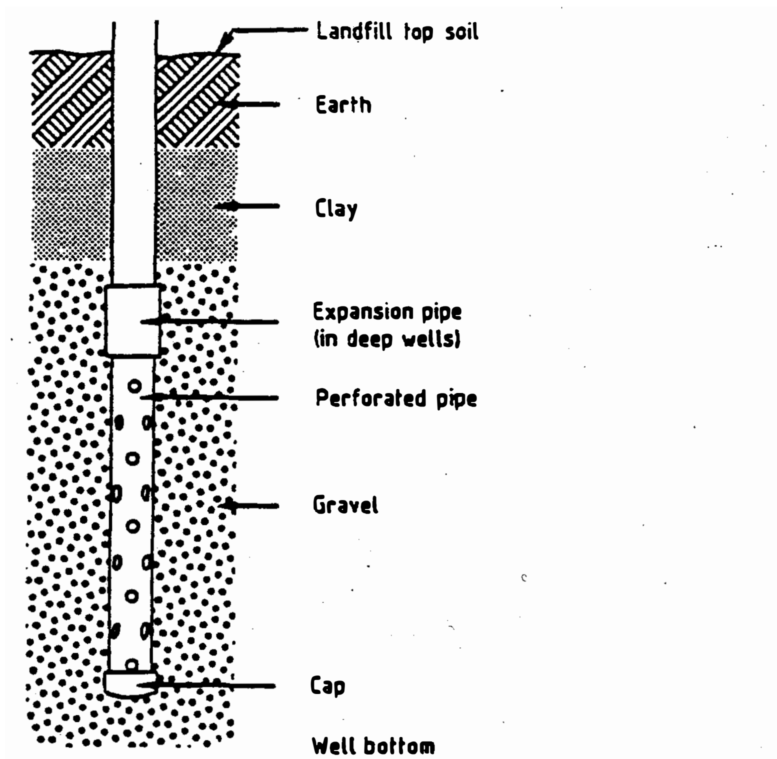
Because emissions are not reduced or destroyed using passive systems, EPA does not consider them effective and they are not considered best demonstrated technology (BDT). However, passive systems will likely be allowed when the owner or operator can demonstrate that the well spacing is adequate to effectively collect gas from all areas of the landfill, and the landfill is contained by synthetic liners on all sides, and top and bottom.

Commercial active gas collection systems are presently being used at more than 100 landfills nationwide (909). They consist of various configurations of gas extraction wells and/or trenches and gas moving equipment such as header piping and blowers. The design objective is to create a pressure gradient that will effectively collect the emissions without air infiltration from the surface and the sides of the landfill. Such site-specific factors as the gas generation rate, size and depth of the landfill, and refuse and cover permeability will affect the design of such a system.

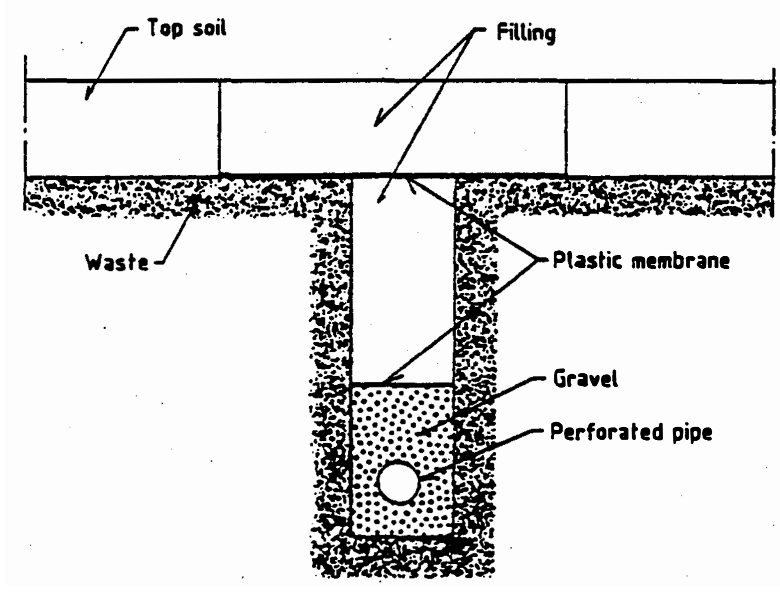
Active collection systems can be further categorized as vertical well systems and horizontal trench systems, illustrated in Figure F-7. EPA's proposed standards and guidelines indicate that landfill perimeter vertical wells are to be placed in the refuse no more than one perimeter radius of influence from the perimeter and no more than two times the perimeter radius of influence apart. Interior well placement follows the two times radius spacing; such wells are to be positioned to cover all areas of the landfill where refuse is placed.

Vertical extraction wells are proposed to be constructed with materials and specifications indicated by Figure F-8 (909). Each well is to be connected to the collection header pipe by a well head (not shown) where monitoring and adjustments can be performed. Landfill gas is conveyed through the header by a blower or compressor to a control device. The gas collection header must be designed to accommodate additional wells that must be installed in each area of the landfill within 2 years of the first deposition of refuse in that area. Further, since excessive infiltration poses a safety hazard, EPA has determined that N_2 concentration, a surrogate for infiltration air, should be maintained below 1 percent.

Horizontal trench placement is proposed to be no more than two times the radius of influence apart in the horizontal direction, with a vertical spacing of one-fourth the horizontal spacing (909). Horizontal trenches may be constructed of slotted or perforated nonporous materials, such as PVC, HDPE or corrugated steel piping. Each layer of trenches are to be connected to a common header leg that extends to the surface, and connects the gas header pipes in the same way as active vertical collection systems. Monthly testing of pressure and air content is performed at the common header leg and adjustments made as necessary.



Cross section of a vertical gas recovery well.



Cross section of a horizontal recovery pipe.

Figure F-7. Gas Collection Wells (140)

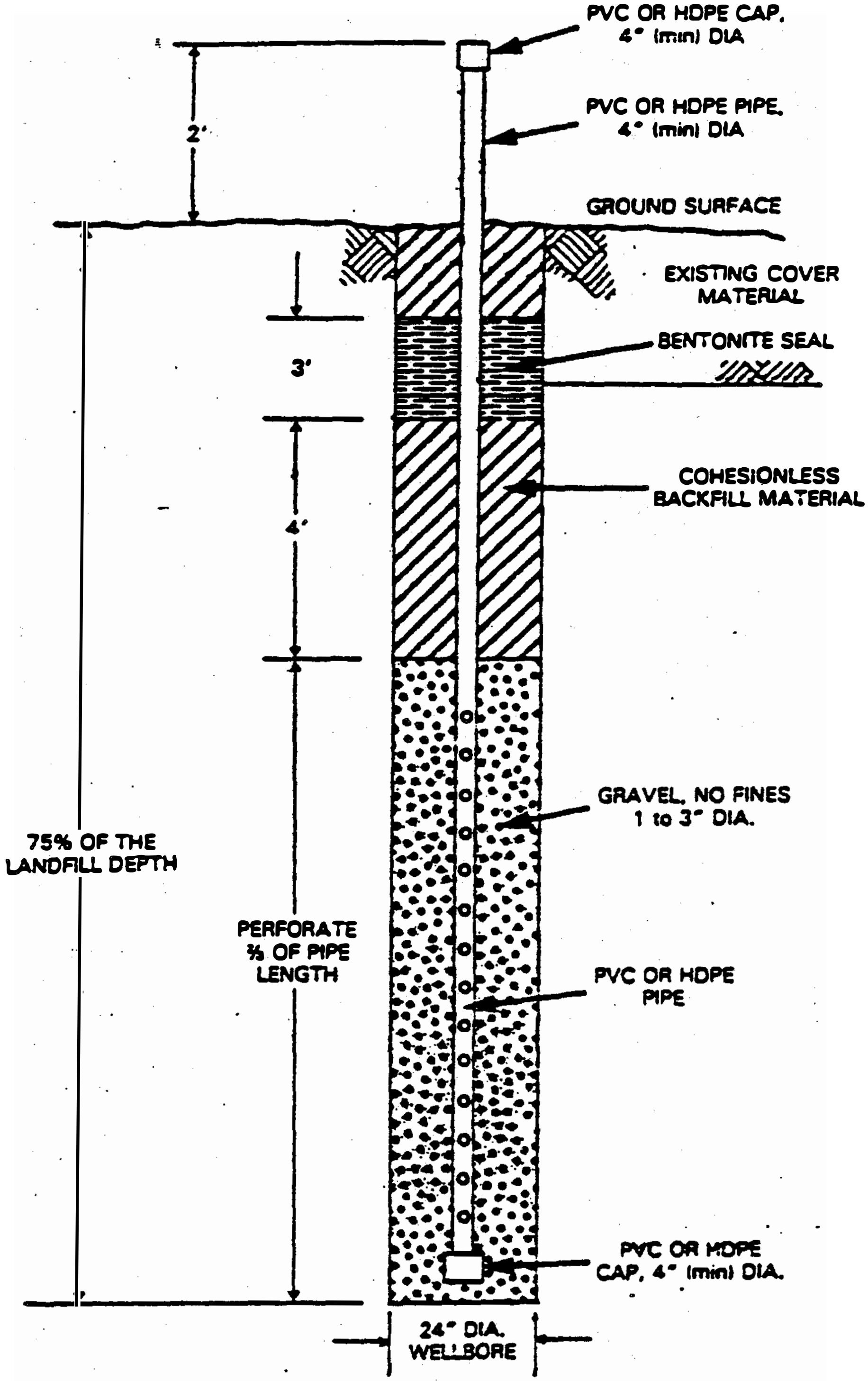


Figure F-8. Gas Extraction Well (909)

Horizontal gas collection wells allow gas to be extracted from lower levels while the landfill is being filled higher up. The landfill does not have to reach its final grade before the gas can be extracted. The advantages and disadvantages of vertical and horizontal wells are presented in Tables F-6 and F-7, respectively.

F.2.5.3 Gas Utilization

Conversion of landfill gas to energy is a viable gas management alternative. Landfill gas has been collected and utilized to produce energy since 1975 when the first facility began operation in Rolling Hills Estates, California. As of 1985, over 1 billion cf of gas has been recovered and converted to energy at this facility (232). Landfill gas has a heat value after minimal processing of about 550 Btu, thus classifying it as a medium Btu gas (232). The available options for utilizing landfill gas as a fuel in its natural state include direct sales to industrial customers and use in generating electricity.

For its proposed landfill gas regulation (909), EPA has determined that the following control devices are capable of achieving the prescribed destruction efficiency (i.e., 98 percent by weight of NMOCs) and can be used to comply with regulations.

- Flares - Open and enclosed flares are in wide use. Open flares generally have one burner tip and can be located at ground level or can be elevated. Enclosed flares are usually composed of multiple gas burner heads and capable of a wide range of flowrates. (EPA often refers to enclosed flares as enclosed combustion devices).

- Enclosed Combustion Devices - In addition to enclosed flares, other kinds of enclosed combustion devices include boilers, gas turbines, internal combustion (I.C.) engines and incinerators. (Lean-burn I.C. engines are currently in use in NO_x nonattainment areas.)

- Purification Systems - These systems are used to upgrade landfill gas to pipeline quality natural gas by the removal of water, condensible NMOCs and CO_2. However, halogenated compounds and sulfur derivatives that must also be removed for pipeline quality gas are typically vented. Purification of these constituents is economically infeasible. As such, EPA has not considered purification systems as candidate BDTs.

TABLE F-6.
VERTICAL GAS COLLECTION WELL ADVANTAGES AND DISADVANTAGES (594)

Advantages	-	May be installed in the completed part of a site, filled by progressive restoration, while waste is still being deposited in other areas.
	-	Each well can extract gas from several layers in a deep site.
	-	If the perforated sections extend high enough, a rising leachate level may only partially block the wells and they will still be effective.
Disadvantages	-	Can only be installed in parts of sites which have been brought up to final level; therefore, some gas may be lost prior to their installation.
	-	Specialist drilling contractors are required for installing the wells.
	-	If the perforated sections become blocked by leachate, the wells will cease to function. This is more likely to occur in shallow sites where the wells only have short sections of perforations in the base of the site.

TABLE F-7.
HORIZONTAL GAS COLLECTION WELL ADVANTAGES AND DISADVANTAGES (594)

Advantages	-	Installation of horizontal trenches can be relatively inexpensive because local construction companies may be hired to excavate the trenches.
	-	Can be readily used for extracting gas from shallow sites.
	-	May be placed in the higher, unsaturated layers within partially flooded sites.
	-	May be used to extract gas from lower levels of waste while waste is still being deposited at higher levels.
Disadvantages	-	A deep site may require several layers of trenches and hence become expensive in terms of length of pipe installation costs.
	-	Only short lengths of trench could be installed at any one time in sites which are being filled in cells or small areas (as per recommended practice).
	-	Trenches in lower levels of waste may become completely blocked by rising leachate and necessitate the installation of more trenches at higher levels.
	-	Uneven settlement in deep sites may result in damage to horizontal pipes.

F.2.5.3.1 Industrial Use. Piping of unprocessed gas to industrial users for use as a boiler fuel is normally economically limited to users located less than three miles from the landfill (222). Some form of pretreatment is required before the gas can be fired in a boiler. The main purpose of pretreatment is to remove water, which degrades the Btu value of the fuel for direct firing in an industrial boiler. Typical pretreatment processes include: pretreatment to remove water, intake scrubbing to remove free water, processing with triethylene glycol to dehydrate the gas, and removing water through the use of a chiller [(702) as cited in (271)].

F.2.5.3.2 Electrical Energy Generation. Three state-of-the-art methods are presently available for converting methane gas to electricity: reciprocating engines, gas turbines, and steam turbines (462). The decision between turbines and engines is based on the quantity of the gas supply since turbines operate poorly at partial load. If a sufficient quantity of gas is available to operate a turbine at full load, the turbine is preferred because of its lower maintenance requirements and its slightly higher reliability (411).

Reciprocating engines. State-of-the-art reciprocating engines are turbo-charged engines offering low emissions, good fuel efficiency, clean burning, and high reliability. Examples are Superior Clean Burn Engines built by Cooper Industries and the Fairbanks Morse MEP engine (462).

Gas turbines. State-of-the-art gas turbines are characterized by low emissions, good reliability, and relatively low conversion efficiencies (462). Gas turbines can operate on lower Btu fuel than reciprocating engines. Examples of gas turbine manufacturers are Kongsberg, Solar, and Mitsui (462).

Steam turbines. Steam turbines require ancilliary equipment such as water treatment, cooling towers, blowdown water disposal, water make up, water pumps, and a boiler (s), etc. These requirements serve to limit the use of steam turbines to very large landfill sites (462).

Fuel cells. A currently unproven technology for converting methane to energy, fuel cells can convert methane directly to electricity by electronically combining fuel and oxygen. Potentially high efficiency and very low emissions can result from a fuel cell operation. The restricting factor may be cost.

F.2.5.3.3 Upgrading to Pipeline Quality. Upgrading landfill gas to pipeline quality (i.e., high Btu content) consists of removing carbon dioxide and other contaminants so that the resultant gas has a Btu content of 900 - 1000. Installation of equipment for upgrading landfill gas to pipeline quality is very expensive and at the present there is little incentive to do so. Upgrade techniques include solid adsorption, liquid adsorption, and membrane separation (478).

Solid absorption. This process typically uses molecular sieves which are a range of alumino silicates packed in towers. The sieves absorb carbon dioxide from the landfill gas. They are usually preceded by silica gel or glycol towers to remove water and by an activated carbon unit to remove the higher molecular weight contaminants. The absorptive materials can be regenerated at the expense of a substantial amount of energy (595).

Liquid absorption. This family of processes uses liquids to remove contaminants such as carbon dioxide, hydrogen sulfide, water, halocarbons, and heavy hydrocarbons. The Selexol process uses glycols as the solvent. The glycols can be recovered easily at low cost. The Kryosol process first uses pressurized methanol followed by monoethanolamine or diethanolamine (595). The absorbant is relatively easily reclaimed.

Membrane separation. This process uses a synthetic membrane to separate one gas from another. It is based on the principle that certain gas species pass through a membrane faster than other species. Two commercial processes are the Monsanto Prism Process and the Separex process (595).

F.2.5.4 Landfill Gas Recovery System Status

A schematic for a landfill gas plant is shown in Figure F-9. Both publicly owned and privately owned landfills use gas recovery. The operations are usually run by developers who lease the gas rights from the landfill owners (409). The number of landfill gas collection and energy recovery systems in operation has been steadily increasing since the early 1980s. In 1987, about 113 systems were in operation throughout the world, with 36 located in the United States (Table F-8).

By 1989, operational facilities in the U.S. increased to 77 plants; an additional 78 plants were in various stages of development (Table F-9). Twenty-five different vendors were involved with these 155 facilities. Gas production rates in cubic feet per ton per year for selected landfills are presented in Table F-10.

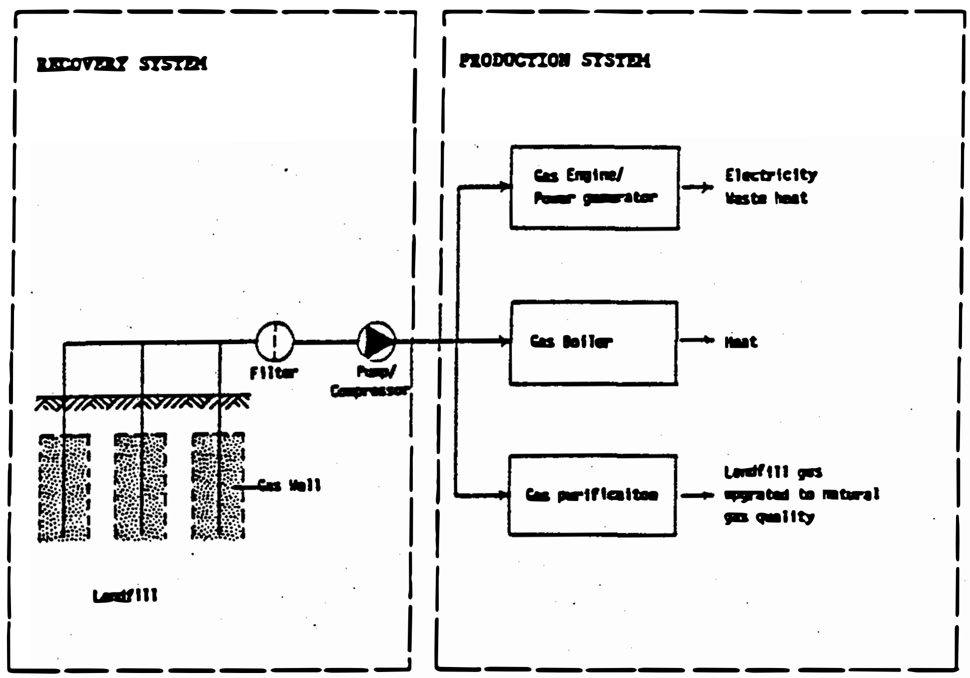


Figure F-9. Landfill Gas Plant (140)

TABLE F-8. STATUS OF LANDFILL GAS PRODUCTION SYSTEMS - 1987 (140)

Country	No. of Plants
Germany	40
USA	36
Great Britain	13
Sweden	8
Switzerland	4
Brazil	3
Denmark	3
France	2
Netherlands	2
Austria	1
Norway	1
	113

Gas recovery facilities have also been reported to be in place in Asia and Australia (478).

TABLE F-9. U.S. LANDFILL GAS PRODUCTION SYSTEMS - 1989 DATA (389)

1989 Status	No. of Plants
Operational	77
Shakedown	3
Temporarily Shutdown	7
Under Construction	19
Conceptual Planning	21
Advanced Planning	28
	155

Regional Location	No. Plants Existing	No. Plants Planned	Total No. of Plants
West	41	17	58
Northeast	22	20	42
South	12	19	31
North Central	12	12	24
	---	---	---
Total	87	68	155

TABLE F-10. LANDFILL GAS PRODUCTION RATES (140)

Location	cf/ton/yr
United States	
Mountaingate	94.27
Olinda	66.02
Bradley	93.32
Industry Hills	63.17
Puente Hills	225.69
Calumet	231.08
Mountain View	322.82
Davis Street	245.68
Montery Park	141.25
Toyon	97.45
Penrose	172.99
Great Britain	
Blue Circle	314.25
Stewartby	106.65
Calvest	243.78
Aveley	243.46
Yorkshire	158.70
Merseyside	35.23
Germany	
Heuchelheim	308.85
Hohberg	72.37
Burghof	231.72
Kemna	27.93
Karlsruhe	119.00
Rastorf	307.90
Sweden	
Malmo	60.30
Halsingborg	73.01
Vanersborg	41.26
Vasteras	126.97
Kovik	19.05
Hassleholm	53.96
Denmark	
Viborg north	79.35
Viborg south	123.79
Grindsted	150.77
Tune	54.60

F.2.6 Shredfill

MSW can be shredded prior to landfilling to increase the efficiency of the entire landfill operation. The advantages of shredfill are as follows [(708) as cited in (271)]:

- Shredded MSW can be compacted to a greater density (about 27% greater) than unshredded refuse; this will extend the life of the landfill accordingly
- Shredded refuse can be more quickly compacted
- Less cover material is required
- The fire hazard potential is reduced
- More leachate is produced during initial landfill stages when landfill is receiving much attention and less leachate is produced during the later stages.

The primary disadvantage of a shredfill is the high initial capital expenditure required for the shredder. Other disadvantages are the potential for opening up batteries exposing mercury and cadmium and the potential for explosions in high speed hammermills (662). Shredding can be combined with other on-site operations such as recycling and bailing. Shredding has not really gained widespread acceptance because of the relatively slight resulting density increase compared to the high capital and O&M costs (239). As of 1986, there were over 100 landfills in the U.S. receiving shredded refuse (271).

Example shredfill locations (662) are as follows:

Dade County, Florida. Has used three 70 TPH Williams hammermills since 1981. Has found historically that daily cover is unnecessary and that rat infestation is largely eliminated. [Facilities receiving waste on or after 9 October 1993 will be required to provide disposed solid waste with at least 6 inches of earthen materials at the end of each operating day. (Subtitle D, Part 258.21)]

Charleston County, South Carolina. Uses two 18.2 tons per hour Heil hammermills and one 45.5 TPH Saturn shear shredder to shred about 545 tons per day. Vector control has apparently been achieved without providing a daily cover. [Part 258.21 of RCRA Subtitle D will also apply here.]

San Diego, California. Used two 1,000 horsepower Heil hammermills for 2 years and then closed because of high operations and maintenance costs and low ferrous market prices. Found that daily cover was not needed, rats were eliminated, the MSW was easy to compact, and the amount of litter blown by winds was reduced. [Section 258.21 of RCRA Subtitle D requires use of a daily cover.]

Springfield, Illinois. Used a 300 horsepower Saturn shear shredder for the purpose of recovering ferrous metals. This shredder operated until a decline in ferrous prices ruined the economics. Found the benefits of shredding to be similar to that found at the other case study sites.

F.2.7 Balefill

Baling is another means of waste treatment that can improve landfill operations. Baling can result in waste densities around 1,700 pounds/cubic yard, compared to about 1,100 pounds/cubic yard from conventional landfill compaction equipment (239). This is a density increase of 54 percent as compared to conventional landfilling. Baling can be done on-site or at an off-site baling/transfer facility. An off-site baling facility decreases the cost of transportation by increasing the load per truck. The advantages of balefilling are as follows [(709) as cited in (271)]:

- Extends landfill life by increasing waste density
- Reduces negative impact of disposal site by reducing litter, dust, odor, vermin, vectors, fires, traffic, noise, leachate, safety hazards, earth moving, and settling
- Reduces cost and increases operating efficiency since fewer workers, operating equipment, and less cover material are required
- Increases potential future use of the site by improving the bearing capacity of the landfill and reduces the waiting period for land stabilization
- Increases resource recovery opportunities by providing a central processing facility for simplifying the start-up of material separation and baling for storage or sale

As with shredding, the high capital cost of balefilling is the main deterrent to its widespread use. However, increased costs may be justified if it improves public opinion of the landfill operation (239). Light industrial buildings can be constructed on balefills after two years of stabilization without piles or other special foundations (271). Of the nearly 50 balefills operating throughout the world in 1985, 40 were located in north America (271).

While there do not appear to be any specific regulations governing construction on balefills, or solid waste landfills in general, some guidance is provided in Section 258.61 of the new landfill regulations (908). The post-closure care provisions require that the owner or operator maintain the integrity and effectiveness of the final cover, leachate collection system, ground water monitoring system, and gas monitoring system for up to 30 years after closure. Further, a description of the planned uses of the property during the post-closure period must be included in the post-closure plan, which must be approved by the State.

F.2.8 Tekkaseki Compression System

A Japanese firm has developed a system for compressing MSW into extremely dense blocks for landfilling. Although the technology is new to the U.S., the Japanese have been using it for about 15 years. Currently (1991), there are 130 plants in Japan and several in Belgium, Italy, and the U.K. (124). The compression device incorporates three compression stages to achieve a 60 percent density increase. A typical 3-foot cube weighs 1 ton and has a density of 2,000 pounds/cubic yard, about an 82 percent increase in density as compared to conventional landfill waste density.

A typical facility has a capacity of 1,200 tons per day, operates two shifts, and employs 34 people per shift. Prior to compression, waste is blended with a crane, bagbreakers open bags, and a magnetic separator removes ferrous metals. Five compressors, each with a capacity of 240 tons per day, compress the MSW into blocks. Bales are bound with a wire net and/or 20 mil plastic sheeting. The blocks can be coated with concrete (1,000 pounds required per block) for use as a building material. The blocks have been approved by the New Jersey Division of Solid Waste for use in several applications. Additional processing equipment can be placed at the front end of the process to recover other materials.

Much of the liquid portion of the waste is squeezed out during the compression cycles. This leachate must be collected and treated prior to discharge to a sewer system or surface water budy such that requirements of the Clean Water Act are met. By removing the liquids in the process, leachate is drastically reduced in the landfill.

F.2.9 Reusable Landfills

The concept of a reusable landfill has recently been suggested as a new philosophy of landfill design. This involves accelerating the waste decomposition by leachate recirculation and, after a certain time period, excavating the landfill and recovering the soil cover and degredation product. The Delaware Solid Waste Authority has constructed such a landfill at its Southern Solid Waste Facility (665).

Excavation of the landfill will begin after 5 years of decomposition to recover materials for testing. Most of the organic material will be excavated within a 10-year period. The liner system and the leachate collection system will be rebuilt when the landfill is reclaimed.

Landfill reclamation was apparently demonstrated at Collier County, Florida in 1987 (46). This study concluded that:

- o Solid waste in existing landfills can be mined in a safe, economical, and environmentally sound manner
- o The mined material can be separated into a dirt or cover fraction (approximately 85%) and a plastic fraction using materials separation equipment
- o The heating value of the recovered plastic exceeded 5,600 Btu/pound on a wet basis and 7,400 Btu/pound on a dry basis

F.3 ECONOMIC DATA

F.3.1 Landfill Costs

The following discussion of landfill development, operation, closure, post-closure, and indirect costs is based on a state-of-the-art landfill that was designed to meet the proposed Subtitle D requirements and proposed MSW landfill air emissions regulations. This hypothetical landfill contains a liner system, leachate collection system, final cover system, regular and detailed inspection and recordkeeping, vector control, landfill gas control system, surface water run-on and run-off control, incoming waste restrictions, detailed closure and post-closure plan, financing to cover closure and the post-closure period, groundwater monitoring well system, groundwater monitoring program, and contingency plans.

F.3.1.1 Predevelopment Costs

Predevelopment costs (Table F-11) can vary considerably from project to project, depending on the local land value, complexity of state regulations, and the amount of assistance required from external consultants, engineers, or permitting agencies (684). Predevelopment costs are generally less than 10 percent of the total site development costs for state-of-the-art landfills.

TABLE F-11. TYPICAL PREDEVELOPMENT COSTS -- 1988 DATA (397)

Land	$1,500 to $10,000 per acre
Engineering	$100,000 to $800,000
Legal Fees	$1,000 to $50,000
Licensing/Permit Review Fees	$5,000 to $20,000

F.3.1.2 Construction Costs

Landfill construction costs are directly related to the site size and design features such as liner system, leachate collection system, gas control system, etc. Typically, the costs are most influenced by the liner and leachate collection system costs. Construction costs are usually 15 to 25 percent of the total site development costs (684). Typical costs are shown in Table F-12.

Actual costs vary on a regional basis, as well as due to local site and regulatory conditions. The construction costs provided in Table F-13 were taken from bid tabulations for Wisconsin and Minnesota clay liner projects from 1984 to 1986 (397).

TABLE F-12. TYPICAL LANDFILL CONSTRUCTION COSTS -- 1988 DATA (684)

Site Access Construction	
Gravel Access Road	$12.00 - $16.00 per linear foot
Bituminous Access Road	$22.00 - $24.00 per linear foot
Earthwork Construction	
Clearing and Grubbing	$1,500 - $3,000 per acre
Topsoil Excavation/Placement	$1.80 - $2.50 per cubic yard
Topsoil Excavation/Stockpiling	$1.05 - $1.40 per cubic yard
Base Area Preparation	
Subsoil Excavation/Stockpiling	$1.10 - $2.00 per cubic yard
Subsoil Excavation/Placement	$1.35 - $3.00 per cubic yard
On-Site Clay Haul/Placement	$2.40 - $4.00 per cubic yard
Sand Blanket Placement	$8.80 - $12.00 per cubic yard
Flexible Membrane Liner	$7.20 - $10.00 per square yard
Seed, Fertilizer, Mulch	$1,000 - $1,500 per acre
Leachate Collection/Transfer System	
Collection System Piping	$17.50 - $22.00 per linear foot
Clean-Outs	$1,400 - $1,500 each
Drainage System Control Devices	
Flat-Bottom Ditch Construction	$1.00 - $2.50 per linear foot
Underdrain system	
Drainage Pipe	$17.50 - $25.00 per linear foot
Select Granular Fill	$8.80 - $12.00 per cubic yard
Gas Migration Control	$5,000 - $10,000 lump sum
Administration, Construction, and Other Misc Costs	$150,000 - $300,000 lump sum
Miscellaneous	
Facility Sign and Gate	$2,000 - $3,000 lump sum
Scale House Equipment Shed	$66,000 - $80,000 lump sum
Facility Fencing	$10,000 - $15,000 per linear foot
Truck Scale	$36,000 - $40,000 each
Other Misc Site Upgrading	$10,000 - $15,000 lump sum
Gas Venting System Installation	
Blower Assembly	$93,000 - $150,000 lump sum
Gas Extraction Wells	$7,300 - $10,000 each

TABLE F-13. CONSTRUCTION COSTS -- 1984-1986 DATA, U.S. Midwest (397)

Topsoil Excavation	\$0.75 - \$2.80 per cubic yard
Common Excavation	\$0.70 - \$1.00 per cubic yard
Clay Liner Placement	\$0.95 - \$3.50 per cubic yard
Leachate Collection Pipe 6-inch Dia., Sch 80 PVC, with excavation, bedding, and gravel - typical range	\$1.50-\$2.50 per linear foot
Fiberglass Storage Tank, 10,000 gal, in place	\$10,000-\$15,000 lump sum
Manhole with Lift Station, 10-15 feet deep, 6-foot Dia. with duplex pumps	\$18,000-\$23,000 lump sum
Lysimeters (30 feet x 30 feet) to monitor liner leakage	\$10.00-\$13.50 per square yard
Sand Blanket (off site 20 mile round trip haul)	\$7.68-\$8.62 per cubic yard
Ditching (2' depth, 10 foot bottom)	\$0.05-\$1.70 per linear foot
Sedimentation Basin	\$10,000-\$20,000 lump sum
Maintenance Bldg/Scale 60 foot x 80 foot pole bldg with automatic scale	\$90,000-\$105,000 lump sum
Acess Roads	
Gravel	\$10.00-\$12.00 per linear foot
Bituminous Concrete	\$17.00-\$21.00 per linear foot
Fencing (8-foot chain link)	\$10.00-\$13.00 per linear foot

F.3.1.3 Operating Costs

Operating costs represent 40 to 50 percent of the total development cost, by far the highest percentage of any group of costs (684). Leachate treatment (if required) and discharge can add significantly to the operating cost depending on the quantity and quality of the leachate. Gas control system costs can vary considerably depending on the type of system used. The summary of typical operating costs, provided in Table F-14, is based on a 40 acre, 600-750 ton per day landfill with an efficient liner and leachate collection system with good drainage producing 6,000 to 10,000 gallons per day during operations and 10,000 gallons per day after closure (684).

TABLE F-14. TYPICAL OPERATIONS COSTS - 1988 DATA (684)

General Operations Costs including workers, equipment, facilities, and maintenance	$600 - $700,00/year
Leachate Collection and Treatment off site, no on-site pre-treatment	
By Truck, 20 mile round trip	$0.02 - $0.03/gallon $66 - $219,000/year
By Sewer - sewer charge	$0.01 - $0.03/gallon $22 - $66,000/year
Pre-treatment (varies with degree of pre-treatment required)	$0.10/gallon $292,000/year
Environmental Monitoring (air & water)	$8 - $40,000/year
Groundwater only, $/well/sample	$250 - $500
Gas Management and Control	$10 - $30,000/year
Engineering	$0 - $20,000/year

F.3.1.4 Closure Costs

The cost of placing the final cap on the landfill is the lowest of the landfill development cost groups. Much of this cost is often absorbed into the operating budget if the personnel and equipment are available to perform the work. Site closure costs can range from 3 percent to 5 percent of the total site development costs (684). Typical costs are provided in Table F-15.

TABLE F-15. TYPICAL CLOSURE COSTS - 1988 DATA
[(705) as cited in (587)]

Final cover	$2.00 - $5.00 per cubic yard
Unspecified Soil	$1.00 - $2.00 per cubic yard
Topsoil	$1.20 - $2.50 per cubic yard
Seed, fertilizer, and mulch	$1,000 - $1,500 per acre
Soil Testing	$150 - $250 per acre
Ditches	$0.50 - $2.00 per linear foot
Sedimentation Basin	$5,000 - $15,000 each
Gas Venting Trench	$4.00 - $6.00 per linear foot
Gas Extraction System	$50,000 - $250,000 each
Leachate Head Wells	$1,000 - $10,000 each
Survey & Certification	$2,000 - $10,000 lump sum
Landscaping	Varies
Administration	5% of total

F.3.1.5 Post Closure Costs

Post closure care consists of the routine maintenance required to insure that the landfill does not adversely affect human health and the environment following the landfill's active life. The final cover, leachate collection and treatment system, groundwater monitoring wells, and gas collection system all require long term maintenance. Landfill gas, surface water, groundwater, and leachate all require extended monitoring. The post-closure care period, from Section 258.61 of RCRA Subtitle D, is 30 years. All post closure costs are assumed to be set aside at the time the landfill opens. Post closure costs represent 10 percent to 20 percent (and perhaps more) of the total site development costs. Typical costs are shown in Table F-16.

TABLE F-16. TYPICAL POST CLOSURE COSTS - 1988 DATA
[(705) as cited in (587)]

Annual Inspections	$60 - $200 each
Land Surface Care	$500 - $1,000/year
Leachate Treatment	
Hauling	$0.01 - $0.05/gallon
Treatment	$0.003 - $.010/gallon
Environmental Monitoring	$8,000 - $40,000/quarter
Gas	$10 - $20/point/year
Groundwater	$1,000 - $5,000/well/year
Leachate	$1,000 - $10,000/year
Surface Water	$150 - $200/point/year
Gas Control	$10,000 - $30,000/year
Leachate Collection	
System Cleaning	$25 - $0.40/foot/year
Lift Station Maintenance	$1,000 - $2,000/year
Landscape Maintenance	$50 - $100/acre/year
Leachate & Gas Extraction	
Systems Maintenance	$1,000 - $5,000/year
Electric Power	$500 - $1,000/year

Landfill closure and post-closure costs are summarized in Table F-17.

TABLE F-17. APPROXIMATE CLOSURE AND POST-CLOSURE COSTS
1988 DATA [(705) as cited in (587)]

Closure Costs	
Final Cover Without Membrane	$5,000 - $10,000/acre
Final Cover With Membrane	$15,000 - $30,000/acre
Total Closure Cost	$10,000 - $50,000/acre
Closure Cost Per Ton	$0.075 - $1.25/ton
Post-Closure Costs	
With Leachate Collection System	$3,000 - $10,000/year
Without Leachate Collection Systems and Full Cap	$30,000 - $250,000/year
Post-Closure Cost Per Ton	$2.00 - $4.00/ton
Typical 40 Acre Site, 2,000,000 Ton Capacity, Leachate Collection System, Cap, 30-Year Period	$2,500,000 - $8,500,000

F.3.1.6 Indirect Costs

A final group of indirect costs may be incurred in the development of a landfill. These costs are unanticipated in the sense that they are not directly related to the landfill development or operation, but rather are attached to the project externally. Examples of such indirect costs are usually state-mandated assessments for subsidizing such programs as recycling or groundwater clean-up. Some specific examples of indirect costs, both in existence and proposed in 1988, are presented in Table F-18.

TABLE F-18. INDIRECT COSTS - 1988 DATA (684)

PA	Resource Recovery Fee	$1.50/ton (proposed)
WI	Environmental Repair Fund	$0.15/ton $1.00/ton (proposed)
	Groundwater Fund	$0.10/ton
	Waste Management Fund	$0.15-$0.35/ton $1.00/ton (proposed)
	Resource Recovery Fee	$2.00/ton (proposed)
IL	Recycling Grant Fee	$0.95/ton
NJ	Sanitary Landfill Fee	$0.50-$1.05/ton
CO	Hazardous Waste Fees	$0.15/ton (proposed)
OH	County Plan Fund	$0.40-$0.80/ton

F.3.1.7 Landfill Cost Models

In 1989, SCS Engineers prepared a landfill cost model that reflected the current state-of-the-practice landfill conditions in Michigan at that time [(706) as cited in (587)]. The cost model included all phases of a landfill's development from pre-development through post-closure. The following summarizes the characteristics of the model landfill:

General

- Capacity of 1,000 TPD
- Site Life = 20 years
- Fill Area = 80 acres
- Total Property including setbacks = 560 acres
- Groundwater on site
- No interference from bedrock
- Landfill excavation 19 feet below surface
- Terrain relatively flat
- Site is heavily wooded
- Ten residences on planned property
- Developer required to improve and maintain 1 mile of road
- No sewer serving site
- Leachate hauled 20 miles to wastewater treatment plant
- 3 phase power available 1 mile away
- All space heating is with propane

Construction

- Purchase residences at $150,000 each
- Purchase remaining land at $4,000 per acre
- Liner system as follows:
  - 3 feet of prepared subgrade material
  - 3 feet of clay at 10 E-7 cm/sec permeability
  - 60 mil HDPE membrane liner
  - Filter fabric geotextile
  - 2 feet of sand
- On-site storage lagoon for leachate
- Six gas collection wells, each 46 feet deep
- Groundwater monitoring - ten well clusters installed, each with two well points
- Stormwater control systems - ditches, inlets, etc
- 4,000 feet of new on-site roadway
- 2,000 square foot administration building
- 5,000 sqare foot maintenance building
- Parking area, recycling station, fencing, screening berms, seeding and mulching, landscaping, signage

Operation

- Nine pieces of heavy equipment: 2 bulldozers, 1 compactor, 2 scrapers, 1 backhoe, 1 grader, 1 sweeper, 1 loader
- Five other vehicles: 1 water wagon, 1 tractor mower, 3 pick-up trucks
- Total operating staff of 24 people: 1 Administrator, 1 Operations Manager, 1 Supervisor/Foreman, 1 Engineer, 1 Technician, 1 Salesperson, 1 Government Liaison Officer, 1 Safety/Personnel, 1 Waste Approval Coordinator, 2 Secretaries/Receptionists, 1 Accountant/Bookkeeper, 1 Check Station Clerk, 4 Laborers/Spotters, and 7 Equipment Operators

Operation (cont)

- Groundwater sampling conducted four times per year
- Allocation for community service included

Closure

- Entire landfill closed at once
- Final cap of 2 feet of clay at 10 E-7 cm/sec permeability and 6 inches of topsoil
- Seeding and mulching over entire 80-acre area
- Passive gas venting - no active gas removal
- Demolition and removal of site structures
- Stabilization of landfill surface
- Surface water control facilities

Post-Closure

- 30 year post-closure term
- 1,000 gallons per day of leachate generated over the post-closure term
- Groundwater monitoring: three inorganic rounds and one organic round conducted each year at each monitoring point
- Gas monitoring: annual monitoring
- Upkeep of retention ponds, leachate storage and handling facilities, roadways, and landfill surface

Other Costs

- Interest - for financing pre-development costs, landfill cell construction, and equipment costs, etc.
- Insurance - general business liability and environmental impairment liability
- Bonding
- Taxes - federal, state and local
- Contingencies - no allowance included in model
- Remediation - no allowance included
- Corporate overhead and profit - not included in model

A summary of the costs derived from this cost model are presented in Table F-19. The total landfill development cost in 1988 dollars is $124,909,000.

TABLE F-19. MODEL MICHIGAN LANDFILL COST DATA

[(706) as cited in (587)]

Cost	Amount	Notes
Pre-Development	$7,260,000	Two failed sites for each success at $2,420,000 per site.
Construction	$25,566,000	Likely constructed in phases. Total cost at $25,566,000.
Operations	$84,105,000	21 year site life at $4,005,000 per year operations cost.
Closure	$2,452,000	Likely closed in phases. Total cost at $2,452,000.
Post-Closure	$5,526,000	30 year post-closure period at $184,200 per year.
Subtotal	$124,909,000	

Additional Costs: Interest, Insurance, Bonding, Taxes, Contingencies at 21% - 56%, Remediation, Corporate Overhead, and Profit

In 1990, SCS Engineers developed a similar cost model to reflect proposed landfill regulations in Kentucky [(707) as cited in (587)]. The following summarizes the characteristics of the model landfill:

General

- Capacity of 750 TPD
- Site Life = 20 years
- Fill Area = 80 acres
- Total Property including setbacks = 500 acres
- Groundwater on site
- Bedrock 7 to 8 feet below surface
- Landfill excavation 25 feet below surface
- Terrain is rolling hills
- Site is heavily wooded
- Five residences on planned property
- No sewer serving site
- Leachate hauled 25 miles to wastewater treatment plant
- All utilities required (electric, gas, water, etc.) must be developed on site and self-contained
- Heating by propane

Construction

- Purchase residences at $50,000 each
- Purchase remaining land at $1,000 per acre
- Liner system as follows:
  - 1 foot of clay at 10 E-7 cm/sec permeability
  - 60 mil HDPE membrane liner
  - 12-inch drainage layer at 10 E-3 cm/sec permeability
  - Filter fabric geotextile
  - 3-foot clay layer at 10 E-7 cm/sec permeability
  - 60 mil HDPE membrane liner
  - 1 foot of sand
  - Filter fabric geotextile
- On-site storage lagoon for leachate

Construction (Cont)

Six gas collection wells, each 46 feet deep
Groundwater monitoring - ten well clusters installed, each with two well points
Stormwater control systems - ditches, inlets, etc
1,500 feet of new on-site roadway
2,000 square foot administration building
5,000 square foot maintenance building
Parking area, recycling station, fencing, screening berms, seeding and mulching, landscaping, signage

Operation

10 pieces of heavy equipment: 3 bulldozers, 1 compactor, 2 scrapers, 1 backhoe, 1 grader, 1 sweeper, 1 loader
5 other vehicles: 1 water wagon, 1 tractor mower, 3 pick-up trucks
Total operating staff of 24 people: 1 Administrator, 1 Operations Manager, 1 Supervisor/Foreman, 1 Engineer, 1 Technician, 1 Salesperson, 1 Government Liaison Officer, 1 Safety/Personnel, 1 Waste Approval Coordinator, 2 Secretaries/Receptionists, 1 Accountant/Bookkeeper, 1 Check Station Clerk, 4 Laborers/Spotters, and 7 Equipment Operators
Groundwater sampling conducted four times per year
Allocation for community service included

Closure

Entire landfill closed at once
Final cap consisting of:
Filter fabric geotextile
12 inches of sand gas venting layer at 10 E-7 cm/sec permeability
Filter fabric geotextile
40 mil geomembrane
12-inch drainage layer at 10 E-3 cm/sec permeability
36 inches of topsoil
Seeding and mulching over entire 80-acre area
Passive gas venting - no active gas removal
Demolition and removal of site structures
Stabilization of landfill surface
Surface water control facilities

Post-Closure

30 year post-closure term
1,000 gallons per day of leachate generated over the post-closure term
Groundwater monitoring: three inorganic rounds and one organic round conducted each year at each monitoring point
Gas monitoring: annual monitoring
Upkeep of retention ponds, leachate storage and handling facilities, roadways, and landfill surface

Other Costs

Interest - for financing pre-development costs, landfill cell construction, and equipment costs, etc.
Insurance - general business liability and environmental impairment liability
Bonding
Taxes - federal, state and local
Contingencies - no allowance included in model
Remediation - no allowance included
Corporate overhead and profit - not included in model

A summary of the costs derived from the above cost model are presented in Table F-20. The total landfill development cost in 1989 dollars is $213,159,000.

TABLE F-20. MODEL KENTUCKY LANDFILL COST DATA - 1989 DATA

[(707) as cited in (587)]

Cost	Amount	Notes
Pre-Development	$6,681,000	Two failed sites for each success at $2,227,000 per site.
Construction	$77,910,000	Likely constructed in phases. Total cost at $77,910,000.
Operations	$113,265,000	27 year site life at $4,194,800 per year operations cost.
Closure	$9,777,000	Likely closed in phases. Total cost at $9,777,000.
Post-Closure	$5,526,000	30 year post-closure period at $184,200 per year.
Subtotal	$213,159,000	

Additional Costs: Interest, Insurance, Bonding, Taxes, Contingencies at 21% - 57%, Remediation, Corporate Overhead, and Profit

Table F-21 presents an itemization of landfill development costs for a 100-acre site with a 20-year life and a 30-year post closure period.

TABLE F-21. SAMPLE LANDFILL DEVELOPMENT COSTS - 1988 DATA (587)

Site Characterization Costs	
Feasibility Study	$100,000
Ecological Study	$45,000
Archeological Study	$30,000
SUBTOTAL - Site Characterization	$175,000
Preliminary Development Costs	
Land Acquisition	$180,000 - $1,500,000
Hydrogeologic/Geotechnical Studies	$325,000
Site Engineering Support	
Design	$195,000
Permitting	$100,000
Technical Support and Consultation	$125,000
Legal Consultation	$360,000
SUBTOTAL - Preliminary Development	$2,605,000
Final Development Costs	
Clearing and Grubbing	$300,000
Excavation and Stockpile (assumes 20 ft deep)	$6,450,000
Linear and Leachate Collection Systems	
Single Natural Liner	$14,200,000
Single Composite Liner	$21,500,000
Double Composite Liner	$42,500,000
Leachate Management	
Pumps and Forcemain Installation (assumes 1 cell/10 acres, and1 pump/cell)	$450,000
Leachate Pretreatment Facility (includes construction & startup)	$4,000,000
Surface Water Controls	
Sedimentation Pond Construction (assumes 3 acre-ft storage, four ponds per 100 acres)	$27,500
Ditch Construction (assumes 4 ft deep, 10 ft bottom width, 3:1 sideslope, 8,350 lf/100 acre)	$54,450
Final Cover Construction	
Natural Clay Cover (6 inch topsoil, vegetation, 3 ft compacted clay)	$5,700,000
Synthetic Liner (2 ft cover, geonet, install HDPE, import 1 ft clay, place and compact, QA/QC)	$9,800,000

TABLE F-21. SAMPLE LANDFILL DEVELOPMENT COSTS - 1988 DATA (Cont)

Gas Management System	
System Design	$70,000
Gas Monitoring Program	$5,000
Gas Migration Assessment	$100,000
Installation	$1,630,000
Groundwater Monitoring System	
Install Wells (assumes one well/5 acres)	$200,000
Site Structures	
Maintenance Building/Offices	$2,000,000
Scale (single scale)	$50,000
Scale House	$50,000
Fencing	$140,000
SUBTOTAL - Final Development (single composite liner, natural clay cover)	$42,726,950
Environmental Management Costs	
Leachate Management	
Treatment and Transport (assume 10,000 gpd by truck)	$4,380,000
Gas Monitoring and Control	
Maintain Gas Probes (assume 20 probes)	$48,000
Monitor Gas Probes (assume every 2 weeks, 40 hrs/month)	$384,000
Calibrate Equipment	$44,000
Groundwater Monitoring	
Well Maintenance (assume 1 well/5 acres)	$260,000
Maintain Equipment	$4,000
Testing and Analysis (groundwater and surface water, assume 20 samples/event, quarterly sampling)	$1,920,000
SUBTOTAL - Environmental Management	$7,040,000
Post-Closure Costs	
Inspections	$240,000
Land Surface Maintenance	$3,300,000
Leachate Management System	$7,520,000
Gas Management	$480,000
Groundwater Monitoring (assumes 20 wells, semi-annual testing)	$1,864,000
Subtotal for Post-Closure	$13,404,000

F.3.2 Gas Collection System Economics

Typical gas collection system unit costs reported in the literature are $500 per acre (222) and $2,000 to $5,000 per acre for wells only (710). Piping costs can vary considerably depending on the piping material selected and whether the piping is installed above or below ground.

Costs for a blower/flare station can be $100,000 to $250,000 or higher (710). Annual operation and maintenance costs for a gas collection system can be $50,000 or more (710).

F.3.3 Gas Recovery System Economics

The economics of the conversion of landfill gas to energy are marginal at present. The low cost of conventional fossil fuels combined with the phasing out of tax incentives for alternate fuels has reversed the cost advantages landfill gas systems have enjoyed in the past (409). Further, the utility commissions in some states (Maine and New York, for example) have passed or are considering implementing all-source bidding procedures in order to comply with the Public Utility Regulatory Policies Act (PURPA) (409). These all-source bidding procedures require that landfill gas projects bid on the same basis against other qualifying energy sources for utility energy contracts. This situation will further threaten the economics of landfill gas to energy systems. DeBaere et al (290) report that the overall economics of recovering biogas from landfills will probably always be rather marginal. The costs of energy generating systems are highly variable and are site specific (411). The payback period of gas recovery systems for two systems reported in the literature, one operational, and one planned, were both 10 years (290).

A gas extraction test should be considered to be a prerequisite for developing a landfill gas recovery system. This test realistically estimates the gas production rate so that the economics of the energy recovery system can be evaluated. The cost of such a test has been reported at $40,000 to $80,000 (710) and at $100,000 (411). Failure to obtain such a determination is the number one cause of gas recovery system failure (710).

A typical cost for gas compression and dehydration equipment for a 2 million cubic foot/day gas recovery system is $1 million dollars excluding the cost of a building to enclose the system (222). Energy recovery from a landfill smaller than 2 million tons in capacity is not considered to be economical at 1989 energy prices (409).

Waste Management, Inc. reported that energy recovery from landfill gas is unprofitable at gas recovery rates of less than one million scf per day (411), and that at least 4 million scf must be available to justify an upgrade system (222). Another general planning value reported is $300,000 for a one million ton landfill. Rough annual maintenance costs for the same one million ton landfill are reported to be $15,000 (411).

Economic data for several gas recovery facilities in the U.S. and Europe are presented in Table F-22.

TABLE F-22. ECONOMIC DATA FOR SELECTED GAS RECOVERY FACILITIES - 1988/1989 DATA (140)

	Investment	Invest per MW Produced	Income per Yr of Gas Sold	O&M Costs	Pay in Years
		($000)			
United States					
Olinda	11,000	516	- -	- -	- -
Puente Hills	39,500	249	27,900	4,550	1.7
Calumet	6,500	249	1,800	- -	- -
Mountain View	1,300	250	490	- -	- -
Davis Street	2,000	126	1,500	- -	- -
Monterey Park	10,000	224	2,900	- -	- -
United Kingdom					
Blue Circle	4,600	220	1,530	- -	5
Aveley	2,250	124	920	**	3
Yorkshire	4,200	3,818	- -	- -	- -
Merseyside	2,550	500	**	**	- -
Germany					
Hohberg	900	720	180	30	6
Karlsruhe	2,460	367	- -	- -	- -
Hailer	3,000	455	800	250	5.5
Lampertheimer W.	3,000	423	800	250	5.5
Sweden					
Malmoe	370	370	74	- -	- -
Denmark					
Viborg	860	1,686	150	45	8
Grindsted	640	1,391	87	30	11

- - = Not Available
** = Confidential

F.3.4 Tipping Fees

Landfill tipping fees vary considerably from region to region depending on market conditions. A 1990 survey (667) found that landfill tipping fees varied from $3.00/ton in South Dakota to $150.00/ton in New Jersey (see Table F-1).

F.3.5 Balefill Economics

Capital costs for balefill equipment are about $5,000 per ton per day, and operations and maintenance costs typically range from $12 - $20 per ton (271). The cost of a Tekkeseki system is reported to be 30 percent of the cost of an incinerator even with the cost of an on-site wastewater treatment facility included for treating 30,000 gallons per day. Maintenance is reported to be substantial.

F.3.6 Reusable Landfill Economics

The estimated cost for reclaiming the Collier County, Florida landfill was $2,600,000 compared to about $8,000,000 to close the landfill plus $63,000 per year for monitoring. An additional cost savings was the avoided cost of $2,100,000 for cover material for the next four years. (46)

F.4 ENVIRONMENTAL RELEASES/IMPACTS

F.4.1 Acceptability of Landfills

Siting of new landfills has become more difficult because of intense opposition by the public. A 1990 survey showed that 59 percent of the general public would object to having a new landfill in their community (166).

F.4.2 Leachate

Since MSW is heterogeneous by nature, the contaminants and their concentrations in the resulting leachate will vary considerably throughout a landfill and from landfill to landfill. The stage of decomposition also will influence the type and concentration of contaminants. Any processing of the MSW prior to landfilling may affect the leachate characteristics (271). For example, shredded refuse was found to initially generate high contaminant levels followed by a sharp decline in contaminant concentrations [(692) as cited in (271)]. Table F-23 shows the reported concentration range for various leachate contaminants.

TABLE F-23. LEACHATE CHEMICAL CHARACTERISTICS

[(693-697) as cited in (271)]

Parameter	Range Reported, mg/l
Total Alkalinity (as CaCO3)	0 - 20,850
Aluminum	0.5 - 41.8
Arsenic	ND - 40
Barium	ND - 9.0
Beryllium	ND
Five day Biochemical Oxygen Demand	9 - 54,610
Boron	0.42 - 70
Cadmium	ND - 1.16
Calcium	507,200
Chloride	5 - 4,350
T. Chromium	ND - 22.5
Hex Chromium	ND - 0.06
Chemical Oxygen Demand	0 - 89,520
Conductivity, micromhos/cm	2,810 - 16,800
Copper	ND - 9.9
Cyanide	ND - 0.08
Fluoride	0.1 - 1.3
Hardness (as CaCO3)	0.22 - 800
Iron	0.2 - 42,000
Lead	ND - 6.6
Magnesium	12 - 15,600
Manganese	0.06 - 678
Mercury	ND - 0.16
Ammonia Nitrogen	0 - 1,250
NO_2 and NO_3 Nitrogen	0 - 10.29
Nickel	ND - 1.7
Phenol	0.17 - 6.6
Total Phosphorus	0 - 130
pH (standard units)	1.5 - 9.5
Potassium	2 - 3,770
Selenium	ND - 0.45
Silver	ND - 0.24
Sodium	0 - 8,000
Total Suspended Solids	6 - 3,670
Sulfate	0 - 84,000
Zinc	0 - 1,000

Although the goal has always been to limit leachate production, moisture is a necessary ingredient in the decomposition process. It has been found that decomposition can be greatly accelerated by a controlled recirculating of leachate through the landfill mass (323). The recirculated leachate nurtures the stabilization process and in the process stimulates gas generation and substantially lowers the COD and volatile acids. Table F-24 shows the comparative characteristics of leachates from a single pass and a recirculated landfill cell (323). Leachate treatment costs are accordingly reduced. When methane production drops off; the leachate should be allowed to drain from the landfill for removal and treatment (323). The landfill will then reach maturity and become dormant. Another advantage to leachate recirculation is that by encouraging and managing leachate generation during the early years of a landfill's life, leachate will be limited during the later years when attention has diminished (167).

TABLE F-24. COMPARATIVE CHARACTERISTICS OF LEACHATE FROM SINGLE AND RECYCLE CELLS (323)

Parameter	Single Pass	Recycled Leachate
Chemical Oxygen Demand	6,222	2,006
Total Volatile Acid	4,670	113
pH	5.3	7.1
ORP, mV Ec	-198	-232
Total Alkalinity as CaCO3	1,829	3,222
Conductivity, micromhos	1,475	4,084
Cadmium	0.05	0.05
Calcium	13	316
Chromium	0.1	0.1
Copper	0.1	0.1
Iron	298	102
Lead	0.3	0.3
Magnesium	5.9	25.2
Manganese	4.0	0.1
Nickel	0.04	0.1
Potassium	1.6	226
Sodium	5.6	913
Zinc	0.3	1.8
o-Phosphate - P	0.1	0.1
Ammonia - N	1.6	105
Sulfide	0.06	0.3

The issue of health risks from ground water contamination by landfill leachate are addressed in the revised Subtitle D regulations (908). As described on page 51086 of the CFR rule, MSWLF owners and operators, rather than the States, are required to set ground water protection standards (GWPS) at the maximum contaminant level (MCL) for all of the constituents identified in Appendix II (Federal Register, Vol 56, No. 196, 9 October 1991, pages 51033-51039). If there is no MCL promulgated for a detected constituent, the GWPS must be set at the background. To protect owners and operators from remediating below background, in those cases where the background level is higher than the promulgated MCL for a constituent, the GWPS is to be set at the background level.

For constituents without an MCL, approved States are also allowed to establish an alternative GWPS for carcinogens within a risk range of 1×10^{-4} to 1×10^{-6}. When approved States decide to set an alternative GWPS for a toxic chemical that causes an effect other than cancer or mutations, the alternative level must be equal to a concentration to which the human population could be exposed on a daily basis without appreciable risk of deleterious effects during a lifetime. Whereas the GWPS must be based on EPA-approved analyses and States are not precluded for setting more stringent GWPS, the risks to an individual should not exceed 1×10^{-4}.

F.4.3 Landfill Gas

In the early 1980s, several fires at the Oceanside, California landfill and an explosion at the Greentree landfill in Madison, Wisconsin prompted regulatory agencies to test landfills for the presence of harmful gas emissions (228). Since that time, at least 350 different compounds have been identified at the part-per-billion or greater level in the trace contaminant portion of landfill gas (415).

The exact make-up of landfill gas is determined by the waste components in the landfill. Generally, a single site can generate 100 to 200 different compounds (415). Many of these compounds may pose a serious risk to the public health (228). Vinyl chloride, for example, a known carcinogen, is formed by the bacterial decomposition of solvents containing chlorine. New Jersey tested the Pennsauken landfill in 1985 and found significant emissions of the carcinogens benzene and perchloroethylene (228). The EPA prepared a generic risk assessment for a landfill without gas control and found the risk to be in the range of 100 to 10,000 cases per million people exposed (228). This is greatly in excess of what is considered the acceptable risk of 1 to 10 cases per million. It should be noted, however, that in evaluating the statistical validity of maximum individual risk (MIR) of cancer from toxics emitted from MSW landfills, EPA concluded that the uncertainties in the data base precluded calculation of cancer risk. EPA is also unable to statistically quantify the noncancer health effects at this time (909).

California has enacted a law that requires landfill operators to conduct testing to characterize the landfill gases emmitted from their site, to detect any off-site underground migration, and to monitor the ambient air adjacent to the site (47). A review of the data from 60 of the sites indicates that toxic and potentially toxic compounds are present at most landfills. Methane appears to pose the most significant hazard. One third of the sites showed gas migration at the perimeter. Very little vinyl chloride was found in the ambient air (47). Wisconsin has also promulgated requirements for the testing of landfill gas (409).

Table F-25 summarizes the results from a landfill gas sampling program in the San Francisco Bay area (47). Sixty landfill sites were tested; included were sites that have been inactive for over twenty years and two which reportedly contained only non-putrescible materials.

TABLE F-25. LANDFILL GAS TEST SUMMARY - SAN FRANCISCO BAY AREA (47)

Compound	LOD (PPB)	NO. of Values > LOD	% of Values > LOD	Range of Values > LOD (PPB)
Vinyl Chloride	500	30	50	690 - 41,000
Benzene	500	32	53	540 - 6,540
Ethylene Dibromide	1	1	2	6
Ethylene Dichloride	20	13	22	23 - 6,000
Dichloromethane	60	31	52	61 - 59,000
Perchloroethylene	10	39	65	21 - 52,000
Carbon Tetrachloride	5	4	7	5 - 2,100
Methylchoroform	10	24	40	13 - 12,000
Trichloroethylene	10	36	60	13 - 11,000
Chloroform	2	14	23	4 - 3,260

LOD = Limit of Detection
PPB = Parts per billion

Recently, some progressive landfill operators and EPA representatives have been investigating the merit of stimulated landfill gas production. By introducing a pressurized gas into landfill wells, the production rate of methane and NMOCs can be increased by 2 to 3 times over normal active collection methods. Such an accelerated method apparently has the advantage of causing reduced emissions later in the life of the landfill (910).

F.5 ENERGY PRODUCTION/REQUIREMENTS

Landfills can produce energy if a gas recovery system is utilized. Total gas production has been estimated at 4.5 cubic feet per pound of MSW (222). In the natural state, the gas has a heat value of 500 Btu per standard cubic foot. Thus, as a minimum, a landfill can be expected to produce 2,250 Btu per pound of MSW. Landfill gas can be upgraded to pipeline quality, with a heat value of 1,000 Btu per standard cubic foot (478).

A typical active gas collection system would be expected to require a relatively small amount of energy to run the blowers and pumps (909). If a flare is selected, auxiliary fuel would not be needed because of the high heat content of landfill gas. From an operations point of view, if a recovery device such as a gas turbine is used, an energy savings would result.

Energy recovery systems applied to MSW landfills have the potential to offset the cost of control (909). All of these systems, however, have capital costs that exceed those for flares, the most commonly used control. Without site-specific studies EPA concluded that they cannot establish the technoeconomic feasibility of energy recovery systems, leaving the selection of appropriate control to landfill operators themselves. As such, "...EPA concluded that it would be inappropriate [for EPA] to further consider these systems [in the proposed rule] in the selection of BDT."

F.6 ADVANTAGES AND DISADVANTAGES OF LANDFILLING

F.6.1 Advantages

Properly sited, designed, and operated landfills offer several advantages over alternative disposal options as indicated below (271).

- Provision of ultimate disposal - Landfills provide a final resting place for waste materials. All other MSW management options produce some residue that must find ultimate disposal in an MSW landfill.

- Protection of public health and the environment - If properly engineered and constructed, a landfill can control and contain emissions, and minimize adverse impacts on the environment. Federal regulations to control liquid wastes and air emissions from MSW landfills are designed to help States achieve that goal.

- o Recovery of degraded land - Degraded land can be recovered and renovated so that it can serve as a resource for the community (e.g., ski hill, golf course, park)

- o Aesthetic acceptability - A properly constructed landfill should be aesthetically acceptable to the community.

F.6.2 Disadvantages

Landfills have three inherent potential problem areas (48):

- o Ground water contamination from leachate

- o Methane gas migration to form explosive pockets

- o Landfill gas emissions

These three potential problems can be minimized through the installation of a leachate collection system, a liner system, a cap system, and a gas recovery system that meet current and proposed regulations (808, 809). However, the vast majority of the active and inactive landfills in the United States are uncontrolled in that they do not have leachate or air emissions systems (173).

Landfills also have negative social impacts (585):

- o Traffic will be increased in the vicinity of the landfill

- o Air pollution will occur from vehicle exhaust and fugitive dust

- o Nothing substantive can be constructed on the site for up to 50 years. The presence of landfill gas and the chemically aggressive nature of the landfill material can prevent the construction of buildings on the landfill. The site itself will settle for 10 to 20 years or more resulting in a 20 to 30 percent height reduction.

- o Surrounding property values will be decreased by the presence of a landfill.

F.7 SUMMARY/CONCLUSION

Landfilling will always be a key component in any solid waste management plan, either as the primary disposal option, or as the recipient of residue or reject materials from other processes. Because the number of landfill closings far exceeds the number of openings each year, the trend appears to be toward large regional landfills (306).

The cost of landfill development will increase in response to current and proposed Federal regulations and with the implementation of more stringent State regulations. Tipping fees will also rise accordingly. Landfilling should remain competitive, as the economics of scale can work in favor of large landfills by spreading fixed costs across a larger number of users. Depending on the relative costs of other available disposal options, there may be an incentive for users to pay more for transportation and less for disposal fees.

Presently, landfill gas recovery systems cannot compete with other energy sources on a life cycle economic basis. However, proposed regulations concerning landfill gas emissions will force the installation of a gas recovery system in many cases, making the economic viability a moot issue. The economies of scale at large regional landfills will help ease certain fixed cost increments that may be associated with smaller landfill gas recovery systems.

Although the benefits of shredfills and balefills have been proven, the economics have not. Both are technically viable options to direct landfilling. Other solid waste management approaches that have received attention are landfill reclamation and accelerated or stimulated landfill gas production.

Because of environmental pollution problems resulting from pre-sanitary landfill dumps, any landfill development project is likely to receive substantial opposition from the public. Improved Federal and State MSW landfill regulations will help to allay the public's inherent fear of landfills by requiring systems to minimize the effect the landfill will have on the environment.

APPENDIX F. LANDFILLS
REFERENCES

046 Cobb, C.E. and K. Ruckstuhl, "Mining and Reclaiming Existing Sanitary Landfills," Proceedings of ASME National Waste Processing Conference, Philadelphia, PA, May 1988, pp. 145-151.

047 Siu, W., D.A. Levaggi and T.F. Brennan, "Solid Waste Assessment Test Results from Landfills in the San Francisco Bay Area," Air & Waste Management Association 82nd Annual Meeting. Anaheim, CA, June 1989.

048 Wallgren, D.A., "Modern Landfill Technology: The Cornerstone of an Integrated Solid Waste Management Program," Integrated Solid Waste Management, Options for Legislative Action. F. Kreith, ed, Genium Publishing, Schenectady, NY, 1990.

123 Taylor, F.X., "PVC Geomembrane Liners and MSW Leachate," Waste Age, April 1991, pp. 51-54.

124 "Putting the Squeeze on Landfills," Waste Age, April 1991, pp. 58-62.

126 O'Leary, P. and P. Walsh, "Lesson 2, the Landfill Course: Landfilling Principles," Waste Age, April 1991, pp. 109-114.

140 Willumsen, H., "Landfill Gas," Resources, Conservation and Recycling 4, 1990, pp. 121-133.

161 Steele, C. "Methane Gas is Rising in Power," Consulting-Specifying Engineer, September 1987, pp. 96-100.

166 Chilton, J. and K. Chilton, "Municipal Landfill Risks: How Real are They?" Source unknown.

167 Alter, H., Statement of the U.S. Chamber of Commerce on Solid Waste Disposal Act Amendments (H.R. 3735, 3736). January 1990.

173 Wollschlager, M.L. and A.R. Oestmann, "Environmental Issues Common to Multiple Solid Waste Management Methods," Proceedings of ASME National Waste Processing Conference, Long Beach, CA, June 1990, pp. 85-93.

222 Maxwell, G., "Will Gas-to-Energy Work at Your Landfill?" Solid Waste & Power, June 1990, pp. 44-50.

228 Minott, D.H., "Choosing Between Resource Recovery Facilities and Landfills," Solid Waste & Power, April 1989, pp. 18-24.

232 Flanagan, K., "Methane Recovery Does More Than Provide Energy," Solid Waste & Power, Aug 1988, pp. 30-33.

239 Schaper, L.T., "Options for Modern Solid Waste Planning," Solid Waste & Power, August 1990, pp. 20-29.

271 Robinson, W.D., ed., The Solid Waste Handbook, A Practical Guide, John Wiley & Sons, Inc., 1986.

290 deBaere, L., P. van Meenen et al, "Anaerobic Fermentation of Refuse," Resources and Conservation, Special Issue: Materials and Energy from Refuse, vol 14, 1987.

306 Buell, D., K. Dietly et al, "Economic Incentives and Trends for Regionalization of Municipal Solid Waste Landfills," Proc., First U.S. Conference on Municipal Solid Waste Management: Solutions for the 90s, Vol I. Washington, DC, sponsored by U.S. EPA Office of Solid Waste, June 1990.

323 Pohland, F.G., "Controlled Landfills: A Systematic Approach to Solid Waste Disposal," Proc.,First U.S. Conference on Municipal Solid Waste Management: Solutions for the 90s, Vol I. Washington, DC, U.S. EPA Office of Solid Waste, June 1990.

372 Congress of the United States Office of Technology Assessment, "Facing America's Trash: What Next for Municipal Solid Waste?" Reprinted in Integrated Solid Waste Management: Options for Legislative Action. F. Kreith, ed., Genium Publishing Corp, Schenectady, NY, 1990.

384 Cadwallader, M., "Landfill Liner Systems Keep Waste from Water," American City & County, May 1988, p. 46.

389 Berenyi, E., "Landfill Gas Has a Future!" Waste Age. Aug 1989, pp. 173-176. August 1989, pp. 173-176.

391 Meade, K., "Age of the Mega-Fill," Waste Age, December 1989, pp. 43-44.

397 Glebs, R.T., "Landfill Costs Continue to Rise," Waste Age, March 1988, p. 84.

409 Zack, M. and D.H. Minott, "New Federal Controls on Landfill Gas Emissions and Economics of Landfill Gas Recovery." Energy from Biomass and Wastes XIII, D.L. Klass, ed., Institute of Gas Technology, Chicago, IL, 1990, pp. 1119-1144.

411 Wolfe, B. and G. Maxwell, "Commercial Landfill Gas Recovery Operations. Technology and Economics," Energy from Biomass and Wastes XIII, D.L. Klass, ed., Institute of Gas Technology, Chicago, IL, 1990, pp. 1251-1262.

415 Zimmerman, R.E. amd R. Isaacson, "Toxic and Non-Toxic Components in MSW Landfill Gases," Energy from Biomass and Wastes XII, D.L. Klass, ed., Institute of Gas Technology, Chicago, IL, 1989, pp. 503-516.

457 Parson, P.J. and A.J. Smith, "The Environmental Impact of Landfill Gas," Proc: Energy From Landfill Gas. Conference jointly sponsored by UK DEN and US DOE. W.Midlands, UK. October 1986, pp. 17-21.

462 Toth, L., T. Cortopassi and T. Williams, "State-of-the-Art in Landfill Gas Power Conversion," Proc: Energy from Landfill Gas. Conference jointly sponsored by UK DOE and US DOE. W.Midlands, UK. October 1986, pp. 458-469.

465 Texas A & M Univ., Role of Landfill Disposal in Municipal Solid Waste Management. Prepared for U.S. EPA, June 1989.

478 Bogner, J.E., The U.S. Landfill Gas Resource: Low-Cost Biogas from Municipal Solid Waste, Argonne National Laboratory ANL/CNSV-TM-206, January 1988.

507 Eldredge Engineering Associates, Inc., Municipal Solid Waste Landfills, Vol. 1, General Issues. Nov 1989.

584 Morelli, J., "Municipal Solid Waste Landfills: Optimization, Integration and Reclamation," NYSERDA, 1989.

585 Pas, E.I., P.A. Vesilind and S. Hirshfeld, "Assessing the True Cost of Landfills," 1987.

586 Eldredge Engineering Associates, Inc., Municipal Solid Waste Landfills: Vol II Technical Issues, May 1990.

587 National Solid Wastes Management Association, Technical Data Report 1: Landfill Costing Data, June 1990.

594 Fletcher, P., "Landfill Gas Extraction - Vertical Wells or Horizontal Trenches?" Proceedings of the IMechE Conference: Engineering for Profit from Waste, Coventry, UK, March 1988.

595 Moss, H.D.T., "Landfill Gas Abstraction and Commercial Use," Proceedings of the IMechE Conference: Engineering for Profit from Waste, Coventry, UK, March 1988.

659 Smith, B.D., G.D. Cox and R.A. Quick, "Technical Issues in the Siting and Design of Municipal Solid Waste Landfill in the 90's," Proceedings of Sixth International Conference on Solid Waste Management and Secondary Materials, Philadelphia, PA, December 1990.

662 Jones, D.R., "To Shred, or Not To Shred?" Waste Age, June 1988, 4 p.

665 Vasuki, N.C., "Why Not Recycle the Landfill!" Waste Age, November 1988, 4 p.

667 Glenn, J. and D. Riggle, "Nationwide Survey: The State of Garbage," BioCycle, April 1991, pp. 34-38.

678 "EPA Proposed Air Emissions Standards for Municipal Solid Waste Landfills," Solid Waste Report, 20 May 1991.

679 "Environmental Groups Sue EPA Over Subtitle D Rule Delays," Solid Waste Report, 28 May 1991.

684 Glebs, R.T., "Subtitle D: How Will it Affect Landfills?" Waste Alternatives/Landfill of the 90s, National Solid Wastes Management Association, December 1988, 8 p.

688 U.S. Environmental Protection Agency, Municipal Solid Waste Landfill Survey, Washington, DC, 1986. As Cited In: Glebs, R.T., "Landfill Costs Continue to Rise," Waste Age, March 1988, p. 84.

689 U.S. Environmental Protection Agency, Criteria for Municipal Solid Waste Landfills, Subtitle D of the Resource Conservation and Recovery Act, Regulatory Impact Analysis of Proposed..., Washington, DC, National Technical Information Service, PB88-24251 1988. As Cited In: Texas A & M Univ., Role of Landfill Disposal in Municipal Solid Waste Management. Prepared for U.S. EPA, June 1989.

690 U.S. Environmental Protection Agency, Lining of Waste Impoundment and Disposal Facilities, Matrecon, Oakland, California, SW-870, Washington, DC, September 1980. As Cited In: Robinson, W.D., ed., The Solid Waste Handbook, A Practical Guide, John Wiley & Sons, Inc., 1986.

691 Daniels, P. E., and Brown, K. W., "Landfill Liners: How Well Do They Work and What is Their Future," presented at a Workshop on Engineering and the Natural Environment of Hazardous Landfills, University of Cambridge, U.K. 9-11 Sep 1987. As Cited In: Robinson, W.D., ed., The Solid Waste Handbook, A Practical Guide, John Wiley & Sons, Inc., 1986.

692 Ham, R. K., "Decomposition of Residential and Light Commercial Solid Waste in Test Lysimeters," U.S. Environmental Protection Agency (SW-190c) Washington, DC, August 1978. As Cited In: Robinson, W.D., ed., The Solid Waste Handbook, A Practical Guide, John Wiley & Sons, Inc., 1986.

693 Clark, T. P. and R. Piskin, "Chemical Quality of and Indicator Parameters for Monitoring Landfill Leachate in Illinois," Illinois Environmental Protection Agency, Joliet, IL, May 1976. As Cited In: Robinson, W.D., ed., The Solid Waste Handbook, A Practical Guide, John Wiley & Sons, Inc., 1986.

694 Chian, E. S. and F. DeWalle, "Evaluation of Leachate Treatment," U.S. Environmental Protection Agency EPA-600/2-77-186a, 1977. As Cited In: Robinson, W.D., ed., The Solid Waste Handbook, A Practical Guide, John Wiley & Sons, Inc., 1986.

695 Uloth, R., and Mavinic, J. S., "EPA Procedures Manual for Groundwater Monitoring at Solid Waste Disposal Facilities," U.S. Environmental Protection Agency EPA/530/sw-611, August 1977. As Cited In: Robinson, W.D., ed., The Solid Waste Handbook, A Practical Guide, John Wiley & Sons, Inc., 1986.

696 Myers, T. E., "Chemically Stabilized Industrial Wastes in a Sanitary Landfill Environment," in Disposal of Hazardous Waste, Proceedings of the Sixth Annual Research symposium, EPA-600/9-80-010, March 1980, pp. 223-241. As Cited In: Robinson, W.D., ed., The Solid Waste Handbook, A Practical Guide, John Wiley & Sons, Inc., 1986.

697 James, S. C., "Metals in Municipal Landfill Leachate and Their Health Effects," American Journal of Public Health, 67, 1977, pp. 429-432. As Cited In: Robinson, W.D., ed., The Solid Waste Handbook, A Practical Guide, John Wiley & Sons, Inc., 1986.

698 U.S. Environmental Protection Agency, "Report to Congress on Solid Waste Disposal in the United States," EPA/530-SW-88-011B, Chapter 4, Washington, DC, 1988. As Cited In: Pohland, F.G., "Controlled Landfills: A Systematic Approach to Solid Waste Disposal," Proc.,First U.S. Conference on Municipal Solid Waste Management: Solutions for the 90s, Vol I. Washington, DC, U.S. EPA Office of Solid Waste, June 1990.

699 Robinson, H. D. and Maris, "Leachate From Domestic Waste: Generation, Composition, and Treatment: A Review," Technical Report TR 108, Stevenage, Herts., Water Research Centre, Stevenage Laboratory, March 1979. As Cited In: Robinson, W.D., ed., The Solid Waste Handbook, A Practical Guide, John Wiley & Sons, Inc., 1986.

701 U.S. Envrionmental Protection Agency, "Preliminary Draft EIS: Air Emissions From Municipal Solid Waste Landfills Background Information for Proposed Standards and Guidelines," Research Triangle Park, NC, March 1988. As Cited In: Zack, M. and D.H. Minott, "New Federal Controls on Landfill Gas Emissions and Economics of Landfill Gas Recovery." Energy from Biomass and Wastes XIII, D.L. Klass, ed., Institute of Gas Technology, Chicago, IL, 1990, pp. 1119-1144.

702 Lofy, R., "Gas Venting/Control Techniques and Facility Design," presented at University of Wisconsin Extension Seminar, Sanitary Landfill Gas and Leachate Management, December 1984. As Cited In: Robinson, W.D., ed., The Solid Waste Handbook, A Practical Guide, John Wiley & Sons, Inc., 1986.

705 Glebs, R. T., "Determining Closure and Post-Closure Costs," presented at Waste Expo 1989, Chicago, Illinois, 2 May 1989. As Cited In: National Solid Wastes Management Association, Technical Data Report 1: Landfill Costing Data, June 1990.

706 SCS Engineers, "Sanitary Landfill Costs in Michigan," for presentation to Special House Democratic Task Force on Solid Waste Disposal, 4 Dec 1989. As Cited In: National Solid Wastes Management Association, Technical Data Report 1: Landfill Costing Data, June 1990.

707 SCS Engineers, "Sanitary Landfill Costs in Kentucky," for presentation to Natural Resources Cabinet on Solid Waste Regulations and Environmental Quality Commission, 22 Feb 1990. As Cited In: National Solid Wastes Management Association, Technical Data Report 1: Landfill Costing Data, June 1990.

708 Reinhardt, J. J. and Ham, R. K., "Final Report on a Milling Project at Madison, Wisconsin, Between 1966 and 1972," Vol. I, Washington, D.C., U.S. Environmental Protection Agency, March 1973. As Cited In: Robinson, W.D., ed., The Solid Waste Handbook, A Practical Guide, John Wiley & Sons, Inc., 1986.

709 Stone, R., "Balefill Costs More Initially, But Can Pay Off in Public Acceptance, Lower Operating Dollars," Solid Waste Systems, Mar/Apr 1977 pp. 16-18. As Cited In: Robinson, W.D., ed., The Solid Waste Handbook, A Practical Guide, John Wiley & Sons, Inc., 1986.

710 Pioli, D. M., and Hartsock, D. R., "An Orderly Approach to landfill Gas Systems Development," Waste Age, July 1991, pp. 95-98.

717 Will County, IL, Will County Solid Waste Management Plan, Vol VI - Landfill/Ashfill. January 1991.

719 Illinois Department of Energy and Natural Resources, Economic Impact Study of Landfill Regulations (1288-7), November 1989.

908 U.S. Environmental Protection Agency, Criteria for Municipal Solid Waste Landfills; Final Rule. Federal Register, 40 CFR Part 258. 9 October 1991.

909 U.S. Environmental Protection Agency, Standards of Performance for New Stationary Sources and Guidelines for Control of Existing Sources: Municipal Solid Waste Landfills; Proposed Rule, Guideline and Notice of Public Hearing, Federal Register, 40 CFR Parts 51, 52 and 60. 30 May 1991.

910 Thorneloe, S., Status of U.S. Research on Landfill Gas Production, in: Landfill Gas Enhancement Test Cell Data. Final Report of the Landfill Gas Expert Working Group; T.S. Larson, D.J. Campbell, A. Lagerkvist and J.E. Meijer. International Energy Agency Report AEA-EE-0286. 1991.

Document Control Page	1. NREL Report No.	2. NTIS Accession No.	3. Recipient's Accession No.
	NREL/TP-431-4988H	DE92016433	

4. Title and Subtitle

Data Summary of Municipal Solid Waste Management Alternatives. Volume VIII: Appendix F—Landfills

5. Publication Date
October 1992

6.

7. Author(s)
SRI International

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

SRI International
333 Ravenswood Ave.
Menlo Park, CA 94025-3493

10. Project/Task/Work Unit No.
WM21.1010

11. Contract (C) or Grant (G) No.

(C) RF-1-11003

(G)

12. Sponsoring Organization Name and Address

National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401

13. Type of Report & Period Covered
Subcontract Report

14.

15. Supplementary Notes
NREL Technical Monitor: Bimleshwar Gupta and Philip Shepherd (303) 231-1760

16. Abstract (Limit: 200 words)

The overall objective of the study in this report was to gather data on waste management technologies to allow comparison of various alternatives for managing municipal solid waste (MSW). The specific objectives of the study were to:

1. Compile detailed data for existing waste management technologies on costs, environmental releases, energy requirements and production, and coproducts such as recycled materials and compost.
2. Identify missing information necessary to make energy, economic, and environmental comparisons of various MSW management technologies, and define needed research that could enhance the usefulness of the technology.
3. Develop a data base that can be used to identify the technology that best meets specific criteria defined by a user of the data base.

Volume I contains the report text. Volume II contains supporting exhibits. Volumes III through X are appendices, each addressing a specific MSW management technology. Volumes XI and XII contain project bibliographies.

17. Document Analysis

a. Descriptors
municipal waste; waste to energy; resource recovery; recycling

b. Identifiers/Open-Ended Terms

c. UC Categories
249

18. Availability Statement
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

19. No. of Pages
76

20. Price
A05

Form No. 0069E (6-30-87)