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Research and Development

GUIDANCE FOR LANDFILLING WASTE IN ECONOMICALLY DEVELOPING COUNTRIES

FOREWORD

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Final Report

Guidance for Landfilling Waste in Economically Developing Countries

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Abstract

This report offers guidance on all aspects of the planning and implementation of landfills in economically developing areas. The intended audience includes municipal officials, as well as solid waste managers, engineers, and planners.

Covered within the 18 chapters of the report is guidance on the siting, design, and operation of landfills. Equally important, the social, economic, and institutional topics relevant to developing landfills in economically developing areas are also discussed.

The guiding principle of the report is the application of good landfill practices within the conditions and availability of resources prevailing in large urban cities and in small communities in economically developing areas. The guidance also considers a common occurrence in economically developing areas, namely that solid wastes and hazardous wastes are disposed of together on the land.

While the preparation of the report was funded by the U.S. Environmental Protection Agency (EPA), the content does not represent EPA regulations and policies. The guidance reflects the opinions of the authors, based in part on their experience, on modern landfill practice in the United States, and on contributions made by the Working Group on Sanitary Landfilling organized within the International Solid Waste Association.

Preface

The preparation of the draft landfill guidance document was brought about through the cooperation of a number of organizations and individuals. The basis of the document was one prepared several years ago by CalRecovery, Inc., under contract to The World Bank. The current document contains substantial modifications to chapters of the former document, includes coverage of additional topics, and reflects the content of course materials used by the International Solid Waste Association's (ISWA's) Working Group on Sanitary Landfilling (WGSL) during the conduct of courses from 1993 to 1996 in economically developing countries, on the topic, Landfilling of Wastes. To date, the guidance document has been an evolving document, benefiting from modifications of content based on the results of the courses given.

Funding for the preparation of the guidance document was provided through the Environmental Technology Initiative and administered by the U.S. Environmental Protection Agency (EPA), as part of its U.S. Technology for International Environmental Solutions (U.S. TIES). U.S. TIES is an innovative EPA program designed to promote the application of U.S. technology in solving environmental problems worldwide. Additionally, in-kind services were provided by members of ISWA's WGSL and CalRecovery, Inc.

Individual members of the WGSL who contributed material to the guidance document in the form of lecture and class notes include: Dik Beker, The Netherlands; Geoffrey Blight, South Africa; Luis F. Diaz, United States; Derek R. Greedy, United Kingdom; Robert K. Ham, United States; Anders Lagerkvist, Sweden; Rainer Stegmann, Germany; N.C. Vasuki, United States; and Isabelle Paris, France.

The draft document has been peer-reviewed by members of the WGSL (Robert Ham, chairman; David J.V. Campbelll; Isabelle Paris; and Rainer Stegmann). Additionally, review has been conducted by Susan A. Thorneloe, Allen J. Geswein, Paul F. Cassidy, and David A.

Carson, U.S. EPA; Lars M. Johannessen and Carl R. Bartone, The World Bank; and Forbes R. McDougall, Procter & Gamble.

While the preparation of the document was funded by the U.S. EPA, the content is not meant to and does not represent the EPA's regulations and policies. The content reflects the authors' analyses and judgements concerning appropriate methods, procedures, and topics relevant to land disposal of solid wastes in economically developing countries. The conditions relevant to solid waste management in economically developing countries are substantially different than those of industrialized countries.

CalRecovery, Inc. performed the majority of the preparation of the guidance document, under subcontract to Roy F. Weston, Inc. (Weston). Weston contributed to the preparation of portions of the document, including topics related to design, operation, and environmental monitoring.

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Chapter 1
Introduction

1.1 Background

The management of solid waste in a manner that protects the public health and the environment is a difficult task that requires substantial knowledge and experience. With regard to the design and operation of landfills, many issues must be considered and resolved, and the process requires the efforts of many professional disciplines. The intent of this guidance document is that it provide a resource for designing and operating landfills that will protect the public health and the environment, while accommodating the social, cultural, and financial conditions that exist in economically developing countries.

In many economically developing countries, limitations of technical and financial resources adversely influence the ability to effectively and safely manage solid wastes. The results of the limitations of resources on the ability to manage wastes usually include inadequate provisions for storage at the point of generation, inefficient and deficient collection, and unsatisfactory final disposition. The rapid growth of the population and economy in many economically developing countries, combined with the lack of training in modern solid waste management practices, further complicates efforts to improve solid waste services. Some substantial improvements in waste management systems in economically developing countries are being planned, or actually have been made, in the storage and collection of the wastes. On the other hand, improvements in disposal practices are very limited in extent.

Final disposal of urban wastes in many locations of the economically developing world usually is a matter of transporting the collected wastes to the nearest available open space and then discharging them (generally, no differentiation or distinction exists between the dumping and commingling of municipal solid waste and hazardous wastes in a particular location, as is the practice in some industrialized countries). The only attention given the dumped wastes comes from scavengers reclaiming items deemed useful, and from birds and animals in search of food. In some instances, the wastes are purposely set on fire in order to reduce their volume and to minimize the attraction of animals and vermin. These poor means of management lead to many problems, including pollution of surface and groundwaters, migration of combustible gas from the site, litter, odors, and breeding of disease carriers. Photographs showing typical disposal sites in economically developing countries are given in Figure 1-1.

In recent years, recycling, composting, and incineration projects have been proposed as methods of minimizing the use of land disposal of wastes. These alternatives have been implemented in many industrialized countries on a substantial scale within the past 5 to 10 years for the purpose of reducing dependency on land disposal. However, even practices that take advantage of material and energy recovery generate residues that must be disposed on the land. A promising and appropriate approach, which currently is gaining popularity in economically developing countries, is to landfill the wastes with the goal of eventually improving the practice to a point at which it would merit the designation of a "modern sanitary landfill." Sanitary landfilling (controlled disposal of waste on the land), especially if integrated with some type of material recovery, is well suited to economically developing nations because of the flexibility, relative simplicity, and cost of this method of final waste disposal. Additionally, in many economically developing countries, the solid waste has a high moisture content and is readily biodegradable; consequently, landfilling is an appropriate method of stabilizing the waste. The readily degradable nature of the waste and the use of modern landfill practice can also combine to provide potential benefits to the community in terms of improving marginal land to higher forms of land use and in terms of conducting sustainable landfill operations, i.e., reuse of the same volume occupied by waste placed in the fill earlier in its lifetime.

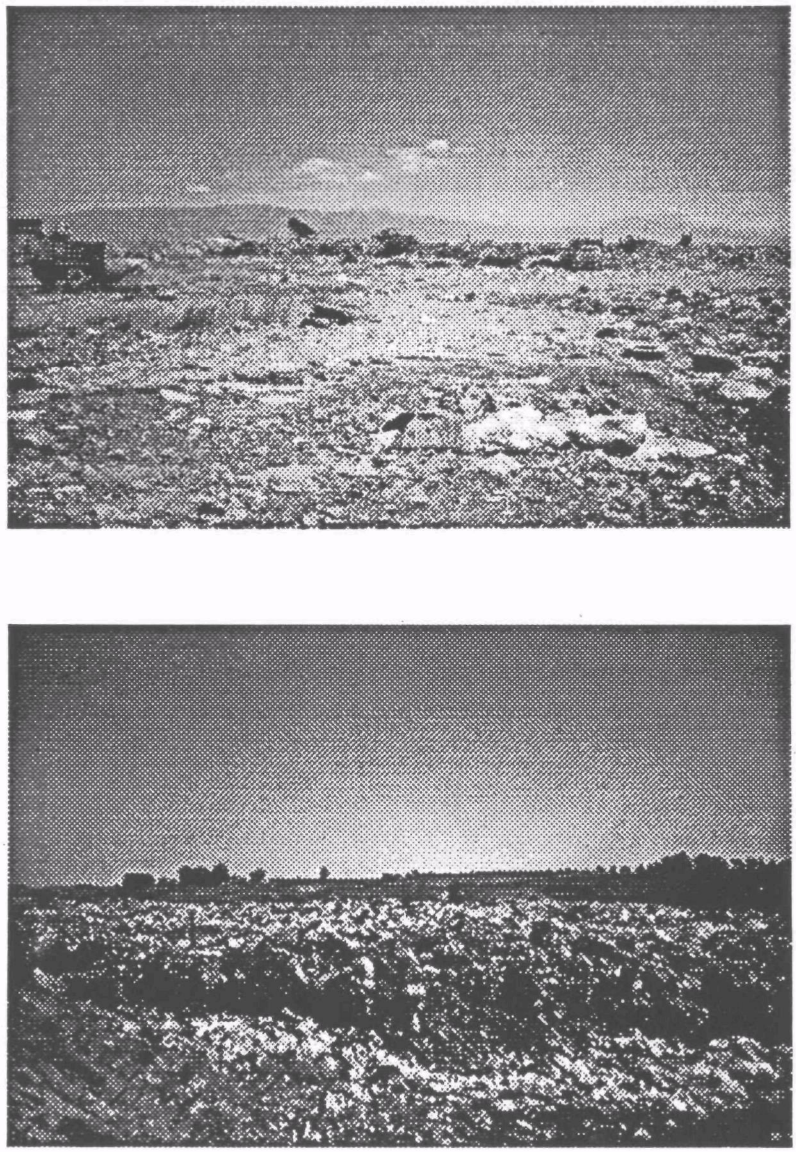

Figure 1-1. Examples of Solid Waste Disposal Sites in Economically Developing Countries

1.2 Need for Guidance

At present, the adoption and practice of landfilling in many municipalities in economically developing countries are impeded by the lack of reliable and practical information such as that compiled in a good guidance document specific to developing countries. This guidance makes every effort to fulfill this need by including, under one cover, explanations and descriptions of technologies and procedures proven appropriate in practice. Within the document are summary explanations of underlying principles, as well as clear and concise guidance for putting the technologies into practice.

Currently, the few available documents on landfilling in many economically developing countries are based on technologies and practices suited only to conditions in, and to the requirements of, industrialized nations. However, technologies and practices suited to industrialized nations rarely can be successfully transferred to developing nations without having been adapted to local conditions. This guidance document presents methods for planning and implementing landfills. The methods that are discussed span the spectrum of landfill practice from complex, engineered systems designed for virtually complete control and containment of impacts to human health and safety, to less complex systems that can be afforded particularly by small communities in economically developing countries while promoting acceptable control of the impacts of land disposal of wastes.

The document presents suggestions for review and evaluation, often based upon best engineering judgement. The guidance is intended to be of sufficient breadth and generality to cover the wide range of conditions (technical, regulatory, social, economic, institutional, and others) that exist in economically developing countries, and not necessarily to provide rigid rules to be applied in all circumstances. The document will assist the users in arriving at decisions in a logical, well-defined, and well-documented manner. Comprehensive and detailed engineering design and analysis are used only in those cases where they are the only manner of conveying an important concept. Specific descriptions, tables, sketches, and drawings are used liberally in order to convey important concepts to the reader. References are cited in most chapters of the document should the reader wish to further explore a particular subject. The references have been selected while keeping in mind their accessibility to the readers. In addition, a listing of other pertinent publications is included at the end of the document, in Appendix A.

1.3 Objective

The primary objective of this guidance document is to provide those responsible for solid waste management with the basic tools for the development, implementation, and monitoring of a landfill. Secondary objectives are to provide the information necessary to make intelligent decisions on the degree of complexity of a particular landfill design, as well as its advantages and disadvantages, and to provide the steps required to upgrade an open dump (uncontrolled disposal of wastes on land) to a sanitary landfill. The information presented in the guidance document recognizes the limited capital and other resources in economically developing countries, and the impact that the limitations have on the ability of a country or community to plan and implement a sanitary landfill.

1.4 Scope of the Guidance

The guidance document discusses the principal aspects of planning, constructing, and operating a landfill. The emphasis is placed on conditions, technologies, and practices that exist in economically developing countries. However, the coverage is sufficiently broad to accommodate the levels of industrialization found in the metropolitan areas of economically developing countries. The range of conditions covered in this guidance will provide for minimum acceptable disposal standards. As urban income grows and cities urbanize, operational capacity and budgets of sanitation departments may increase sufficiently to permit the imposition of more stringent design and operating standards on waste disposal.

Typically, in developing countries, solid waste includes types of wastes that are normally considered separately as "municipal solid waste" and "hazardous waste" in industrialized countries. Both of these types of solid wastes are almost universally disposed at the same location in economically developing countries. Also, in economically developing countries, liquid wastes and sludges are also disposed, in many instances, at locations where solid wastes are disposed. Thus, the guidance document recognizes this fact and addresses these types of wastes, as well as municipal solid waste. However, the emphasis of the guidance offered herein is directed primarily toward municipal solid waste and disposal facilities designed to accommodate that type of waste (i.e., landfills).

The guidance document begins with a description of the fundamentals (definitions, principles) of landfilling and subsequently examines all of the aspects of the practice -- from planning to implementation.

This document is written primarily for engineers, planners, and operating staff. However, it is also of utility to management and high-level public officials for the purposes of planning and budgeting. Municipal officials, by virtue of a review of this document, can gain an awareness of the issues and complexities of landfilling and the importance of these facilities to managing solid waste in a manner that protects the public and the environment.

The guidance document has been prepared such that the design and operation of the disposal site can be improved as additional capital and technical resources become available. In addition, the document presents guidance applicable to a large number of small communities throughout the world. The document describes the design and operation of very small landfills, as well as the methodology for upgrading an open dump to a landfill.

Chapter 2

Sanitary Landfill Fundamentals

2.1 Introduction

The development of the modern sanitary landfill has occurred in response to the shortcomings of the open dump as a method of land disposal of wastes. The shortcomings include adverse impacts to both the environment and to human health and safety. Numbered among the advantages of sanitary landfilling as a method of land disposal over open dumping are the provision of a barrier between the environment and the wastes, management and control of gaseous emissions from the decomposition of the wastes, and collection and treatment of leachate. Additionally, modern sanitary landfill practice includes returning the completed disposal site to a similar environmental setting and acceptable and compatible land use, which in many situations can benefit the community. Waste disposal by the methods and procedures of sanitary landfilling achieves the following: 1) contact between solid wastes and the environment outside of the landfill boundary is minimized, 2) access to the wastes by vectors (disease carriers) and rodents is substantially prevented, and 3) the wastes are concentrated and contained within a well-defined space. Consequently, not only are the wastes contained, but their impacts on human health and safety and on environmental quality are managed and controlled.

The quantities and characteristics of the wastes that are to be disposed are two of the more important factors that influence the design and operation of a sanitary landfill. As an example, for a given landfill capacity and set of operating conditions, the rate of disposal of wastes determines the active lifetime of the landfill. Also, the existence or future implementation of waste recycling programs influences the quantities of wastes that ultimately will require disposal. Thus, an analysis of a landfill project requires that the existing and future rates of recycling be considered during the analysis. Given that one of the first items of consideration in the design of a landfill is the rate of disposal, the following subsection discusses solid waste and the factors that influence the quantities that will be produced for disposal (i.e., disposed waste).

2.2 Generated, Diverted, and Disposed Wastes and Their Characteristics

The quantities of solid wastes that will require disposal are those that remain after any diversion of materials from disposal has occurred (e.g., after any recycling, composting of them). Diversion of materials can occur at various places and times within the solid waste management system after the wastes have been generated and placed out for collection. As used in this document, generated wastes are those that are produced at the source of generation and are subsequently set out for collection. Generated wastes exclude any wastes that are processed in an environmentally acceptable manner within the generator's property. There are a variety of sources of generation. Commonly, the main types of generators are referred to as residential, commercial, institutional, and industrial. In addition, there are several subtypes of major sources. For example, multi-family dwellers are a subtype of residential generators, and markets are a subtype of commercial generators. Since industrialized countries have almost 100% collection coverage, the quantities of wastes that are collected are almost equal to those generated. On the other hand, in economically developing countries, due to a variety of reasons, the quantities of waste collected generally are substantially less than those that are generated. This situation must be considered when planning a collection and disposal system. Trends in growth of population and of commerce must also be taken into account when determining waste generation over a planning period.

After the wastes are collected, they can be disposed or recycled. Thus, generated wastes equal the sum of disposed wastes and recycled wastes (or secondary materials). The process of landfilling, by definition, involves only wastes that are directed to final disposal, i.e., disposed wastes.

Additional discussion of diversion of waste from landfill disposal and the impacts of diversion on disposed waste characteristics is provided in Chapter 5.

2.3 Waste Collection from Marginal Areas

Marginal areas are those that encompass populations that lack basic sanitation services and exist outside of governmental control. The populations of marginal areas are sometimes substantial in comparison to the formal community. Regardless of their size, the populations of marginal areas are centers of waste generation and, if their wastes are to be collected and disposed, the quantities must be taken into account during the planning of a waste management system.

2.4 Waste Disposal Sites

Two general types of waste disposal sites are the subject of this document: landfills and open dumps. The majority of the document addresses landfill practice. However, references to open dumps are made throughout the document and a portion of the document describes corrective measures for situations involving open dumps. A landfill is differentiated from an open dump in that the landfill is an engineered design, consisting of a variety of systems for controlling the impact of land disposal on human health and safety and on the environment. An open dump is an uncontrolled system and has not been the subject of an engineering design.

For the purpose of this document, a waste disposal site is generally defined to consist of that portion of the site wherein wastes are buried, as well as any surrounding property within the boundary of the site. The surrounding property may serve as a buffer, support landfill-related operations and facilities (e.g., maintenance) or unrelated activities (e.g., recycling depots), or contain access routes and roadways.

2.5 Principles of Landfilling

Accepted definitions of a modern landfill are based on the concept of isolating the landfilled wastes from the environment until the wastes are stabilized and rendered innocuous as much as possible through the biological, chemical, and physical processes of nature. The main differences among definitions of a landfill involve the degree of isolation and the means of accomplishing it. Isolation includes prevention of water from entering the landfill, as well as isolation of discharges directly from the fill to the environment. The rate and extent of decomposition of the wastes are a subcategory of the design concept of isolation. As opposed to the rate and extent of decomposition that occur in a fill that is designed to minimize intrusion of water, certain designs and operating procedures can be used to accelerate the decomposition of the wastes, e.g., recirculation of landfill leachate. The benefits of these designs (termed bioreactor or wet cell designs) include less time to reach biological and chemical stabilization and leachate of lesser strength. Detracting features of these designs include the added complexity of the design and operations compared to landfill designs lacking systems to accelerate decomposition.

In the case of industrialized nations, the degree of isolation considered necessary to protect the environment and human health and safety usually is much more than would be technically and financially practical in many economically developing countries. In the case of many industrialized countries, the high level of containment requires a complex and expensive engineered system.

Emphasis must be placed on the proper use and application of the definition of a modern sanitary landfill because in many developing countries, any final disposal site (either a dump site or a controlled fill) is commonly referred to as a "sanitary landfill." The use of the term leads to confusion and skepticism, particularly among the public, and improper use can and does impede acceptance of improved sanitary conditions and the willingness to devote the financial resources that are required.

In the 1960s and early 1970s, the definition of a sanitary landfill in the United States and other industrialized nations was primarily prescriptive, calling for the engineered landfilling and compaction of wastes, followed by covering the fill with a layer of soil at the end of each working day. During this period of time, the main distinction between a sanitary landfill and an open dump was the daily covering with soil [1,2].

By the closure of the 1970s, the definition of a landfill in the United States was specified in terms of performance requirements: a landfill is a land disposal site at which is employed an engineered method of disposing solid wastes in a manner such that environmental hazards are controlled by spreading the solid wastes in thin layers, compacting the solid wastes to the smallest practical volume, and applying and compacting cover material at the end of each day.

Since then, definitions of sanitary landfilling practice have been further expanded and modified to call for the installation of an impermeable liner, as well as provisions for collecting and treating the leachate, for managing water in and around the fill, and for controlling landfill gases. Despite the expansions, however, all of the definitions include three basic types of practices and requirements:

1. consolidation of wastes into the working face; compaction of the wastes to conserve land resources; design and operation of the fill to control settlement, to optimize the chemical and biological processes (e.g., for landfill gas recovery), or both;

2. covering the wastes with cover material on a daily basis to control the risk of hazards from exposed wastes; and

3. control or prevention of adverse environmental impacts of wastes disposed on land to soil, water, and air resources and of their subsequent impact on public health and safety.

In order to conform to the definition of a modern sanitary landfill, a landfill must meet the above three key conditions regardless of the stage of economic development of the country in which the landfill is located. However, meeting the three conditions may be technologically and economically difficult or impractical in several economically developing countries. Therefore, the short-term, or immediate, goal should be to meet the conditions to the extent possible under existing circumstances. The long-term goal should be to eventually meet all three of the conditions. This approach is recommended since the benefits associated with a modern sanitary landfill are realized only to the extent that a land disposal facility fully meets the three basic conditions. The most important condition is the prevention of negative impacts on the public health and the environment.

A schematic diagram showing the basic conditions and key processes of a sanitary landfill is presented in Figure 2-1. A photograph showing a sanitary landfill is presented in Figure 2-2.

2.6 Methods of Operating a Landfill

The primary methods of landfilling (e.g., area fill, trench fill) are described in the document. Regardless of the type of construction, the proper operation of the land disposal activity is one of the key aspects of modern sanitary landfill practice. Modern sanitary landfills are operated as systems. Consequently, the management, monitoring, and evaluation of the operations are important elements of ensuring safe and environmentally sound practices. Modern sanitary landfills commonly employ heavy equipment and other types of mechanical, hydraulic, and electrical equipment (e.g., pumps, blowers) that require training and skill to operate and maintain in good operating condition.

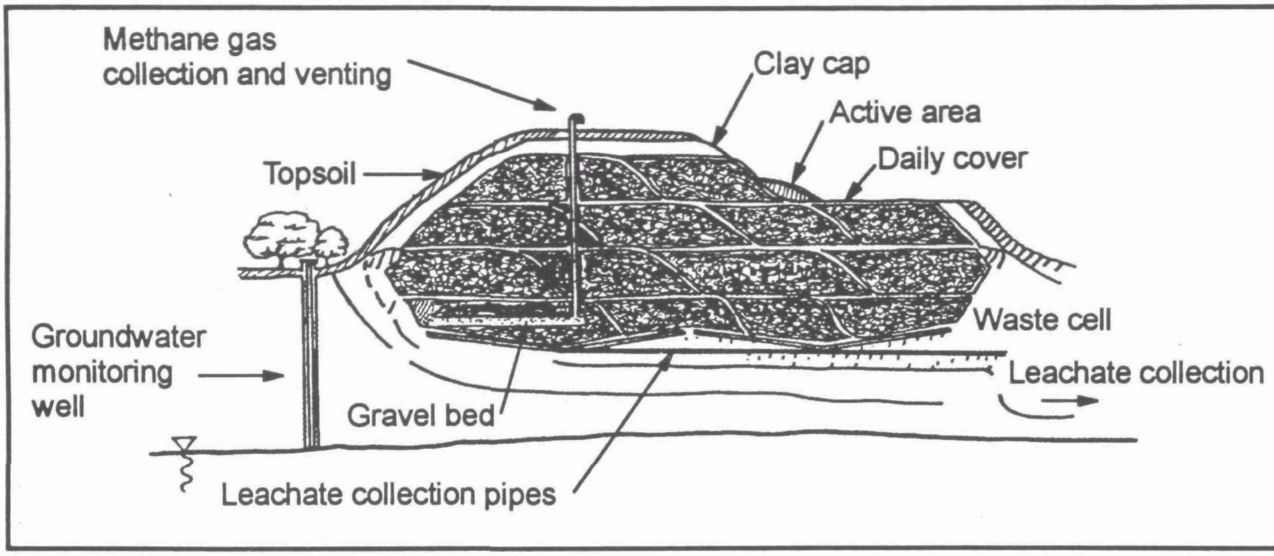

Figure 2-1. Key Aspects of a Sanitary Landfill

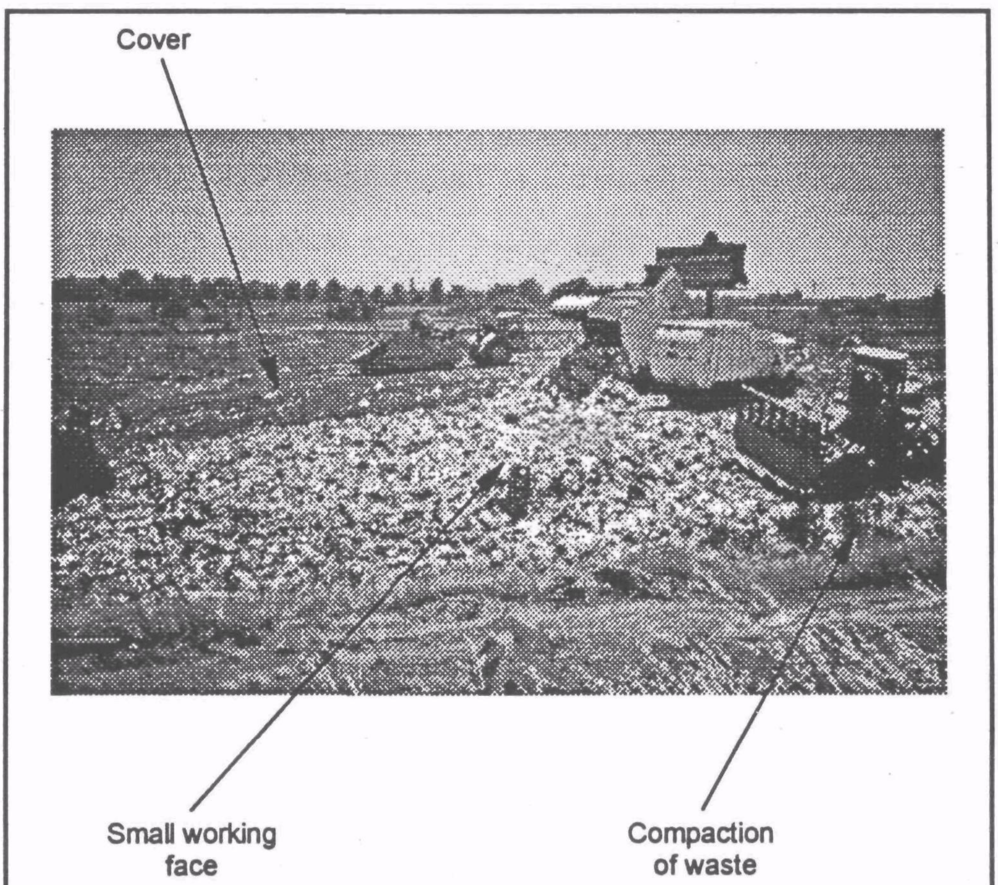

Figure 2-2. An Example of a Modern Landfill

2.7 Closing an Open Dump

Modern landfill practices can be applied to the improvement or closure of an open dump. The prevalence of open dumps in economically developing countries presents the opportunity to apply methods of closing and maintaining land disposal sites that have been developed for modern landfills after their active lives. The methods of engineering presented in the guidance document can be used to analyze and select alternatives for controlling or eliminating the adverse consequences of open dumps on both human health and safety and on the environment. The alternatives include capping the dump or moving the contents of an open dump to a landfill.

2.8 The Role of Scavengers

Two types of scavenging are relevant to the planning, implementation, and operation of land disposal sites in economically developing countries. First, the occurrence of scavenging between the point of waste generation and the disposal location influences the quantities of wastes that will be disposed. Thus, this aspect of scavenging must be taken into account during the process of estimating waste quantities and characteristics.

Second, scavenging is a widespread occurrence at existing land disposal sites in economically developing nations (as opposed to the situation in most industrialized countries) and is to be expected at new disposal sites unless policies and/or programs are implemented to prevent the practice. Since scavengers normally are part of the socioeconomic structure, their displacement from a disposal site can have many direct and indirect consequences. While unsupervised and uncontrolled scavenging is detrimental to the health and safety of the scavengers, as well as personnel operating the facility, the exclusion of scavengers from disposal sites is not necessary if their activities are managed and controlled. The document describes the impact of scavenging on disposal operations and methods of properly incorporating scavengers into the overall method of managing waste disposal.

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2. *Sanitary Landfill Planning, Design, and Operation*, Div. General Engineering and Radiological Health, New York State Dept. of Health, Albany, New York, 1968.

Chapter 3

Status of Landfill Legislation

3.1 Introduction

A solid waste management strategy cannot be implemented without the support and guidance of a legislative framework. Legislation should be carefully drafted and should include a series of ordinances and regulations aimed at managing the solid wastes. The legislation should not only include procedures for controlling emissions, but they should also deal with methodologies for monitoring and enforcing the regulations. Ideally, the legislation would be succinct, fair, and cost-effective. In addition, a thorough analysis of the potential impacts of the laws should be carried out prior to their issuance in terms of public health protection, environmental preservation, and overall influence on economic development.

Following are brief descriptions of either current or draft legislation for some countries.

3.2 Australia (Perth, Western Australia)

The criteria for landfill management for Western Australia were first released as a discussion document in January 1992. The final criteria were published in October 1993 [1], which take into consideration comments on the discussion document by government agencies, local government, private sector, non-government organizations, and the public.

The criteria apply to all regulated landfills in the Perth metropolitan area and other areas, as determined by the Executive Director of Public Health.

The regulations for Western Australia are comprehensive and provide guidance for all aspects of landfill design and operation. As such, suggestions are made on buffer zones, general requirements (fencing, roads, pest control, fire control, compaction, supervision, and others), weighing, control of water contamination, and post-closure site management.

3.3 France

The new French Environmental Protection Law was passed in July of 1992 [2]. This law has had a major impact on the content and management of landfills. The new law reinforces two existing laws and makes an effort to reduce waste production and increase the value of waste by means of resource recovery, treatment of wastes whose value cannot be increased, and storage of final residues (generated through waste treatment). The final disposal of the waste will be part of an integrated waste management plan, as the final step of the waste treatment hierarchy to be developed for each department and each region.

Financing of this ambitious effort to manage the wastes occurs through a tax that is levied for each Mg (1,000 kg, 1 tonne, 1.1 ton) of municipal solid waste that is deposited in landfills. The tax is collected by the French Environmental Agency (ADEME). The funds collected through the tax are used to develop new waste management techniques to treat household and commercial waste prior to final disposition.

At the time the law was passed, estimates were that more than 95% of municipal solid waste was collected and treated in the country. Similarly, the rate for collection and treatment of commercial wastes was relatively high. On the other hand, the approximately 80 million Mg of hazardous wastes generated in the country each year were not managed adequately. The new law was aimed at improving the management practices for these wastes.

The first steps taken by the legislators and the operators of the landfills were aimed at the security of the landfill. Legislation is leading toward strict technical requirements, particularly those applicable to the selection of sites for landfilling municipal wastes. The new legislation clearly defines the criteria for site selection, particularly its geology and hydrogeology, and requires a minimum permeability and thickness of liners, as well as the management of leachate and landfill gas.

Since it is difficult to predict the lifespan of the pollution potential of the confined wastes, the new legislation is trying to limit landfilling to disposal of "final waste" and to allow the final disposal in landfills of only the "safer" waste types. Thus, the new legislation introduces the concept of "final" waste. Final waste may or may not result from the treatment of raw waste. Final wastes are those wastes which can no longer be treated given the current technical and economic conditions. Consequently, the characteristics of final waste cannot be definitively fixed since they will evolve as technology progresses. According to the law, after the year 2002, only final waste will be landfilled.

The law of 1992 requires the development of departmental and regional plans for the management and disposal of waste. The plans should be discussed and accepted by all of those who are involved in waste management at the local or the regional levels.

The quantity and composition of the waste which will be allowed to be landfilled will depend upon the decisions made for the structure of the regional plans and the solutions adopted for waste treatment.

Three major categories of final waste can be identified: 1) final waste from hazardous waste, 2) final waste from municipal solid waste, and 3) final waste originating from the treatment of municipal solid waste (MSW) incineration gases (i.e., fly ash).

The law indicates that fly ash from MSW incinerators has to be stabilized and has to comply with a certain set of criteria before the materials can be landfilled. In general, fly ash does not meet the criteria and, consequently, it is expected that it will have to be solidified and stabilized.

The legislation has made an attempt to classify the different types of final waste for MSW. The MSW is divided into several categories based on their potential behavior in the landfill.

The law of July 1992 is expected to have a sizeable impact on the quantity and composition of the waste reaching the landfill. At the present time, the majority of the waste is either incinerated or landfilled. The new law will promote several options for waste treatment in order to reduce the quantity of waste intended to be landfilled and to reduce its organic content [3].

3.4 Guatemala

The primary environmental law in Guatemala is the Law of Protection and Improvement of the Environment. The Health Code is the main legal instrument regarding sanitary issues. The Health Code assigns to the Ministry of Public Health and Social Assistance the responsibility to dictate the norms and regulations for the collection, treatment, and final disposition of solid wastes. The Health Code, in turn, requires that municipalities in Guatemala adopt the norms dictated by the Ministry of Public Health and Social Assistance. The Guatemalan Municipal Code assigns the authority to the municipalities to establish, modify, and deliver services for the collection and final disposition of municipal solid wastes. In addition, the Municipal Code requires that the municipalities guarantee the efficient, secure, continuous, comfortable, and hygienic functioning of the solid waste management service to the population. In 1988, Decree 58-88 of the Municipal Code incorporated a series of articles that dealt with sanitation. Specifically, Article 31 indicates that public services will be provided and administered through either of two modalities: directly by municipalities and/or by the private sector through franchises assigned in accordance to the law. In addition, Article 40 indicates that the municipal corporation must provide sanitation services; street sweeping; as well as collection, treatment, and final disposition of solid wastes.

Guatemala's constitution also gives the right to, and requires that every citizen actively participate in, the planning, execution, and evaluation of programs dealing with public health. The requirements set forth by the constitution are reinforced by what is stipulated by the

Health and Civil Codes, which requires every citizen to obey and fulfill the regulations related to public health.

The Health Code, Municipal Code, and the Law for Protection and Improvement of the Environment establish administrative sanctions. On the other hand, the Penal Code establishes judicial sanctions. The administrative sanctions are applied by administrative entities and the penal sanctions are applied by courts of law. The imposition of administrative sanctions has been difficult due to the dispersion of existing legislation and the duplication of responsibilities of the various administrative entities. In addition, the application of existing legislation is a difficult task, primarily due to the fact that current legislation is inefficient and ineffective.

Several legal instruments in Guatemala require the development and implementation of regulations to deal specifically with solid waste management. Unfortunately, thus far, regulations for solid waste management have not been developed.

Constitutionally, Guatemala recognizes the fundamental right to health. Essentially everyone (the government, institutions, and individuals) is obligated to look after the health of every citizen. The regulation and control of solid wastes has special importance because of the potential negative impact that the wastes can have on public health and the environment. There are several Guatemalan laws and regulations which address the management of solid waste in the country.

The primary regulations of the national environmental law are: the Political Constitution of the Republic, the Law of the Protection and Improvement of the Environment, the Health Code, and the Municipal Code.

Specific regulations that deal with solid waste management have not been developed at the national level. For instance, municipalities do not have regulations aimed at controlling the siting, design, construction, and operation of solid waste management facilities (e.g., transfer stations, recycling plants, and sanitary landfills).

Environmental control of municipal solid waste services is the responsibility of municipalities. However, in most municipalities, the selection of waste disposal facilities does not take into consideration environmental concerns or potential negative environmental and/or sanitary impacts.

3.5 Japan

The Waste Management and Public Cleansing Law in Japan was enacted in 1970 and later amended in 1991. At that time, the Ministry of Health and Welfare encouraged local governments to construct or retrofit their waste treatment facilities. Investments in waste treatment facilities were encouraged through subsidies from the central government. The subsidy program was started in 1963 and is revised every five years. Municipalities are assisted in their planning efforts through the publication of Technical Guidance Documents, under the direction of the Ministry of Health and Welfare.

Since the publication of the first guidelines for landfill facilities in 1979, the characteristics of the wastes disposed in landfills have changed substantially. In addition, land suitable for the establishment of landfills has become more and more scarce. New landfill guidelines were promulgated in 1988. Since then, a new technical guidance document has been prepared.

In 1989, there were more than 2,300 landfills in Japan, which received approximately 34% of the total MSW stream (including bulky waste).

Some of the fundamental policies of final disposal in Japan can be summarized as follows:

- A landfill, as a rule, should be the point of final disposal for waste. Ocean dumping should be an exceptional alternative.

- All waste can be disposed in a landfill. However, some wastes must be processed before disposal in order to avoid environmental contamination or to be assimilated in the environment more readily.

- The types of wastes that can be allowed to be disposed in the ocean should be strictly restricted and should be processed prior to disposal.

- Disposal criteria for waste containing hazardous substances should be more stringent than those for non-hazardous wastes.

Thus, in accordance with the policies set forth in the previous paragraphs, criteria for waste disposal were presented in the Enforcement Ordinance of the Waste Disposal Law. The criteria were formulated in order to achieve the following: 1) prevent surface and groundwater contamination by leachate; 2) encourage waste reduction and stabilization prior to land disposal by means of appropriate technologies; and 3) pursue sanitary landfilling by controlling odors, litter, and access to animals.

The Waste Disposal Law requires that the owner or operator of a landfill site must operate and maintain the site according to criteria set forth in the Mandate of the Ministry of Health and Welfare and Prime Minister's Office of 1977. This is also known as the "Mandate of 1977."

The technical criteria require that landfill sites that receive MSW be equipped with a perimeter fence, a notification board, embankment to contain the waste inside the site, a liner system (if necessary), leachate collection and treatment (if necessary), and surface water diversion and drainage systems. In addition, the site should be engineered such that slides and subsidence are prevented.

The Mandate of 1977 requires the following operational and maintenance procedures: control of litter and foul odor, fire control, disease vector control, fencing, updating of notification board as needed, periodic inspection of embankment and liner system, control of explosive gases, maintenance of leachate and drainage facilities, monitoring of groundwater, run-on/runoff control, application of final cover, recordkeeping, and closure requirements [4].

3.6 Mexico

Currently, there is legislative framework for the management of solid wastes in Mexico at the federal, state, and municipal levels. However, the standards and rules relating to the siting, design, construction, operation, and monitoring of sanitary landfills are not set out in adequate technical detail. Although the standards and rules still are not sufficiently described and developed, the country has some basic ordinances concerning solid waste management and the deposition of municipal solid wastes on land.

The laws define non-hazardous solid wastes, and assign responsibility for their management to federal and municipal entities.

The laws also require that federal entities issue technical rules to regulate the collection, treatment, and final disposition of all types of solid waste.

The General Law of Ecological Balance and Environmental Protection, published by the now defunct Secretariat of Urban Development and Ecology (SEDUE) in 1988, repealed the Federal Law of Environmental Protection published in 1982, and provides more flexibility in the application of environmental law on a country-wide basis. The law initially establishes a limitation of responsibilities for both the federal government and federal agencies. Specifically, the law establishes the responsibilities of the states and of the Federal District. Similarly, the law defines a series of criteria relative to prevention of soil pollution originated by the poor management of solid wastes.

The law attempts to prevent and control soil contamination by the final disposition of solid wastes in sanitary landfills and by authorizing installation and operation of confinement or deposits for solid waste.

Practically every state has a law similar to that of the Federal government. Specific articles assign responsibility to the state for the selection of sites for final disposition of solid waste.

Only a limited number of municipalities have regulations which are applicable to the management of solid wastes.

3.7 The Netherlands

The first General Administrative order addressing landfills in The Netherlands was published in 1980 [5]. This order provided the first set of instructions on how to operate a landfill. One of the most important aspects of this order was that the waste had to be placed at least 0.5 m above the highest groundwater level. In addition, the installation of a bottom liner was suggested but not required. No additional technical information was supplied by the instructions.

In 1985, the 1980 order was replaced by a new General Administrative order [5]. The most important modification in the new version was that a bottom liner was required for landfills. However, no technical guidelines were provided for the construction of the liner. It was suggested to use synthetic as well as natural liners.

In March 1993, the Dutch legislation dealing with landfills changed considerably. A new law on environmental protection and a new General Administrative order on landfills were published [5]. The new order indicated that all landfills that were operated or opened after March 1, 1995 must meet new technical criteria and those landfills that were closed before March 1, 1995 would be required to meet the 1985 order.

Some of the more important technical criteria indicated in the new order deal with: 1) the use of a bottom liner system, 2) the application of a leachate drainage system, 3) the use of a control system to protect groundwater, and 4) the use of a composite capping system. The latest set of criteria was elaborated in considerable more technical detail than the earlier set of criteria.

3.8 Paraguay

A draft set of national regulations has recently been prepared by the Ministry of Public Health and Social Welfare. It is expected that the regulations will be approved and become law in the near future.

Section IX of the regulations pertains to the "sanitary" disposal of solid wastes and stipulates that it must be conducted such that the natural renewable resources are protected. In addition, it is stipulated that disposal should be performed in accordance with the technology of the sanitary landfill.

The proposed regulations suggest minimum requirements for the selection of a site for final disposition of the solid wastes. In addition, approval of the site requires the submittal of a technical document which should address a number of items pertaining to siting.

The draft regulations suggest that a landfill can be operated at the following levels: controlled dump site (level 1), basic sanitary landfill (level 2), medium sanitary landfill (level 3), and advanced sanitary landfill (level 4). Each of the levels is defined and described. The degree of sophistication in the requirements and design increases as the level increases.

3.9 Peru

The first regulations addressing sanitary landfilling were promulgated in Peru in 1964. The Sanitary Code was amended in 1969 to include the potential of recovering resources from the waste. Much later, the concept of "market" was included for the first time in the area of solid waste management in the Environment Code, the law for private investment, and the law for the promotion of private investment in the field of sanitation. These modifications establish responsibilities in the waste management sector and allow the participation of the private sector in the area.

The articles in the regulation are general in nature and deal with the preparation of plans by an engineer, place the responsibility for collecting the wastes on the municipality, require daily collection, and indicate that collection vehicles should be covered and that the number of vehicles should be sufficient to satisfy the needs of the collection frequency.

The regulation defines a sanitary landfill as a method of final disposition of solid wastes on the land, whose objective is to eliminate the nuisances and risks to public health and, through the use of appropriate technologies in sanitary engineering, the wastes are deposited in layers on the soil, isolating them from the environment at the end of each day of operation or at necessary intervals. The conditions that must be met for a disposal site to qualify as a sanitary landfill are made in very general terms, e.g., distance from the city, accessibility, wind direction, and proximity to sources of water supply. In addition, brief descriptions are made of the type of soils that would be preferable, such as clay, and it is noted that the use of sand would require thicker layers.

The regulations dealing with the design and operation of a landfill indicate that only two methods of landfilling would be acceptable in the country: the area and the trench. The section addresses dimensions of layers and lifts for each of the types of landfills. This section also indicates that the layers should be compacted and covered with a layer of soil each day. The last layer of waste should be covered with a layer of soil within one week of completion of the landfilling process. Additional suggestions are made dealing with access to the site, fencing, special wastes, burning of waste, and other items.

The annexes consist of sketches describing the area and trench methods, including the process of discharge and compaction.

3.10 South Africa

The rules for disposing of solid waste on land in South Africa were promulgated in 1994 by the Department of Water Affairs and Forestry in a document entitled *Minimum Requirements for Waste Disposal by Landfill* [6].

The primary objective of the minimum requirements is to ensure that the most cost-effective means are used to protect the environment, particularly the water regime, and public health from both the short- and long-term adverse impacts of waste disposal.

In order to facilitate the application of the standards to a wide range of existing waste disposal sites, the standards are based on a landfill classification system. The classification system is based on waste type, size of the landfill, and the potential to generate a significant quantity of leachate.

Some of the basic design components relevant to the minimum requirements include: cut-off drainage system, separation between waste body and the groundwater, underliner systems, leachate and contaminated water collection systems, provision of adequate covering, and stability of slopes.

3.11 United Kingdom and the European Union

3.11.1 United Kingdom

The development of a sanitary landfill in the United Kingdom begins with the need for planning permission. The first phase of the process is the conduct of a detailed site investigation and, in most cases, an environmental assessment. Specific topics that must be addressed during the first phase are: location (siting), access, proximity to housing, geology, hydrology, and hydrogeology. During the planning process, the landfill's operational practices and site infrastructure are generally described, with the detail provided later during the licensing process. The planning process is open to public participation and debate, whereas the licensing process is not. Hence, the need for such detail at the planning stage, which takes place at the local level. When the planning requirements are satisfied, the licensing process can commence. It is a prerequisite of any waste management license that planning approval has been given.

The licensing provisions form part of the Environmental Protection Act 1990. The waste management licensing regulations were implemented in 1994, some four years after the act received its Royal assent. The Act generally specifies which issues are to be covered by regulations. Regulations are subsequently developed to technically define the manner of meeting the requirements of the legislation.

The license sets the standard expected of the landfill operator. The operator then produces an operations plan that conforms to the set of standards. The operations plan can be subsequently revised, if necessary, to meet changes in conditions.

The license or permit is issued and regulated by the Environment Agency. Regular visits and site inspections are carried out to ensure compliance. The license remains in force until a completion certificate is issued. The completion certificate is issued to the operator at the time that the completed fill has reached a stable regime, a date many years after the fill has terminated acceptance of wastes. Long-term monitoring of the site is a requirement of the license.

The regulations are supported by guidelines, some of which are mandatory and while others are discretionary and for consideration only. In terms of the legislation, the guidance can be placed in the following key categories:

- landfill design construction and operational practice,
- licensing of waste management facilities, and
- landfill completion.

New guidance is being prepared for the co-disposal of wastes (i.e., municipal solid waste and hazardous waste) and special types of wastes.

3.11.2 European Union

A number of European countries have formed an alliance known as the European Union (EU). The EU issues directives which set the standards for its member governments with respect to particular issues.

Currently, a landfill directive has been drafted by the EU which incorporates many of the existing requirements of the United Kingdom legislation. However, the directive contains a new element in terms of landfill gas emissions, namely control of methane generated by landfills because of its contribution to global warming. In particular, the directive considers the reduction of organic carbon by treating the wastes prior to landfilling. The directive also seeks to stop the landfilling of tires and the co-disposal (commingling of municipal solid waste and hazardous) of waste.

3.12 United States

The United States Environmental Protection Agency (U.S. EPA) promulgated the current set of landfill regulations in October 1991 [7]. The U.S. EPA views state and local governments as the implementors of the various solid waste management programs. A discussion of the development and status of landfill regulations in the United States prior to 1991 is given in Chapter 2.

The landfill regulations provide national minimum requirements that each of the states must incorporate into its landfill permitting process.

The municipal solid waste landfill regulations apply only to those sites that receive household waste or waste derived from households. The regulations consist of six major components: 1) location restrictions; 2) operation; 3) design; 4) groundwater monitoring and corrective action; 5) closure and post-closure; and 6) financial assurance for closure, post-closure, and known corrective action. Usually, each of the six components includes: 1) self-implementing design standards with which a landfill owner or operator in an approved state must comply without deviation, and 2) flexible performance-based standards that allow for an unapproved state to accommodate facility-specific conditions.

The U.S. EPA has been involved in several modifications to the landfill regulations, including developing new mechanisms for financial assurance and revised requirements for some small landfills. The EPA also published a companion rule that regulates landfill gas emissions from municipal solid waste landfills.

3.13 Conclusions

A general review regarding the status of legislation and regulations pertinent to landfills in several countries around the world indicates that there is a serious gap between industrialized countries and economically developing countries regarding landfill legislation and regulations.

In response to legislation, regulations in those countries considered to be industrialized have evolved substantially during the last 30 years. The regulations are primarily aimed at the protection of water resources. However, during the last five years, some of the regulations in industrialized countries have been, or are being, modified to reduce the risks from contamination associated with landfills by controlling the type and quality of wastes reaching the sites.

On the other hand, a review of available materials indicates that the large majority of economically developing countries do not have a set of regulations directed toward the protection of the public health and of the environment. Most of the countries do not have regulations at either the national or the local level. Although municipalities have some health codes that were developed a number of years ago, these codes basically address the need to provide collection and disposal services.

A set of regulations in and of itself is not sufficient to protect the public health and the environment. The requirements of the regulations must be implemented and the regulations must be enforced. Some economically developing countries suffer from a lack of regulations and, where regulations are in existence, enforcement is generally lacking due to insufficient motivation, human resources, financial resources, or a combination of these factors.

Environmental regulations developed for industrialized countries have some influence on other countries. Some proposed and existing regulations in economically developing countries are patterned after those prepared for industrialized countries. One of the key requirements that is often taken from landfill regulations of industrialized countries is the specification of extremely low hydraulic permeability for landfill liner systems, with the attendant need in some cases for synthetic membrane liners.

In some rare cases, modern regulations for solid waste management have been promulgated in economically developing countries. Unfortunately, the regulations dealing with sanitation appear, in many cases, to have been developed without careful consideration of scientific issues associated with the regulations. In addition, the regulations do not include or accommodate a number of important aspects, such as social, economic, and cultural issues. Furthermore, the regulations typically lack careful analysis in order to determine the financial impact due to their implementation. The regulations also lack the basic mechanisms for their application and, consequently, they are neither obeyed nor executed.

In most economically developing countries, the institutions responsible for the application of legislation relative to the management of solid wastes lack the human and financial resources to do so. Furthermore, the disorderly production of judicial norms has resulted in jurisdictional overlaps and duplication of responsibilities.

Whenever possible, existing relevant legislation should be to put into effect by promoting the preparation and publication of regulations specific to solid waste management. The regulations should address the following issues for solid waste systems and facilities: 1) minimum requirements for siting, design, and operation; 2) the permitting process; 3) monitoring of the facilities; 4) enforcement of the rules and regulations; and 5) sanctions for not following the regulations. Both the legislation and the regulations should be developed based on sound scientific principles, and they should address social, economic, and similar issues. The legislation and the regulations should also unambiguously identify the institution(s) that would be responsible for implementation of the regulations and the means for obtaining the financial and human resources to perform the designated duties.

Parallel to the development of the regulations, development of an institutional framework is necessary for conducting the various activities outlined by the regulations.

In addition, it is necessary to develop and implement the mechanism for the active participation of the public in the planning, execution, and evaluation of solid waste management systems, as well as to clearly delineate the agency responsible for enforcing the regulations. The responsible agency should be given a sufficient budget to perform its duties.

Key legal issues that exist among economically developing countries with regard to the management of solid wastes are summarized below:

- Imposition of administrative sanctions against violations of the regulations has been difficult due to fractured legislation.

- Current legislation relevant to solid waste management is inefficient and ineffective.
- Regulations specific to all elements of solid waste management have not been developed.
- Regulations dealing with sanitation issues have been developed without due consideration of scientific, social, economic, and other issues.
- Implementation of modern practices of sanitation is hindered by the lack of procedural mechanisms.
- Jurisdictional overlaps result in duplication of responsibilities, obligations, and work effort and substantial opportunities for no action.
- Institutions responsible for the application and enforcement of legislation lack sufficient human and financial resources.
- Disorderly production of norms leads to jurisdictional overlaps and duplicity.

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Chapter 4

Waste Characterization

The successful design and operation of a landfill requires careful planning and attention to detail. One of the more important and earlier activities of the planning sequence is the study and description of the wastes to be landfilled. In this chapter of the guidance document, the planning process is limited to a discussion of waste quantities and characteristics, and to the acquisition of information concerning them. Other chapters of the document discuss aspects of planning as they are encountered in relation to other topics covered in the document, e.g., site selection, and design and construction. This chapter is dedicated to waste quantities and characteristics because their influence is pervasive throughout the planning, implementation, and operation of a landfill project.

A discussion of waste characteristics necessarily includes the use of terms and definitions to describe the wastes. Unfortunately, no set of universal terms and definitions exists as of this writing. Since in several cases a number of definitions are used to describe similar types of waste throughout the world, the terms and definitions used in the guidance document should not necessarily be considered absolute. An attempt has been made to provide sufficient information with respect to types of wastes and their characteristics so that the readers can properly interpret and use the information that is presented in the guidance document and apply it to their local situations and conditions.

Waste characterization is a broad topic. It includes type; quantities; rate of unit generation; and physical, mechanical, chemical, and biological properties of wastes. Of immediate importance to the designer and operator of a landfill are the quantities and characteristics of the waste to be disposed. However, because quantities and characteristics vary over time, an awareness and knowledge of the dynamics of waste generation must be had by all involved in a landfill project. As discussed in Chapter 2, generated wastes are the sum of disposed wastes and diverted wastes (i.e., recycled materials).

Two general types of waste diversion are applicable to economically developing countries, namely informal and formal. Informal diversion, the existence of which is a matter of survival to some poor populations, is not officially sanctioned by the government; lacks controls with respect to protection of human health and safety and of the environment; and usually consists of scavenging (salvaging) at some point on the collection route, at the disposal site, or both. Formal waste diversion programs are sanctioned by the government and can range from simple recycling programs (e.g., drop-off of recyclable materials at communal depots) to complex systems (e.g., separate collection of recyclable materials using especially dedicated vehicles). Scavenging is an important aspect of solid waste management in many economically developing countries and, therefore, it is given a separate and detailed treatment in Chapter 15. If informal scavenging is upgraded to organized, controlled, and managed activities, then scavenging can fall within the definition of formal diversion, as used in this document. Generally, when used in this document, waste diversion refers to formal programs and systems of diverting wastes from land disposal.

A knowledge of the quantities and characteristics of the wastes to be landfilled is fundamental to the proper design and operation of a landfill. Among other things, these parameters influence or control many aspects of the landfill system over its lifetime, including the annual rate of filling, the required volumetric capacity of the fill, production and characteristics of gas and leachate, and environmental impacts.

The quantity of solid waste dictates several critical aspects of landfill design and operation, including number and frequency of vehicles using the site, land area required, and amount of cover material that will be used. Similarly, the composition and other characteristics of the wastes significantly influence the number of passes needed to achieve a particular degree of compaction and the types of heavy equipment needed for the landfill operation. The physical, mechanical, chemical, and biological characteristics of the wastes, along with the operational conditions at the landfill, govern the performance of the various processes (e.g., compaction, anaerobic decomposition, and hydraulic transport) that occur in a landfill and ultimately govern the fate (e.g., settlement, rate of decomposition, and products of decomposition) of the wastes as they are subjected to these processes.

Disposed waste quantities and characteristics (and, therefore, landfill design, operation, and performance) can be influenced or controlled by programs that divert certain components or materials from the generated waste stream. The reasons for the implementation and maintenance of formal diversion programs are many. They include the recovery of valuable resources that would otherwise be disposed as wastes, the reduction of problematic materials entering a landfill and the subsequent adverse effect that they have upon landfill operation and performance (e.g., whole tires, toxic materials), and the reduction of the quantities of materials destined for land disposal in order to conserve resources, e.g., land, and water and air quality. From the standpoint of planning, designing, and operating landfills, an awareness and understanding is needed of: 1) the distinction between the characteristics of disposed wastes and of generated wastes; 2) the potential impacts of diversion programs on disposed waste characteristics; 3) the potential temporal variation in the effects of diversion programs and in disposed waste characteristics; and 4) other factors that influence waste characteristics, e.g., seasonal effects.

Because waste diversion programs may be beneficial both financially and environmentally, they are being implemented in many industrialized countries and in some economically developing countries. Whereas in the past, the characteristics and quantities of disposed wastes could be assumed to be identical or very similar to those of generated wastes, the situation has changed and is changing substantially around the globe. Currently, in some industrialized countries, the extent of diversion programs is such that a substantial portion of generated wastes is being diverted (25% diversion is the national average in the United States), and the characteristics of the wastes destined for disposal are significantly different than those of the generated waste stream. Diversion programs currently are implemented over an extended period of time (e.g., years), due to the number of different programs that are required to achieve large percentages of diversion. Thus, their impacts on the disposed waste stream can be expected to range from initially modest to eventually substantial. Planners and designers of landfills must consider this dynamic condition, its magnitude, and its ramifications on landfill design and operation.

Other influences on disposed waste quantities and characteristics include climate and season; level of economic development; occurrence of special or extraordinary events (e.g., tourist seasons); acts of nature (e.g., monsoons or fires); and type and number of waste generators (e.g., residential, commercial, and industrial).

Four general trends concerning solid waste generation in economically developing countries are worthy of consideration when conducting long-term planning for land disposal of wastes. First, per capita waste generation increases with an increase in degree of national economic development. Second, an increase in the generation of paper wastes (particularly packaging) generally accompanies a nation's advancement in economic status. Third, the concentration of putrescible materials in municipal waste decreases with the advancement of a nation's economic status. Finally, the bulk density of solid waste decreases with increasing levels of economic development, from 400 to about 200 kg/m^3, because of the lower concentration of paper and paper products and the greater concentrations of ash and food wastes.

This chapter describes the following:

- the major classes of municipal solid wastes found in economically developing countries,

- types of wastes that should be either accepted or not accepted for disposal in a landfill, and
- methods for accurately determining quantities and characteristics of the waste.

4.1 Major Classes of Solid Wastes

Traditionally, municipal solid wastes generally have been classified in terms of three major sources of generators: residential, commercial, and industrial. Sometimes, institutional sources are separated from commercial sources and, thus, a fourth source is referred to as institutional. In the traditional scheme of classification, residential (domestic) solid waste consists of household garbage and rubbish, or refuse. The garbage fraction is mostly in the form of wastes derived from the preparation and consumption of food (e.g., meat and vegetable scraps). An alternate term commonly used to describe the garbage fraction is "putrescibles." In the traditional scheme, all wastes not classified as "garbage" are classified as "rubbish." The major constituents of rubbish are:

- glass, metal, and plastic wastes;
- wastepaper and paper wastes; and
- yard and garden debris.

As used in this document, the composition of yard and garden debris, or wastes, includes tree, brush, and bush trimmings, lawn clippings, leaves, and plant debris from gardens. These materials are characteristically readily biodegradable under suitable circumstances. In some localities, yard and garden debris are termed "green wastes."

Other constituents historically (and currently) comprising a substantial portion of the solid waste streams of industrialized countries include automobiles, appliances ("white goods"), and construction and demolition debris.

The list of waste constituents currently in use in industrialized nations is much the same as the traditional list, except that the major categories have been subdivided into many subcategories of material types (e.g., paper and paper products are subdivided into corrugated, newspapers, magazines, office grades, etc.) due to the interest in recycling and the environmental impact of particular types of materials (e.g., household hazardous wastes, lead acid batteries). Biosolids (municipal wastewater treatment sludges) are also receiving attention because they are of municipal origin, can be considered solid waste if adequately dewatered, and are frequently land-disposed. In the case of some economically developing countries, a solid waste class of prominence may be agricultural solid waste (e.g., crop residues) and manures.

Residential wastes are generated by single- and multi-family residences. In economically developing countries, domestic waste contains substantial percentages of putrescible matter and ash. The ash is generated by cooking and heating with solid fuels (e.g., peat and wood). Commercial wastes are produced by retail and wholesale businesses, offices, and light manufacturing facilities. Institutional wastes are generated by government offices, schools, correctional facilities, etc. Industrial wastes are produced by industrial plants, heavy manufacturing operations, and others.

A significant portion of commercial and industrial wastes in economically developing countries is in the form of materials that have value and uses locally, e.g., paper and paper products, scrap metal, plastic, and textiles. Through the activities of scavengers and recyclers, a significant fraction of the commercial and industrial wastes are removed from the waste stream before they reach the land disposal site.

4.2 Types of Solid Wastes

4.2.1 Significance of Type of Waste

The characteristics of the solid waste to be disposed are important considerations in the design and operation of a landfill. The nature and composition of the solid waste buried in the fill are important determinants of the types, quantities, and characteristics of the by-products emitted as a consequence of the processes occurring within the landfill and of appropriate methods of handling the waste. For example, concerning the handling of wastes, a particular type of waste due to its corrosivity, toxicity, or other dangerous property might require special handling in order to protect operating personnel and equipment from injury and harm. An example of the importance of the type of waste to landfill operations is wastes containing a substantial concentration of low-density materials, e.g., plastic film and foam. Such wastes require skillful handling and processing at the land disposal facility if proper compaction and control of litter are to be achieved.

4.2.2 Acceptable Wastes

Most solid wastes generated by residential (domestic), commercial, institutional, and agricultural sources usually can be disposed in a modern sanitary landfill, with minimum risk of directly or indirectly endangering human health and safety and the quality of the environment. For convenience of reference, such wastes are discussed under the term "Acceptable Wastes." This blanket generalization does not extend to solid wastes generated by industrial sources. Solid wastes from industrial generators should be examined carefully to assess their characteristics and whether or not such wastes require skillful and special methods of land disposal. The scrutiny of solid wastes from industrial sources is particularly important and necessary in those locations in which policies or regulations for hazardous waste management and their enforcement are non-existent or inadequate to control the quality of solid wastes that may enter or are entering a solid waste landfill site. Under the definition used in this document, landfills are not designed to accept and process substantial quantities of hazardous wastes. Large quantities of hazardous wastes must be disposed in specially designed landfills. Further discussion of hazardous wastes is presented in the subsection entitled "Unacceptable Wastes."

Ideally, only those wastes for which a given facility has been specifically designed should be accepted by that facility. An exception might be a waste that has been shown to fit within the existing or appropriately modified design capacity of the facility and has the appropriate physical, biological, and chemical characteristics. In many of the economically developing nations, separation of wastes into acceptable and unacceptable or other categories is not practiced. In many economically developing countries, circumstances are likely to be such that the only feasible course of action for disposal is to accept and bury all wastes without exception. The very act of removing the wastes from the open environment and placing them in a controlled environment would represent a substantial advancement over the past and current practices and conditions of waste management and disposal. Under such circumstances, control of the potential adverse impacts of the joint disposal of solid waste and hazardous waste on human health and the environment would be exercised through the proper siting, design, and operation of the land disposal facility.

In general, wastes that can be regarded as being acceptable for disposal in a landfill are solid wastes generated by residential and commercial sources, and dewatered sludges (excepting raw sewage sludge) from wastewater treatment and from water supply treatment facilities. Of these types of wastes, the greater portion will be in the form of residential and commercial solid wastes. The average uncompacted bulk densities for residential refuse generated in various cities is presented in Table 4-1.

Table 4-1. Average Uncompacted Bulk Densities of Residential Refuse

Location	Density (kg/m^3)
Metro-Manila, Philippines	209
Lima, Peru	176
Caracas, Venezuela	220
Asunción, Paraguay	390

Source: Reference 1.

Certain wastes that might otherwise be designated as unacceptable can be accepted for disposal at a landfill if they are subjected to the handling procedures and conform to the conditions described in Section 4.2.4. Among such types of wastes are included bulky wastes (furniture, large appliances, tires, automobile bodies), animal carcasses, hospital and medical wastes, and residues generated by incinerators and air pollution control systems. These wastes rarely are found in the small municipalities of economically developing countries. On the other hand, these types of wastes can be found in large metropolitan areas.

4.2.3 Unacceptable Wastes

In the absence of a formal system of hazardous waste policies, regulations, and enforcement, the decision as to which solid wastes are to be considered unacceptable for disposal in a landfill should be made mutually among the waste generator, the responsible government agency, and the disposal site designer or operator. Unacceptable wastes should be identified in the landfill development plan, and the users of the site should be provided with a list of such wastes. Considerations regarding the acceptability or, conversely, unacceptability of specific classes and types of wastes should include the hydrogeology of the site; the quantities and the physical, chemical, and biological characteristics of the wastes; alternate methods available for processing and disposal; risks and effects of the wastes to the environment and to the public health; and the protection of the health and safety of the operating personnel [2].

Particular types of wastes that should require specific approval of the responsible government agency for acceptance at the disposal site include hazardous wastes, hospital and medical wastes, bulk liquids and semi-liquids, sludges containing free moisture, highly flammable or volatile substances, raw animal manures, septic tank pumpings, raw sewage sludge, and industrial process wastes. Animal wastes should be evaluated in light of the fact that some animal wastes may be infectious because they contain animal disease organisms that can be transmitted to humans (zoonoses). Some types of wastes that represent potentially significant hazards and risks are listed in Table 4-2. The terms used in the table to describe the potential risks and hazards among the various types of wastes are meant to provide the reader with a general notion of the types of problems that might be encountered in the handling and disposal of the wastes. The terms have specific definitions and meanings in legislation and regulations promulgated in some countries.

A definition of hazardous waste that is appropriate for economically developing nations is the following:

> *A waste is hazardous if it poses a substantial present or potential hazard to human health or living organisms because the waste is non-degradable or persistent in nature, because it can be biologically magnified, because it can be lethal, or because it may otherwise cause or tend to cause detrimental cumulative effects.*

4.2.4 Special Wastes

Some special types of wastes (hereafter referred to as "special wastes") are described in this section. Of these, the hospital and medical (infectious) wastes and the sludges generally are encountered more frequently (in terms of concentrations and degree of danger) at land disposal sites in economically developing nations than in industrialized countries. Consequently, attention is given to them in this document. Special wastes generated in

Table 4-2. Types of Wastes Representing Potential Risks and Hazards When Received at Landfills

Waste Type	General Type of Risk or Hazard[a]			
	Toxicity	Explosiveness/ Flammability	Pathogenicity	Radioactivity
Solid Wastes				
Putrescibles			√	
Bulky Combustibles		√		
Bulky Non-Combustibles	√	√		
Small Combustibles		√		
Small Non-Combustibles		√		
Non-empty Cans, Bottles, Drums	√	√	√	√
Gas Cylinders		√		
Powders and Dusts	√	√		
Pathological Wastes	√		√	√
Sludges	√			
Demolition and Construction	√	√		
Abandoned Vehicles		√		
Radiological Wastes				√
Liquid Wastes[b]				
Wastewaters	√		√	
Contaminated Waters	√			√
Liquid Organics	√	√	√	
Tars	√	√		
Slurries	√			
Gaseous Wastes[b]				
Odorous	√	√		
Combustible Particulates		√		
Organic Vapors	√	√		
Acid Gases	√	√		

[a] The terms may have specific definitions and meanings in legislation and regulations promulgated in some countries.

[b] Final disposal of these wastes in a landfill requires an initial transformation to a solid form or alternate methods of final disposal.

economically developing countries other than hospital and medical wastes and sludges are usually good candidates for scavenging and recycling (e.g., construction and demolition wastes) during collection and at the disposal site, a characteristic activity of economically developing nations discussed in greater detail in Chapter 15. In some countries, the term "special waste" has a specific meaning and definition in terms of the specific sources or types of wastes and their characteristics.

The design and operation of land disposal facilities for the special types of waste described in this section should be governed by the fact that some of these wastes can pose substantial risks and hazards to operators and to the public (both short and long term) and to the environment. Alternate methods of treatment and disposal may be worthy of consideration in some cases.

4.2.4.1 Sewage Sludge

Sewage sludge (biosolids) refers to the concentrated settleable solids of sewage generated as a by-product of the processing and treatment of municipal wastewater. A wastewater treatment facility may serve residential, commercial, and industrial septic tanks and public latrines. In economically developing nations, conventional municipal wastewater treatment facilities generally are found only in connection with the sewered sections of large and well-developed metropolitan areas. Consequently, the issue of disposal of sewage sludge in a landfill would arise only for the landfill operations that serve those areas.

Raw (primary) sewage sludge and septic tank and latrine sludges should not be accepted for disposal at landfills because of the grave risk posed to human health, especially the landfill personnel. The grave risk is the consequence of handling and processing a material with the dense concentrations of human pathogens that are characteristic of such sludges. Treated (secondary or digested) sludges may be accepted at a landfill if they have been dewatered to a solids concentration of about 15% or more and if they are mixed with mixed solid wastes (sometimes the process of jointly disposing both liquid and solid wastes is termed "co-disposal," or "combined disposal") such that the moisture content of the mixture is less than 50 to 60%. The immediate application of soil cover is recommended after combined disposal to isolate the mixture from the ambient environment.

Among the considerations of importance in the disposal of municipal wastewater treatment sludge in a landfill are the moisture content of the as-delivered sludge; the ratio of solid waste volume-to-sludge volume required to adjust the moisture content to the recommended range; the degree of treatment accorded the sludge; and, in some areas, the metals content in the sludge. Concentrations of heavy metals above trace levels may place a particular sludge in the hazardous waste category or otherwise warrant treatment of the sludge by methods other than disposal in a landfill. The potential of high concentrations of metals in the sludge would be indicated in those areas where large industries (such as manufacturing) which conduct no on-site wastewater treatment and which are served by a municipal wastewater treatment facility. Prior to allowing the disposal of municipal wastewater treatment sludge at a landfill, alternate methods of management should be evaluated. Alternatives are biological oxidation, lagooning, and composting.

4.2.4.2 Industrial Process Wastes

A wide variety of chemical, physical, and biological characteristics are represented in the residues produced by industrial processes. Among the forms of the industrial wastes that may be delivered to a landfill are liquids, semi-liquids, films, sheets, granules, shavings, turnings, and powders. The wastes may be of any shape and particle size. Combined disposal with relatively dry, absorbent solid waste (paper, sawdust) is recommended for wastes composed primarily of non-hazardous liquids and semi-liquids.

4.2.4.3 Volatile and Flammable Wastes

Wastes in this category include explosives, volatile liquids and gases, and petroleum fuels. Because they can be hazardous and result in fires, these wastes must be subjected to strict control procedures. If the wastes are not highly flammable or volatile, they may be mixed with other wastes. As a precautionary measure, however, all wastes in this category should be disposed in a separate area of the site. The area should be clearly indicated and the exact location should be recorded in the final plan of the completed site. Open flames should not be allowed in the vicinity of such wastes. Moreover, workers should be warned against smoking in the vicinity.

4.2.4.4 Bulky Wastes and Construction and Demolition Debris

Bulky wastes include a wide variety of materials and items. Automobiles, large household appliances and fixtures, and oversize items in construction and demolition debris are common examples of bulky waste generated in industrialized countries. Scavenging and recycling sharply reduce the quantity and concentration of such items reaching the disposal sites in economically developing countries. Those that do reach the site generally are the subject of further scavenging and recycling activities. With respect to the items that survive the scavenging and recycling activities, special procedures should be followed in disposing of them. Long, difficult-to-handle items such as logs, stumps, and usable lumber should be placed parallel to the working face and covered with a layer of mixed municipal solid waste. Wastes that could damage vehicles (e.g., heavy-gauge wire, pipes, cable, scrap metal) should be deposited at the base of the face and covered with mixed solid waste or other suitable material prior to compacting them.

4.2.4.5 Animal Manures

If animal manures (such as those from slaughterhouses serving highly urban areas) are accepted at the landfill, they should be compacted on the working face in the conventional manner and covered immediately. Excessively wet manures should be mixed with solid wastes in a ratio that ensures no free water. The manures or mixture of manures should be covered immediately after placement in the fill. An alternate form of management of animal manures sometimes practiced in economically developing countries is to use the material before or after composting it as a soil amendment or for land reclamation.

4.2.4.6 Animal Carcasses

Carcasses are best disposed at a rendering plant. Such a procedure is both hygienic and results in the production of useful products. However, circumstances may require that carcasses be accepted at the landfill. If only a few animal carcasses are involved, they may be placed on the working face along with the other wastes. If a large number are to be disposed at the fill, the carcasses should be deposited in a special trench and covered with 0.5 to 1 m of compacted soil. If diseased animals are accepted for disposal, the trench should be isolated from the area accepting the conventional solid waste and covered as soon as possible. Regrading of the fill may be required over time to compensate for settlement as the carcasses decompose. The application of lime or other chemical agents may be used to control foul odors.

4.2.4.7 Tires

If vehicle tires are accepted at the landfill, preferably they should be cut into pieces to reduce their bulk density and to control their tendency to migrate to the top of the fill. A less desirable, alternate method of disposal (but feasible if the number of tires is small) is to spread them in a single layer at the bottom of the fill. When available, incoming brush or demolition debris should be placed on top of the tires. The remaining wastes are then deposited on top of the two layers.

4.2.4.8 Low-Density Wastes

Low-density wastes such as plastic containers, synthetic fibers, foam, plastic film, and rubber scraps may rebound after compaction and possibly work up through the fill. To counteract this tendency, the material should be deposited in thin layers, covered with other waste, and compacted.

4.3 Methods for Determining Quantities and Characteristics of Disposed Wastes

A knowledge of solid waste quantities and composition is fundamental to the planning, design, and operation of a landfill. During the planning process, the rate of solid waste flow into the disposal site must be determined, and all factors that influence the flow over time must be identified and evaluated. Both current and future rates of disposed waste flow must be calculated since a landfill operates over a number of years.

The determination and estimation of waste quantities and characteristics should be conducted using scientific methods [3]. Among methods of potential utility and relevance are those that have been developed for statistical sampling, to determine quantities of waste using a weight (gravimetric) survey, and to determine waste composition. Methods are also available to determine other properties of solid waste, e.g., moisture content, concentrations of metals, particle size distribution, and density. The methods include procedures for analyzing the data and for determining accuracy, precision, and quality of the data.

For the highest degree of utility and accuracy, field determinations of waste quantities and composition should be integrated and conducted concurrently. A similar recommendation applies to the field determination of other waste characteristics, e.g., moisture content and bulk density.

Before beginning either a quantity or a composition survey, it is important to make sure that no "illegal" dumping or scavenging takes place prior to collection (or prior to sorting the sampled wastes). If these activities cannot be completely controlled or held in abeyance, then they should be maintained to a minimum or properly accounted for in the analysis of the data. This admonition is in keeping with the overall goal of a quantitative waste characterization study: an accounting of all the wastes generated within the survey area.

The quantities and characteristics of disposed wastes can be estimated using quantitative or qualitative methods. The use of quantitative methods (i.e., sampling and measurements from the subject wasteshed[1]) provides more accurate information than the use of qualitative methods, which use information from the literature or other locations to draw conclusions about the subject wasteshed. Quantitative measurements of current waste characteristics are appropriate for estimating the characteristics over the course of a landfill's lifetime only if the disposed waste stream does not, or is not likely to, vary considerably in characteristics over time, e.g., if recycling of waste-derived materials will not be significant over the planning period. Quantitative methods can also be used to establish seasonal (i.e., within a 12-month period) variations in characteristics of the wastes. In the case where disposed waste characteristics do or can be expected to vary significantly over the lifetime of a landfill (e.g., 10 to 20 years), the future characteristics of the wastes must be estimated by considering and analyzing the entire (i.e., generated) waste stream. This analysis should be supported by adequate quantitative measurements. The estimation is performed from an analysis of the estimated characteristics of the generated wastes and of those wastes that are diverted. In other words, the characteristics of disposed wastes are equal to those of the generated wastes, less those of the diverted wastes.

The fundamental principle underlying the estimation of disposed waste properties is the conservation of mass. The basic conserved properties are mass, composition (i.e., type of materials; e.g., tin cans, newspapers, and food waste), and chemical compounds. The principle of conservation of mass can be used in connection with estimating quantities of various types of materials that will enter a disposal facility, e.g., bulky wastes, food waste, recyclables, water, and chemical compounds. These types of estimates are of utility in the planning and implementation of the landfill facility and its component systems, e.g., landfill gas collection system.

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1 A wasteshed is a geographical area of waste generation.

Using the estimated quantities of types of materials and their estimated chemical properties, the composition of the types of materials (on a weight basis) and the chemical loadings into the landfill can be calculated in a straightforward fashion.

4.3.1 *Typical Waste Characteristics*

Typical compositions of solid waste streams in several areas of the world and some other useful design data are given in Tables 4-3 and 4-4. From a review of the data in the tables, the reader can observe that solid wastes in economically developing countries can have a high putrescible content (and, therefore, moisture content) and a large percentage of inert materials (e.g., ash). The characteristics of the wastes can be expected to vary by source or type of waste, as shown in Table 4-4. Seasonal variations in the waste stream can also be expected, and the waste stream can be affected by local customs, e.g., in some locations, solid fuel, coal, or wood is used for domestic cooking and generates an ash requiring disposal. The characteristics of the wastes influence the design, operation, and performance of both diversion and disposal systems.

Direct, quantitative measurement of many of the properties of bulk (i.e., as-delivered) solid waste is impractical because the range of both very large and very small particles that compose solid waste compromises the ability to collect representative samples and to properly prepare them for laboratory analyses. Consequently, the properties, or synonymously the characteristics, are usually estimated based on those of the components that comprise the mixture. The analyses of component characteristics are much more practical than those of bulk solid waste, and the analytical results can be used readily for purposes of estimation of the characteristics of bulk solid waste.

Although many characteristics of bulk solid waste cannot be determined directly, some analyses of the characteristics can be performed readily and practically, including bulk density.

Table 4-3. Quantity and Composition of Disposed Municipal Solid Waste (% wet wt.)[a]

Material	Urban Areas, India	Ibadan, Nigeria	Manila, Philippines	Asunción, Paraguay	Mexico City, Mexico	Lima, Peru	Rio de Janeiro, Brazil	Caracas, Venezuela	Berkeley, California
Yard, Food, Market Wastes	74.7	76.0	53.7	60.8	56.4	34.3	47.8	40.4	41.5
Paper	2.0	6.6	12.9	12.2	16.7	24.3	31.5	34.9	40.3
Metals	0.1	2.5	5.8	2.3	5.7	3.4	5.9	6.0	3.1
Glass	0.2	0.6	3.5	4.6	3.7	1.7	4.7	6.6	5.6
Plastics	1.0	4.0	1.6	4.4	5.8	2.9	3.9	7.8	6.0
Textiles	3.0	1.4	1.8	2.5	6.0	1.7	4.1	2.0	2.0
Ceramics, Dust, Stones	19.0	8.9	20.7	13.2	5.7	31.7	2.1	2.3	1.5
Generation (kg/cap/day)	0.9	0.4	0.9	1.4	1.5	2.1	1.2	2.1	2.2

Source: CalRecovery, Inc.

[a] Data for Berkeley, California are based on quarterly one-week field sampling events over a 12-month period. Data for other locations are the results of one or two field sampling events, each in the range of about 7 to 14 days.

Table 4-4. Average Composition of Various Types of Wastes Generated in Asunción, Paraguay (wt. %)

Material	Residential	Commercial	Market	Street Sweepings
Putrescibles	70.8	57.9	83.7	23.1
Wood	0.5	2.1	3.4	0
Cardboard	3.1	3.9	3.4	0.8
Paper	8.0	17.0	3.9	3.3
Ferrous	2.6	1.8	0.3	0.5
Glass	4.8	9.9	2.3	2.5
Plastic	3.9	4.8	2.6	1.6
Leather	0.4	0	0	0
Textiles	2.2	1.2	0.1	0.6
Dirt	3.7	1.4	0.3	67.6
Bulk Density (kg/m^3)	384	304	432	688

Source: CalRecovery, Inc.

The starting point for estimation of disposed waste stream characteristics is composition, i.e., the mass fraction of the various components (or types of materials). Using the composition and the characteristics of the individual components, the characteristics of a mixture of components can be calculated in those cases or under those conditions in which the characteristic of interest is a conserved characteristic on a mass basis. A conserved characteristic on a mass basis is one that observes the law of conservation of mass and one in which any losses due to conversion of mass to energy are insignificant. In simple terms, this condition specifies that in a system, the final mass of a conserved characteristic will equal its initial mass.

Characteristics that comply with the conservation of mass and that both affect and are relevant to landfill design and operation include moisture content and elemental content (e.g., heavy metals, carbon, and oxygen).

In the case of mixed solid waste entering a processing or disposal facility, a conserved property of the mixture can be estimated based on a knowledge of the composition of the mixture and of the characteristics of the components of the mixture. The governing relation is:

$$P = \sum_{i=1}^{n} (mf_i * p_i)$$

where:

P = the value of the conserved property, or characteristic, of the mixture of n components;

mf_i is the mass fraction of component "i;" and

p_i is the concentration of property "p" in component i.

The values of non-conserved characteristics do not adhere to a summation of the multiplication of mass fraction *i* and property *i* over all of the components. An example of a non-conserved characteristic is the property of bulk density.

4.3.2 Waste Quantities

Disposed waste quantities can be estimated using several different methods. In terms of accurately and precisely determining the quantities of waste that are generated or disposed over a fixed period of time, weight surveys are the most reliable method. In a weight survey, vehicle weigh scales are used to measure the loaded and empty weights of the vehicles collecting or disposing of loads of waste. The net weight is computed directly as the difference of the loaded and empty weights. The ideal situation is to weigh all of the loads of waste; however, practicality may dictate that only a representative sampling of loads be weighed. Either portable or permanent vehicle scales represent feasible methods of weighing.

The other methods of determining quantities of waste are less accurate and precise than the method described in the preceding paragraph. In order of descending preference, the other feasible options for estimation of quantities use the following procedures:

1. <u>Vehicle count and in-vehicle bulk density of the waste</u>

   This method relies on the collection of the following data over an appropriate interval of time to secure representative results: number count of vehicles, an estimate of volume of the load, and in-vehicle bulk densities for the wastes. The in-vehicle bulk densities can be determined through a weight survey. One of the greater contributors to error in this method is inaccuracies associated with estimating volumes, particularly the volumes of wastes contained in compaction vehicles and other covered loads. (Although not recommended and only for use in cases of financial hardship and of last resort, in-vehicle bulk densities of wastes can be estimated from data in the literature, as long as relevant values are selected from the many that can be found in the literature.)

$$Q\,(kg) = \sum_{i=1}^{n} [volume\,(m^3)\; x\; bulk\ density\,(kg\,/\,m^3)]_i$$

2. Vehicle count and average weight of load of waste

This method is similar to that described immediately above. The main difference is that an average weight of a load of waste is determined as opposed to estimating the volume of the load and applying a value for the bulk density of the wastes.

$$Q\,(kg) = \sum_{i=1}^{n} [avg\ load\ weight\,(kg)]_i$$

Regardless of the method selected for estimating waste quantities, the utility and the accuracy and precision of the estimates can be increased substantially by measuring and compiling the data by type of generator (or source) and by type of collection vehicle [3]. In many instances, the type of generator (e.g., residential) can be related directly to the type of collection vehicle (e.g., rear loading packer). Additionally, the collection of statistical data and information regarding the demographics of the area from which the wastes are collected allows the computation of unit rates (i.e., per capita) of collected wastes and further expands the utility of the data collection activities and analysis. Many factors influence the unit rate of generation of solid wastes, including social and cultural customs, level of technical and economic development, and climate. For a point of reference, unit rates of residential waste generation in economically developing countries typically are in the range of 0.2 to 1.0 kg/capita/day, based on quantities of collected waste from several economically developing countries. The unit values of waste generation, along with population data and other demographic statistics, can be used to estimate approximately the quantities of waste produced over a different universe of the same types of generators or collection vehicles. As alluded to in Chapter 2, if the quantities of collected wastes are to be used to estimate the current quantities of disposed wastes or the quantities that would be disposed if the collection coverage were expanded, the effect of expansion of collection coverage, of scavenging (resource recovery) prior to disposal of the wastes, or both must be accommodated during the process of estimating quantities of disposed wastes.

If resources are lacking for the collection of detailed data concerning generated and disposed wastes, estimates can be made using judiciously selected unit rates of generation and population. This method of estimation is suitable for planning purposes but is not a substitute for the collection of actual data for the purpose of designing and implementing a landfill.

With the selection of appropriate assumptions, the current estimates of disposed waste quantities can be projected to future estimates of quantities of disposed wastes. The identification and quantification of the assumptions primarily involves consideration of: 1) the degree of collection coverage and of the extent of resource recovery in the future, and 2) the rate of growth of population and of economic development.

The initial timeframe of a waste quantification study should be one year, with periodic sampling events scheduled at least quarterly or semi-annually for a duration of at least one to two weeks. In no case should the duration of the periodic sampling activities for a particular type of sampled population be less than the periodicity of scheduled waste collection. For example, if the frequency of waste collection is once every two weeks, then the duration of the sampling period should be at least two weeks. This suggested frequency and duration of sampling and measurement events will provide sufficient data and analyses to allow judgement of the accuracy and precision of the data and the trend of the data. Once these judgements are made, the frequency and duration of subsequent surveys should be adjusted accordingly.

4.3.3 Composition

The composition of disposed wastes can be determined by sampling and sorting representative samples of waste into specified material categories using scientific methods. The number of material categories sorted is a function of a number of variables, including local recycling activities and financial resources. The minimum suggested categories of the initial analysis are shown in Table 4-5.

Table 4-5. Minimum Suggested Composition Categories

Category	Subcategory
Organic Materials	
Paper	Corrugated paper and containers Newspaper Other paper
Plastic	Film Rigid
Food and Market Wastes	
Yard Waste	
Other Organics	(wood, leather goods, etc.)
Inorganic Materials	
Metals	Aluminum beverage containers Steel food and beverage containers Other
Glass	Food and beverage containers Other
Other Inorganics	(concrete, ash, dirt, etc.)
Hazardous and Special Wastes	(toxic wastes, sludges, bulky wastes, batteries, etc.)

The categories shown in the table can be divided further into subcategories, as shown, if such a level of detail is needed, such as for purposes of recycling. The list of sorted materials should be modified, if appropriate, after the results of the initial (and subsequent) sampling and sorting event(s) are analyzed.

The wastes can be sampled at the place of generation, at a waste transfer facility, or at a disposal site, depending on the configuration of the local collection and disposal system. The initial data collection effort should be conducted quarterly or semi-annually over a period of 12 months, with each sampling event encompassing at least a 1- to 2-week period, in order to achieve the collection of reasonably accurate data on the composition of a community's waste output. Similar to the waste quantification study, the length of the sampling period for analyzing the waste composition of a particular sample population should be no less than the minimum period of waste collection service.

As in the case of determining waste quantities, samples of wastes should be analyzed from different types of generators and from different types of vehicles in order to provide data of maximum utility to facility design.

With respect to sample size for determinations involving the composition of residential and commercial wastes, the minimum weight per sample should be on the order of 100 kg. If the weight of the sample is less than 100 kg, then the possibility of obtaining a representative sample is lessened. Accuracy and precision are closely related to the particle size distribution of the material to be sampled. Wastes, or loads of waste, containing large particles (e.g., construction and demolition debris) may require larger sample weights in order to ensure that a representative sample of the waste is collected and analyzed.

The magnitude of errors due to change in moisture content and loss through decomposition can be reduced by beginning the analysis of the samples within 2 to 3 hours after collection.

The recommended method for determination of solid waste composition is that promulgated by the American Society for Testing and Materials (ASTM Designation D 5231-92, *Standard Test Method for Determination of the Composition of Unprocessed Municipal Solid Waste*). The Method describes the procedures and methods for selecting and collecting representative samples from a vehicle load of waste for analysis; for manual sorting, weighing, and recording data; and for statistically analyzing and presenting the data. The accuracy of a composition analysis is a function of the number of samples that are collected and sorted. As a guideline and assuming resources are limited, sampling and sorting should be initially conducted twice per year, with the duration of each study being equal to or greater than the frequency of collection (e.g., 7 days) and with the sampling of 10 to 30 vehicle loads of waste. The samples should be drawn from among the various types of waste generators specific to the area, e.g., residential, industrial.

4.3.4 Other Physical Characteristics

A knowledge of several other characteristics of solid wastes also is required for the proper design and successful operation of a landfill. Among the more important physical characteristics are: 1) moisture content, 2) bulk density, and 3) particle size distribution. For example, a knowledge of the moisture content of solid waste is required in the analysis of leachate production and in the design of material handling systems at the fill. Also, the bulk density of the waste as delivered to the disposal facility must be known to estimate waste quantities in some cases and to estimate the requirements for cover material. An important relation is that bulk density is very sensitive to moisture content. Lastly, the physical size (i.e., particle size) of wastes entering a landfill influences the manner of handling and processing. Large quantities of bulky wastes (i.e., materials of large particle size; e.g., discarded railroad ties, conduit, telephone poles) delivered to a landfill at one time represent operational problems if their existence in the waste stream was not known when the operating plan for the landfill facility was developed.

A quantitative knowledge of the above characteristics is best; but in the absence of quantification, landfill designers and operators should at a minimum have a knowledge of the three above-mentioned physical properties. Methods of qualitative assessment include visual observation of all of the types of solid wastes under current consideration for disposal, as well as observation of wastes delivered to disposal sites in other locations serving populations with similar characteristics as that in question.

In the following subsections, methods and procedures are given for quantitative analysis of moisture content and bulk density. The conduct of the analyses described below requires that a representative sample of wastes be collected. A variety of methods for sampling can be used. One common method consists of mixing sufficient quantities of wastes into a pile such that they are representative of the wastes designated for study and subsequently randomly selecting one-quarter of the pile's volume as the analytical sample (this procedure is called the cone-and-quartering method). In the case of domestic wastes, analytical sample weights in the range of 50 to 200 kg usually would be adequate for determination of uncompacted bulk density and of moisture content unless data are available to indicate that a different weight of sample is needed.

4.3.4.1 Moisture Content

The procedure for determining moisture content is as follows:

1. Weigh the sample as received ("wet weight").

2. Oven dry the sample at 80 to 100°C until no change in weight occurs. Air drying of the sample can be used prior to oven drying if such a procedure is convenient and improves productivity.

3. Determine the moisture content (%) through the following formula:

$$\frac{W_W - W_D}{W_W} x\, 100\%$$

where:

W_W = wet weight of sample, and

W_D = dry weight of sample.

The weight of the sample for determination of moisture content should be sufficiently large to ensure that the measured moisture content is representative of the sampled population. In the case of residential and commercial solid waste, a sample weight of about 25 to 50 kg usually is sufficient. The oven drying of wet, mixed solid waste requires that a large oven be available (e.g., a kitchen oven or commercial, laboratory oven) and that the sample of waste be oven dried in batches if the oven cannot accommodate the entire sample at one time.

Since a sufficiently large oven may not be available for this analysis, an acceptable procedure is to air dry the sample to constant weight, calculate the air dry moisture content as a percent of the wet weight, and add 8 to 10% to the calculated percentage to convert the air-dry moisture percentage to an oven-dry value. This procedure will provide an estimate of the oven-dry moisture content. The difference between the air-dry moisture content and that based on oven drying (i.e., the 8 to 10%) can be determined (or confirmed) experimentally for local conditions by air and oven drying several samples of waste.

The most accurate method of determining oven-dry moisture content of the sample is to oven dry the material.

4.3.4.2 Bulk Density

The uncompacted bulk density of solid waste can be measured by filling a container of known volume with wastes and weighing the loaded container. The measurement of uncompacted bulk density is sensitive to the relation of the dimensions of the container to the particle size distribution of the sampled material. The smallest linear dimension of the container should be at least three times the largest linear dimension of the material particles. Also, the container should be agitated slightly and topped off, if possible, to reduce void space; thus resulting in a representative value of the bulk density of the sampled population. The bulk density is calculated by dividing the net weight of the waste (weight of loaded container minus weight of the container when empty) by its volume. The result is expressed as kg/m^3.

4.3.5 Estimating Gas and Leachate Production

Gas production and leachate production depend on the types of materials placed in the landfill and on their physical, chemical, and biological properties, as well as the operating and environmental conditions in and around the fill. Estimates of gas production and composition can be made based on the estimated elemental analysis of the wastes and the assumption of an anaerobic chemical reaction. Estimates of the concentrations of chemical compounds in the leachate (e.g., the conserved soluble compounds such as chloride) can be made using the estimated loading rates of chemical compounds inherently in the wastes entering the fill and estimates of water flows through the fill, using any one of a number of models for chemical reactions and for hydraulic flows in a landfill system.

The processes of estimation described in the previous paragraph require the use of professional judgement, as well as the use of basic mass balances and chemistry. Professional judgement includes taking into account the effects that are not readily reduced to basic principles when dealing with a landfill environment. The effects include degree of solubility of metals and rate-associated phenomena (e.g., rates of gas and leachate formation, and absorption). However, estimates can be performed on the basis of worst-case or best-case conditions (e.g., all of a chemical compound becomes soluble in the leachate) and modified based on the incorporation of professional experience and the availability of laboratory or field measurements.

Gas production, as well as composition, can be estimated using the basic chemical reaction for an anaerobic process of decomposition. An example is given in Table 4-6. The example illustrates the anaerobic decomposition of a hypothetical mixture of solid waste (on a dry-weight basis and with a specified volatile solids content of 75%), assuming complete conversion of carbon to carbon dioxide and methane.

Table 4-6. Estimation of Landfill Gas Production from Ultimate Analysis of Solid Waste

Governing equation for anaerobic process of decomposition:

$$C_aH_bO_cN_d + [(4a-b-2c+3d)/4]H_2O \rightarrow [(4a+b-2c-3d)/8]CH_4 + [(4a-b+2c+3d)/8]CO_2 + dNH_3$$

where:

C = carbon; H = hydrogen; O = oxygen; N = nitrogen; and
a, b, c, and d = number of moles.

Volatile solids content is assumed to be 75% on a dry weight basis.

The estimations below are based on dry weight of solid waste.

Feedstock

Element	Moles	Atomic Weight	Mass Fraction
C	30	12.01	0.54
H	48	1.01	0.07
O	16	16	0.38
N	0.5	14.01	0.01
			1.00

Landfill Gas Production

Gas Specie	Molecular Weight	Moles	Mass Fraction (kgo/kgvs)	Mass Fraction (kgo/kgi)	Gas Comp. (%)
CH_4	16.05	16.81	0.40	0.30	31.4
CO_2	44.01	13.19	0.86	0.65	67.6
NH_3	17.04	0.50	0.01	0.01	1.0

Legend: kgo = kg output
kgi = kg in of feedstock
kgvs = kg volatile solids in feedstock

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Chapter 5

Waste Diversion Impacts on Landfills

5.1 Introduction

The importance of the characteristics of the wastes entering the landfill was introduced and discussed in Chapters 2 and 4. Prior to landfilling, the characteristics of the wastes can be influenced or manipulated at several points along the path from the point of generation to the point of disposal. Waste diversion programs (i.e., those methods and strategies that reduce the quantities and types of materials discarded for final disposal, that result in the recycling of materials, or both) directly influence and control both the quantity and the properties of the waste stream that enters a land disposal facility. Thus, the planning, design, and implementation of the facility are sensitive to the extent and nature of waste diversion programs. The greater the extent of waste diversion programs, the greater is their impact on the types and quantities of wastes that will be delivered to the disposal site, and thus on the design and operation of the facility. Additionally, if recycling of materials follows the trends of the past 10 years in a number of the industrialized countries, the wastes entering disposal sites should be considered to be in a dynamic condition in terms of quantities and characteristics, and thus require close monitoring. One result of a successful diversion program is that less waste requires disposal; thus, less new disposal capacity is required, or the life of an existing landfill volume is extended.

There are several types of waste diversion programs. Examples include:

- programs that eliminate or reduce the quantities, toxicity, or both of materials entering a land disposal facility; and

- governmentally sanctioned, or unsanctioned (i.e., informal), recycling activities instituted at the point of collection, exercised during the collection process, or exercised immediately prior to covering of the wastes, or any combination of these practices.

5.2 Types of Diversion Programs and Impacts

For the purpose of the guidance document, diversion programs are categorized into the following: waste reduction, recycling, scavenging, composting, and energy recovery.

Waste reduction programs are implemented at the point of waste generation and include those that reduce or eliminate quantities and/or hazardous characteristics of discarded wastes. Recycling programs are defined to be those that are governmentally sanctioned (i.e., formal programs). The recycling programs can be implemented at the point of waste generation and collection (termed "source separation" programs) and/or at a facility or location that is dedicated to the recovery of secondary materials from mixed MSW. In the case of source separation, the generator separates the materials of value from the other materials (i.e., those that have no net value) and sets them out separately for collection and for processing (in a source-separated materials recovery facility). In the case of recovery of materials from mixed waste at a processing facility or location (e.g., a transfer station or a dedicated mixed waste materials recovery facility), the recovery can be effected using manual labor, mechanical processing, or both. The processing can be conducted at a processing facility on or near the landfill.

Scavenging is the unsanctioned removal (or recovery) and marketing of materials of value from discarded wastes. This activity can occur anywhere from the point of setout of the wastes to the point immediately before the covering of the wastes at the landfill. Commonly, in economically developing countries, scavenging occurs during collection and at the disposal site.

Composting is the controlled biological decomposition of organic materials. Discarded organic materials can be composted using one of a number of low or high technology processes. Conventional composting programs include those that collect and process source-separated organic materials and those that process mixed wastes and recover and compost a predominantly organic fraction. Regardless of the manner of collection and recovery of organic materials, the end product of composting is a soil amendment. Given the proper conditions, composting can also be carried out at the point of generation.

Energy recovery is the use of discarded materials for the production of energy using any number of energy conversion processes (e.g., direct combustion, anaerobic digestion, thermal gasification). Discarded combustible materials are the materials sought for energy conversion processes. These types of materials can be furnished by waste management programs that collect and process source-separated combustible materials (e.g., mixed paper) or by mixed waste processing facilities that recover a combustible fraction (i.e., refuse-derived fuel (RDF) systems).

5.3 General Impacts of Waste Diversion Programs

Generalizations regarding the influence of diversion programs on disposed waste quantities and characteristics are difficult when considering the entire economically developing world. Consequently, for the purpose of providing some understanding of the dependence of disposed waste characteristics in economically developing countries on materials diverted prior to landfilling, some examples can be offered of typical conditions and influences.

Programs that divert containers (e.g., glass and metal) result in a net increase in the moisture content and in the organic content of discarded wastes, unless putrescible materials are also diverted. Putrescible materials usually are high in moisture content.

Programs that divert substantial percentages of putrescible materials (e.g., food preparation residues, yard (green) wastes, and market wastes) from generated waste, and no other types of materials, yield a drier and more inorganic disposed waste stream than if the putrescibles are disposed with the mixed wastes.

5.4 Estimation of Diversion Impacts on Landfills

Aggressive diversion programs can substantially change the current characteristics of the wastes that reach the final disposal site. If aggressive diversion programs are implemented, the quantities of wastes that will require disposal will decrease and the characteristics will be changed.

The characteristics of disposed wastes can be estimated based either on relevant information that can be found in the literature concerning the properties of solid waste or its components or on waste characteristics that are measured locally. In addition, the process requires the use of fundamental relations that govern the estimation of the material properties of a mixture based on the properties of the individual components.

Waste properties of utility in the design and operation of landfills include the density of the waste in its as-delivered state, the chemical compounds present in the waste, the moisture content of the waste, and the composition of the waste.

The impacts of diversion programs on the quantities and composition of wastes entering landfills depend on the specific types of diversion programs and on the rate of diversion. A material balance and estimates of the effectiveness of the diversion programs (i.e., percentage of generated wastes that are diverted from the generated waste stream) can be used to calculate the impacts. Illustrations of the impacts of different levels of diversion on disposed waste quantities and composition are shown in Table 5-1.

Table 5-1. Examples of Impacts of Different Levels of Diversion on the Composition of Disposed Municipal Wastes[a]

Material Type	Gen. Comp.[b] (%)	Low			Medium			High		
		% Diverted	Dis-posed Mass[c]	Dis-posed Comp. (%)	% Diverted	Dis-posed Mass	Dis-posed Comp. (%)	% Diverted	Dis-posed Mass	Dis-posed Comp. (%)
Metals	3.0	10	2.7	2.8	25	2.3	3.0	50	1.5	3.1
Glass	3.0	10	2.7	2.8	25	2.3	3.0	50	1.5	3.1
Plastics	4.0	10	3.6	3.7	25	3.0	4.0	50	2.0	4.1
Other Inerts	15.0	0	15.0	15.5	0	15.0	20.2	0	15.0	31.1
Subtotal Inerts	25.0		24.0	24.7		22.5	30.3		20.0	41.4
Paper	20.0	10	18.0	18.6	25	15.0	20.2	50	10.0	20.7
Putrescibles	52.0	0	52.0	53.6	35	33.8	45.5	70	15.6	32.3
Subtotal Organics	72.0		70.0	72.2		48.8	65.7		25.6	53.0
Textiles	3.0	0	3.0	3.1	0	3.0	4.0	10	2.7	5.6
Total	100.0		97.0	100.0		74.3	100.0		48.3	100.0

[a] Sums may not total exactly due to rounding.
[b] Gen. Comp. = composition of generated waste.
[c] For this illustration, mass can be any unit of mass (e.g., kg).

An estimate of the elemental properties of disposed wastes can be calculated from an estimate of the disposed waste composition. An illustration of the estimation of the concentration of the metal lead (Pb) entering a disposal site, based on the diversion scenarios described in Table 5-1, is given in Table 5-2.

An example illustrating the impact of diversion programs on the average ultimate (i.e., carbon, hydrogen, oxygen, and nitrogen) analysis of discarded mixture of solid wastes entering a landfill is given in Table 5-3.

Table 5-2. Examples of Impacts of Different Levels of Diversion on the Concentration of Lead (Pb) Entering a Landfill[a]

Material Type (i)	Pb Conc. (mg/kg_i)	Diversion Rate: Low — Disposed Comp. (%)	Diversion Rate: Medium — Disposed Comp. (%)	Diversion Rate: High — Disposed Comp. (%)	Pb Loadings (mg/kg MSW): Low	Pb Loadings (mg/kg MSW): Medium	Pb Loadings (mg/kg MSW): High
Metals	200	2.8	3.0	3.1	5.6	6.1	6.2
Glass	0	2.8	3.0	3.1	0	0	0
Plastics	20	3.7	4.0	4.1	0.7	0.8	0.8
Other Inerts	100	15.5	20.2	31.1	15.5	20.2	31.1
Subtotal Inerts	NA	24.7	30.3	41.4	21.8	27.1	38.1
Paper	40	18.6	20.2	20.7	7.4	8.1	8.3
Putrescibles	10	53.6	45.5	32.3	5.4	4.5	3.2
Subtotal Organics	NA[b]	72.2	65.7	53.0	12.8	12.6	11.5
Textiles	5	3.1	4.0	5.6	0.2	0.2	0.3
Total	NA	100.0	100.0	100.0	34.7	39.9	49.9

[a] All data are on a wet-weight basis; sums may not total exactly due to rounding.
[b] NA = not applicable.

The implementation of diversion programs and changes in the characteristics of disposed wastes can influence the production and characteristics of landfill gas. Gas production is fundamentally governed by the ultimate analysis of the landfilled wastes and by conditions in the landfill.

The discussions and examples presented in the preceding paragraphs of this subsection illustrate that waste diversion programs can have a major impact on the quantity and characteristics of the wastes reaching the final disposal site. Very few of these types of programs have been implemented in economically developing countries and, consequently,

Table 5-3. Examples of Estimation of Ultimate Analysis of Municipal Solid Waste (MSW)

Waste Component	Comp. (% wet wt.)	Ultimate Analysis (% dry weight)			
		C	H	O	N
Ferrous	3.9	0.8	0	0.2	0
Aluminum	1.2	0.8	0	0.2	0
Glass	5.0	0.5	0.1	0.4	0
Mixed Paper	21.5	44.0	6.2	41.7	0.4
Newspaper	11.6	48.8	6.1	42.7	0.1
Corrugated	4.3	45.5	6.1	44.5	0.2
Plastic	11.5	59.8	8.3	19.0	1.0
Yard Waste	10.1	49.3	6.4	36.3	3.0
Food Waste	15.0	41.7	5.8	27.6	2.8
Other Inorganics	7.1	0.5	0.1	0.4	0
Other Organics	8.8	48.8	6.1	28.3	1.8
MSW	100.0	38.3	5.1	27.2	0.8

Note: Balance of dry weight percentage is sulfur, chlorine, and ash.

little data are available in the literature on any impacts. However, based on the composition of the wastes, experiences had in industrialized countries, and the examples presented in the previous subsections, a few general statements can be made.

In many economically developing countries, the main component of the waste stream is organic (putrescible matter). Consequently, the implementation of any type of program aimed at the diversion of organic matter from final disposal would result in a substantial reduction in the production of gas, and the characteristics of the leachate would be substantially different. For instance, the leachate would have the tendency to contain substantially lower concentrations of biological oxygen demand (BOD) and chemical oxygen demand (COD). Currently, the tendency in several industrialized countries is to develop solid waste management strategies aimed at the processing or removal of most organic matter from the waste prior to disposal on the land. In some cases, the policies are aimed at reaching a concentration of about 5% volatile solids in the materials suitable for final disposal.

Diversion of large percentages of organic matter from disposal also has other impacts on the design and operation of a landfill. Some of the potentially positive benefits include: lower risk of generation of odors, the waste would be less attractive to animals for feeding, and less settlement.

On the other hand, if the diversion programs are limited to removing only those materials that typically are recycled in economically developing countries, such as paper products, some metals, glass containers, plastics, and textiles, the quantities and characteristics of the leachate would probably remain about the same.

Chapter 6

Site Selection

This chapter discusses the process that generally is required for the development of a site for a landfill. The process can be lengthy -- a 5- to 10-year period typically is required in the United States in order to locate suitable land from an engineering standpoint, to secure the approval of the public, and to obtain regulatory approval.

6.1 Non-Geological Aspects

The discussion in this section encompasses the principal non-geological elements that should be considered in the site selection process.

6.1.1 Defining the Need for a Site

Several elements must be considered during an evaluation of the need for a land disposal facility. The overall process involves the identification of waste quantities and characteristics requiring disposal, development of site selection criteria, location of feasible land disposal sites, analysis of the sites, and final selection of a site. In addition to defining the conditions of the current situation, the analysis should consider planned changes to existing systems (e.g., waste collection coverage) and the influence of growth of population, new industrial development, etc.

6.1.1.1 Different Types of Waste to be Accommodated

One of the first steps in the planning process is the definition of the quantities and characteristics of the wastes that are planned to be accepted and landfilled. Unless special or unusual circumstances or requirements exist, the usual types of solid waste accepted at a landfill are residential, commercial, and industrial wastes. Some other types of waste also can be acceptable at a landfill, as described in Chapter 4.

For a given wasteshed, local conditions and circumstances will dictate the type of waste generators and the quantities and characteristics of the solid waste stream. As mentioned previously (Chapter 4), some of the solid wastes generated by industry may have characteristics that dictate that they be handled separately at the landfill site.

6.1.1.2 Measuring Quantities

The knowledge of the types of waste must be supplemented by a determination of the waste quantities, both current and those projected over the planning period. Thus, one objective of the quantification study is to arrive at the current annual quantities of waste to be disposed per unit of time (e.g., Mg/yr). The second objective is to estimate the quantities of waste for subsequent years of the project planning period. The projections usually are based on the current quantities and escalated (or de-escalated) by a mathematical formula. Predicting future quantities of waste is an inexact science, although several methods and procedures have been tried in the past. The use of population projections is suggested as a means of sufficiently estimating future quantities of waste generation. The impact of resource recovery, as well as some other factors, must also be considered during the process of estimation, as related in Chapters 4 and 5.

6.1.1.3 Determining Waste Composition

It is important to have a good understanding of the characteristics of the waste requiring final disposal. Among other impacts, for a given mass of solid wastes, the composition of waste influences in-place density, number of vehicles using the site, land area required, and the amount of cover material needed. Waste composition is discussed in greater detail in Chapter 4.

6.1.2 Review of Existing Facilities

The next stage in planning the final disposal strategy and selecting a suitable site is to perform a thorough review of all of the existing facilities. Part of this task requires an analysis of all existing sites and a calculation of remaining disposal capacity. This analysis may require some form of topographic surveying in order to facilitate the determination of remaining volumetric capacity.

The remaining volumetric capacity of existing disposal sites can be determined from plans showing the topography of existing sites and of the final contours of the sites. If the plans are not available, they should be prepared. The surveying of waste disposal sites does not need to be carried out to a high degree of accuracy to yield results sufficient for planning purposes. Limiting the accuracy can result in reducing the cost of the surveys, as well as the time to conduct them. In some cases, aerial surveys may be the most efficient method of measuring volumes, particularly if the capacity study encompasses a large number of disposal sites.

Accurate determinations of remaining volumetric disposal capacity and of estimated disposed wastes quantities are crucial to the process of siting a landfill because, taken together, they substantially influence the capacity of the new disposal facility.

After the conclusion of the analyses of remaining volumetric capacity for each existing disposal site, all volumetric capacities of existing facilities are summed. The total volumetric capacity is divided by the quantity and the estimated in-place density of annual waste deliveries, yielding an estimate of the number of years of capacity before a new site is required.

The estimation of the required volume of the new site requires an estimation of in-place density of the waste and of anticipated deliveries of waste quantities. The in-place density varies with type of waste, method and degree of compaction, depth of landfill, and other factors. In the absence of better information, a value of 0.8 to 1.0 Mg/m^3 may be used as an estimate for planning purposes if a substantial compactive effort is planned for the new landfill operation. On the other hand, if the landfill compactive effort is planned to be less (or proves to be lax), the in-place density may be 0.5 Mg/m^3 or lower.

A review of existing land disposal sites and their life expectancy and quality can help convince officials and the public of the need for a new site.

6.1.3 Plan

Once the lifetimes of existing and any other proposed facilities have been calculated, it is useful to develop a workplan for selecting the new site. Following the workplan will ensure that the new site or sites will be in full operation by the time the existing facilities reach capacity. The elements of the workplan usually are dictated by the legal and administrative procedures and requirements in force within the area. Typically, they include the following elements: site selection, preparation of an application for land use and submittal to the governing authority, permitting processes and procedures, and conduct of engineering work. In the preparation of the workplan, an awareness should be had that the process may take a considerable amount of time to complete.

6.1.4 Assessment of Potential Landfill Capacity

Upon completion of the workplan, the next step is to begin identification of prospective sites of the new landfill. First of all, the boundaries of the search area must be established. This procedure should be based on demographic and physical limitations such as political or regional boundaries, mountain ranges, and rivers. Subsequent to defining a search area, a suitable study area is established on the basis of haul distance, topography, geology, and surface and groundwater conditions.

The distance of the landfill site from the area where the waste is generated and is collected (the wasteshed) is the haul distance. If the landfill is near the collection area, then the collection vehicles can travel directly to the landfill. If the landfill is remote from the collection area, some form of transfer station usually is planned because collection vehicles are expensive pieces of equipment and are inefficient for long-distance hauling of waste.

At a transfer station, the waste is transferred from the collection vehicles to a bulk transport system. The transport system typically is composed of tractor-trailer equipment. However, rail-haul has also seen limited use.

Normally at this point in the process, the overall cost of the collection and disposal system is considered and analyzed for the purpose of establishing feasible distances for the disposal site and modes of transportation of wastes to the site. As discussed in Chapter 5, the impact of resource recovery must also be taken into account in the analysis because it affects the quantities of waste that will require disposal, and its cost must be included in the analysis of total system cost.

Landfill sites usually benefit greatly from economies of scale. Thus, a very large, remote landfill may be less costly on the basis of unit cost than a small, local landfill.

6.1.5 Identification of Sites

Once the study area has been identified, keeping in mind the boundaries, the access constraints, and the physical limitations, the next step is to identify suitable sites. The type of site can be one of two general types: mineral excavation areas in which waste can be placed to restore the land, and areas of virgin land where a new landform can be established.

The development of a preliminary list of suitable sites can be substantially improved if maps and site visits are used. After the process of reviewing the site maps and conducting visits is completed, a list of potential sites should be prepared. The list should include the names and locations of the sites, as well as notations about their advantages and disadvantages.

In terms of identifying sites of suitable land area for a landfill, an example of initial screening criteria would be sites containing 20 to 50 ha for a community of about 100,000 population.

6.1.6 Preliminary Selection Process

In this phase of the process, some of the potential sites are eliminated from further consideration, while the remainder are subjected to additional analysis. There are four critical factors in the selection of a potential site: availability, planning constraints, access, and capacity. A brief description of these factors follows:

1. Availability -- It is advantageous if the prospective site is one that is currently owned by the developer of the landfill or is for sale.

2. Planning Constraints -- Acquisition or use of the site may require some form of zoning or special planning. In addition, there may be an environmentally sensitive area, or another form of area requiring protection (e.g., drinking water aquifer). These sites should be eliminated from consideration as soon as any of these conditions are identified.

3. Access -- Experience indicates that access is a critical factor in siting a landfill, particularly a landfill in or near a center of population. In some cases, the general public may be more concerned with truck traffic and congested roadways around the proposed landfill than with the actual landfilling of waste within the boundary of the site. Because of the concern of the public, and to support the efficient operation of the disposal facility, adequate access around the potential site must be available or must be included as part of the design. With regard to adequate access and efficient operation, final disposal is a waste management operation that must be performed regardless of weather conditions.

4. Capacity -- Since the development of a new landfill typically requires considerable time and expense, the site should have an appropriate disposal capacity. A minimum of ten years is usually considered desirable.

Other critical factors concerning the preliminary selection may also enter into the process of evaluation based on local conditions and circumstances. Regardless of the number of evaluation criteria, the primary aim of the preliminary site selection process is to identify about 4 to 6 sites with the potential for development into a landfill.

6.1.7 Environmental Assessment

The next stage of the process is to carry out an environmental assessment of the sites selected in the preliminary analysis. The environmental assessment will require the preparation of designs for each site and the calculation of total system costs for developing and operating each site. Once this is completed, the potential environmental effects of each site can be identified.

The environmental analysis can be facilitated by the development and use of an evaluation form. The form should list each site, each evaluation criterion to be considered, and a weighting factor for each evaluation criterion. The environmental evaluation criteria should be weighted according to their relative importance. At the end of the process of evaluation, the scores for each site can be computed and a ranking of the sites can be prepared accordingly.

The evaluation form should include a listing of all of the possible impacts associated with the development and use of the site, together with certain other information already mentioned, such as costs, access, and capacity. Specific items that should be addressed in the analysis include those that are described below. Also indicated below for each criterion are suggested values for the weighting factors (in percent) in the absence of another allocation of importance based upon local conditions and circumstances:

- the effects of the construction and operation of the landfill on human populations near the proposed site or along major access roads (20%);
- the effects on the local flora and fauna (20%);

- the nature and potential consequences of the underlying and surface geology (30%); and
- the effects of potential emissions from the site to land, water, and air resources (30%).

Once the evaluation form has been completed, each site can be carefully evaluated and the potential environmental impacts assessed. Then, potential mitigations for adverse environmental impacts can be identified. An example of a mitigation is building along a bypass road, or the erection of a berm to reduce the noise from, or visual impact of, a landfill. The cost of the mitigations should be added to the cost of planning and implementing the site under evaluation.

Upon completion of these tasks, the next step is to reject some of the sites and reduce the number of potential sites to two or three. At this point, it is advisable to consult with the public.

6.1.8 Public Awareness Campaign

Public interest in environmental matters has increased substantially in recent years. The point at which the developer of a landfill should seek public input or present a proposal to the public is a matter for debate.

If public input is sought too early, unnecessary opposition may be brought about. On the other hand, if the consultation of the public is sought too late in the process, the public may doubt that its comments and advice will be taken seriously.

When several realistic alternatives emerge from the selection process that has been described previously, the time is appropriate for notification of the public and for public review and comment.

The concerns of the general public with regard to the siting and operation of a landfill include the following, broken down by topic:

- Proximity -- the relative distance between the site or access route and the human populations near the proposed site;

- Economic -- the concern of those living near the proposed landfill that property values will decline;

- Leisure Use -- the view that the presence of the proposed landfill will negatively impact leisure activities (e.g., fishing, hiking); and

- Social -- the perception that the presence of a landfill diminishes the quality of life of those living or working near the site.

One of the more important steps that municipal officials or landfill developers can take to solicit public support for a new landfill is to convert any existing open dumps or poorly operated land disposal sites into well-run landfills, including a well-defined plan for the final use of the completed landfill.

6.1.8.1 Objectives of a Public Awareness Campaign

The success of a public awareness campaign for securing the approval of the public for a landfill depends on the formulation of a set of clear objectives. Suggested objectives are the following:

- to ascertain that the public understands the proposals and the purpose and need for developing and operating the landfill,

- to assure the public that its views will be heard and addressed,

- to ensure that the government or public authority is responsive to the public, and

- to provide opportunities for public involvement in the decision-making process.

6.1.8.2 Advantages of a Public Awareness Campaign

Some of the advantages of a public awareness campaign, having the objectives mentioned in the preceding paragraph, include:

- an increase in the likelihood of gaining the support of the public for the landfill plan,
- possibility of providing useful information which otherwise may have been missed,
- familiarization of the public with the final design and intended use(s) of the landfill which may directly benefit the community (e.g., land use as a park),
- assurance to the public that all views have been considered,
- accountability by decision-makers, and
- an effective mechanism to ensure that decision-makers take into account all issues relevant to the public and to the project.

6.1.8.3 Disadvantages of a Public Awareness Campaign

Some of the potential disadvantages of a public awareness campaign include:

- the public becoming mired in certain issues to the exclusion of others,
- uninformed participants that may distribute erroneous information,
- public involvement which adds to the total cost of the project,
- delays that may be brought about by the process of informing the public, and
- the landfill project may become a platform for politicians.

While the disadvantages are listed for the sake of thoroughly discussing the process of involving the public, the magnitudes of the disadvantages listed above are not sufficient to outweigh the benefits of an effective public awareness campaign.

6.1.8.4 Steps in the Public Awareness Campaign

The following is a list of the more important steps of a public awareness campaign:

1. Inform the public of all details of the plan.

2. Establish the need for the new site by explaining the situation, including the status of the existing facilities and the reason that a new disposal site is needed.

3. Explain the alternatives that have been considered and the reasons that they have been rejected or selected.

4. Explain the operations, the process for managing the site, control of leachate and gas, and closure and post-closure procedures.

5. Describe the impacts of the development and operation of the landfill on the local environment and on the people who may be affected.

6. Make every effort to clearly understand the concerns of people who live near the site.

7. Keep options open. If new information becomes available as a result of the consultation with the public, then the selection process should have the flexibility to incorporate the public's comments into the final selection.

8. Review previous assessments of environmental impacts of the potential sites as new or more information is collected as a consequence of the discussions of the situation with people and businesses affected by the proposal.

Finally, the final selection should be made. At this point, the municipality or landfill developer is ready to present a formal application for the development and use of the site. Many of the results and findings of the site selection process will be of use or will be required during the preparation of the final design and the operational plans.

Although the discussion in the preceding sections of this chapter generally have considered that the siting of one landfill is the optimum situation, in some cases multiple disposal sites may be necessary or required given the circumstances. For example, in the case of a large municipality or urban region with little experience in the development of landfills, several small disposal sites might prove to be easier to implement and manage in the short run than one relatively large site.

6.2 Geological Aspects

6.2.1 Introduction

The application of the scientific and engineering disciplines of geology, hydrogeology, and hydrology to landfills requires several years of study and of practical experience. With this realization, the aim of this section is modest. It is meant to serve as an aid to the reader in understanding the key aspects of the above-mentioned disciplines and their relation to the selection of sites appropriate to landfilling of solid waste.

The degree of risk of contaminating land and water resources as a consequence of landfilling solid wastes depends largely upon the geology and hydrogeology of the site.

During the site selection process, the geology and hydrogeology of the area must be thoroughly investigated and taken into account at both the regional and the local levels. This knowledge can be used in the following manner: 1) to select the more favorable areas (i.e., those areas that have a low potential risk of adversely affecting the environment) and, once a given area is chosen; 2) to design the landfill so as to further control the potential for contamination.

This section addresses the following items:

- definition of major relevant geological, hydrological, and hydrogeological concepts;

- the manner and processes by which wastes contaminate the environment;
- procedures for conducting a geological-hydrogeological study; and
- description of best case and worse case scenarios.

6.2.2 *Definitions*

6.2.2.1 Geology

Geology can be defined as the systematic study of the material, processes, environments, and history of the earth. Although the four are complementary, it is the nature and structure of the materials themselves that have the greatest impact on a landfill and which, therefore, are the subject of this chapter. While specific technical definitions exist for rock and soil, they are discussed jointly in terms of the relevance and influence on landfill design and in terms of geologic parameters, such as permeability. Rocks, aggregate, and soil are commonly discussed collectively.

<u>Rock and Soil Types</u>

The rock formations present on the surface of the earth and the soils derived therefrom can be broadly subdivided into three types (sedimentary, igneous, and metamorphic), each corresponding to its own mode of formation; all three categories being linked to one another through the "geological cycle" (see Figure 6-1).

Sedimentary

Sedimentary rock and soils are primarily derived from the destruction (erosion or chemical dissolution) of pre-existing rock formations, and their transport and deposition in layers, generally at the bottom of seas or lakes and rivers. Deposition can also take place directly on the surface, such as is the case with aeolian sandstones.

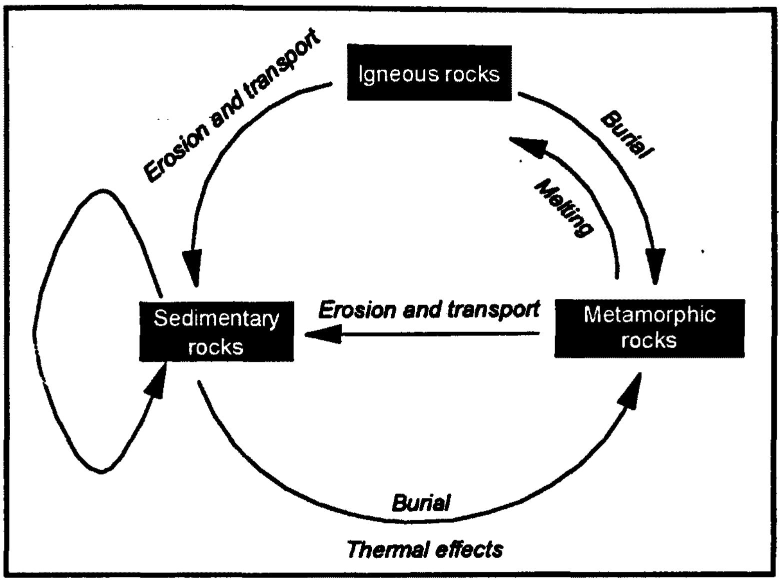


Figure 6-1. The Geological Cycle

Sedimentary rock and soils include conglomerate, sandstones, limestones, chalk, clay, and others.

Igneous

Igneous rock and soils are formed by the cooling of melted magma as it rises to the surface of the earth. The original composition of the melted magma will determine the final characteristics of the cooled rock and their resistance to weathering and fracturing.

Rapidly moving, low-viscosity magma generate the classic volcanic eruptions (basalts, ruffs). Cooler, thicker magma do not move so easily and stop below the surface, where they form coarser rock. This rock becomes exposed on the surface through erosion. Granites are formed in this manner.

Metamorphic

Metamorphic rock formations result from the transformation through heating or regional pressure of existing rock (igneous or sedimentary). The heat and/or pressure applied on the rock can result from the burying of sediments into the depth of the crust, from deformation during the development of mountain ranges, or from the proximity of rising igneous rock. Examples of metamorphic formations include schists, marbles (transformed limestones rock), and gneisses (transformed igneous rock).

A very important distinction can be made between the "hard rock" (basalts, limestones, granites, some sandstones) and the "soft rock" (chalk, clays, soft sand, gravel, weathered granites or basalts). Areas having a relatively high concentration of hard rock are not easily amenable to earth moving equipment and thus are more expensive to work than areas with soft rock and thick soil cover. Soft rock and soils generally can be removed with the use of earth moving equipment.

Geological Hazards

As was previously indicated, geology deals with the study of processes involved in the development of the earth. Most of these processes are slow (e.g., erosion, mountain formation). However, some are very rapid and can drastically alter the surface of the earth. The probability of such processes, grouped under the term geological hazards, to occur must be assessed when looking for a potential landfill site. The most common geological hazards are listed below:

- floods;
- avalanches and lahars (for obvious reasons, but avalanche paths can be easily forgotten, as was the case recently at a French ski resort);
- active seismic zones; and
- fault zones, including inactive zones since they would act as preferential water pathways.

Permeability

Permeability is a term expressing the rate at which water passes through a given medium (substrate). It can be used to describe fluid movements in rock, cement, and other materials. The rate of liquid flow through a medium is fundamentally a function of the characteristics of the medium and the hydraulic pressure gradient. The discussion below refers to the permeability of liquids in fractured rock and soils and, consequently, the values of permeability given in the text relate to the movement of liquid, not to the movement of gases under a pressure gradient.

Permeability (k) is expressed in m/s, or cm/s; the greater the value, the more permeable is the substrate. For example, a highly permeable soil, such as gravel, has a permeability of about 10^{-4} m/s. At the other end of the spectrum, clay is poorly permeable (commonly termed, incorrectly, impermeable) and has a permeability in the range of 10^{-9} to less than 10^{-10} m/s [1]. Water can percolate through clays but at a very slow rate.

Soils can be broadly classified on a permeability scale as follows:

Highly permeable	Permeable	Slightly permeable	Poorly permeable
Gravels	Sand fractured rock	Sandy clays weathered rock	Clays

Examples of typical values of permeability are given for these soil types in Figure 6-2.

However, a given soil type cannot be automatically assigned a definitive k value. The permeability of a material depends on local homogeneity of the substrate (e.g., clay mixed with sand or vice versa), its degree of fracturing, and its state of alternation. Therefore, permeability (k) must always be checked and measured *in situ* to determine the correct local value.

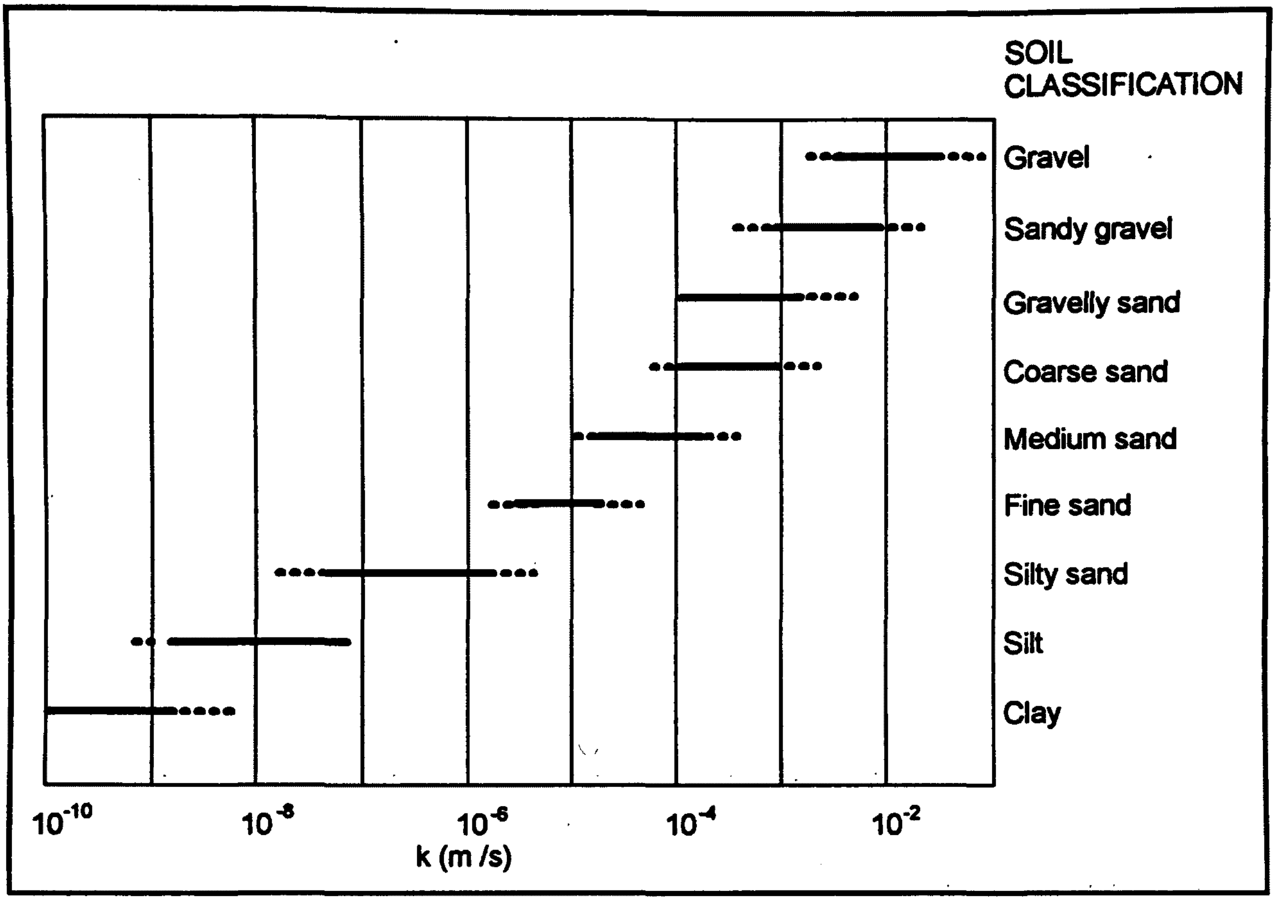


Figure 6-2. Examples of Permeabilities

<u>Geological History</u>

In order to identify the most favorable area for the siting of a landfill, it is necessary to have a good understanding of the historical development of the geological features. Such an understanding allows the identification of the geological hazards previously mentioned.

The understanding of the geological history of an area is achieved through the careful analysis of geological maps, and when these are inadequate or non-existent, through geological mapping and drilling. For instance, the study of a geological map can show the existence of faults under a thin sedimentary cover (not visible on surface); analysis of sedimentary patterns indicates which zones are likely to be homogeneous, permeable, or impermeable; and a study of the geomorphology of rivers, terraces, and recent deposits indicates flood plains.

6.2.2.2 Hydrology

Hydrology is the science that studies the processes involved in the depletion and replenishment of the water resources. These processes can best be understood by examining the water cycle presented in Figure 6-3.

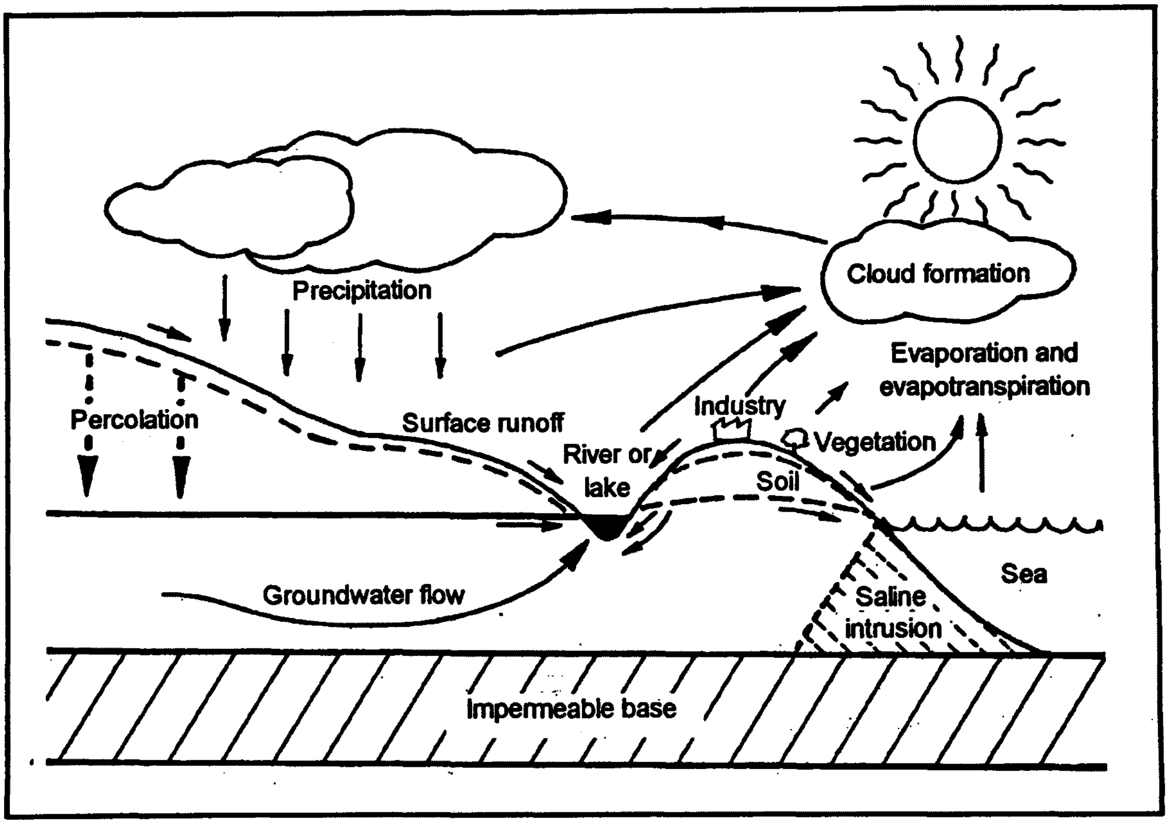


Figure 6-3. The Water Cycle

The driving force for the water cycle is radiant energy from the sun. The radiation results in water evaporating from surfaces; the resulting water vapor becomes part of the atmosphere. Given favorable atmospheric conditions, the water will condense to form clouds from which precipitation may occur. The precipitation may return directly to storage in lakes and oceans, it may accumulate as snow in high mountains and in polar regions, or it may fall as rain over land. In the last case, some of the moisture may be intercepted by vegetation and return to the atmosphere by evaporation. The remainder of the rainfall may collect to form surface runoff or it may enter the ground as infiltration. The surface runoff may then return to storage in lakes and oceans. The water that infiltrates the soil will either be taken up by plant roots and transpired to the atmosphere, or percolate downward through the unsaturated zone and into the water table. The groundwater may then move toward surface discharge points (spring, etc.), where it will become a component of surface runoff moving toward the oceans and lakes.

As far as landfill siting and design is concerned, the following data need to be recorded and assessed.

<u>Climate</u>

Wind, rain or snow, and temperature are climatic conditions that may dictate the type of operation, amount and placement of soil cover, types of roads needed, and type of structures built on a landfill. Hence, to aid in selecting a site for a landfill, it is imperative to have information on: 1) the number of days of wind, freezing temperature, rain or snow; 2) the intensity of precipitation; and 3) the seasonal temperature fluctuations.

Precipitation must be considered with regard to surface water runoff, drainage system requirements, leachate generation, feasibility of sustaining operations at all times on-site, movement of equipment, and access to and from the site. For instance, low-lying sites that might frequently flood or become muddy during rainy weather should not be chosen in areas subject to rainfall of frequent duration.

<u>Climate and Degree of Infiltration</u>

Climate is significant because of its direct bearing on the amount of rainwater that may infiltrate through the unsaturated zone and into a groundwater system. Degree of infiltration is a function of the amount of precipitation, volume of surface ponding and runoff, and the evapotranspiration rate. Ambient temperature and relative humidity also have an impact on infiltration, evaporation, and evapotranspiration. The potential for groundwater degradation from a well-designed and well-constructed landfill in arid and semi-arid regions is quite low, whereas the potential is quite high in humid regions. Another decision factor in selecting a suitable site is the consideration of the seasonality of rainfall.

<u>Stream Density</u>

The likelihood of surface water contamination increases in areas in which an unusually short underground flow path precedes the discharge of contaminants into an area in which streams are closely spaced [2]. However, the overall extent of any groundwater contamination may be limited by subsurface media. Alternately, widely spaced streams may also lead to the development of larger and longer-term groundwater contamination zones.

6.2.2.3 Hydrogeology

Hydrogeology can be defined as the study of groundwater and its chemistry, mode of migration, and relation to the environment. The relationship of groundwater to the water cycle can be seen in Figure 6-3. The possible effect of a landfill on the groundwater regime should always be carefully evaluated.

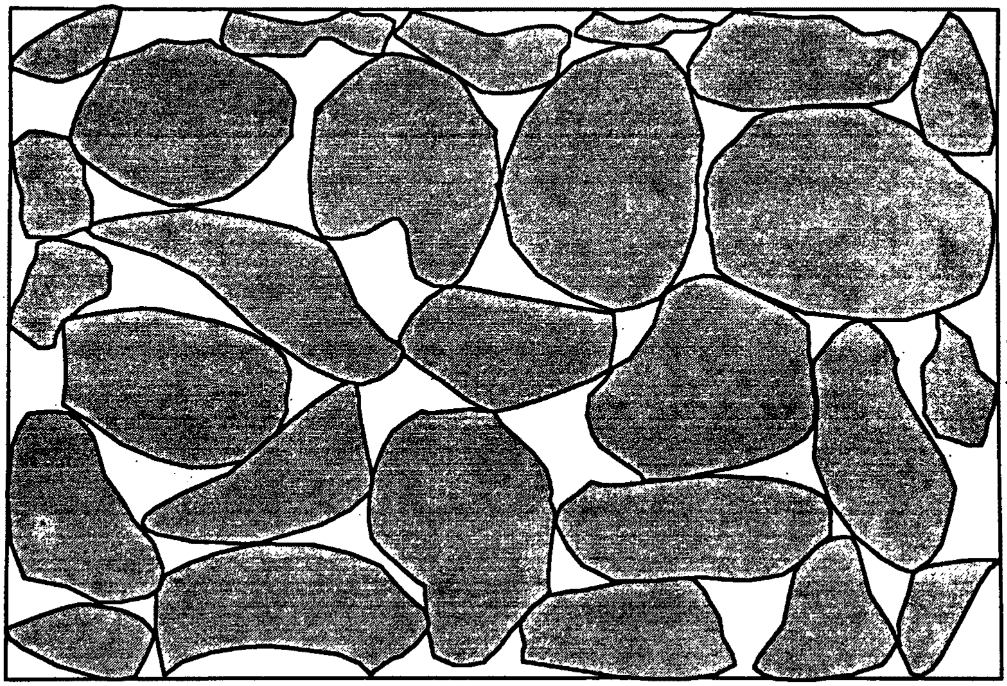
The main terms and parameters necessary to understand and assess the groundwater systems are as follows:

- aquifers,
- recharge and discharge zones,
- saturated/unsaturated zones,
- hydraulic conductivity, and
- porosity and velocity.

Aquifer

An aquifer is a body of rock or soils containing water with sufficient permeability for the water to flow. Three types of aquifers can be distinguished:

1. Sandy Aquifers – In this classification of aquifers, water flows through the voids in between the grains (the intergranular porosity). Such aquifers can be found in sands and gravels. The intergranular porosity is described schematically in Figure 6-4.



(sand, gravel, clay)

Figure 6-4. Intergranular Porosity

2. Fractured Aquifers – These aquifers occur in fractured, poorly permeable rock such as sandstones, chalks, limestone, and volcanic rock. The water flows through interconnecting fractures and cracks (the fissure porosity). A schematic diagram of the fissure porosity is presented in Figure 6-5.

3. Mixed Aquifers – These aquifers contain both fissure and intergranular porosity and occur in a karstic environment. A karstic aquifer is depicted in Figure 6-6.

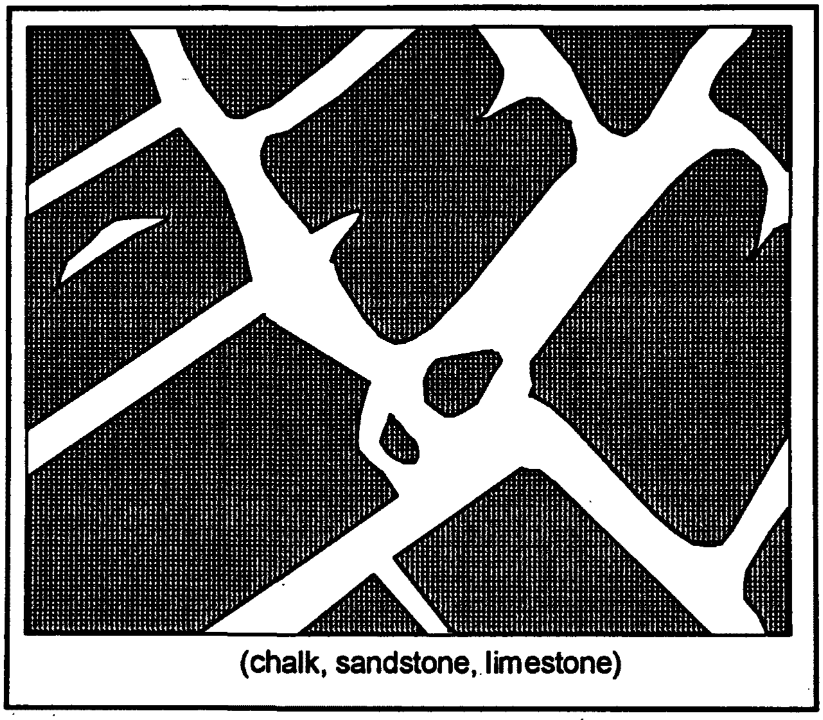


Figure 6-5. Fissure Porosity

The infiltrated water reaches the aquifer more or less rapidly, depending on the permeability of the rock and soils it encounters. Through chalk, for example, infiltrated water can take up to one year to reach the underground water. In schist and granite, in principle impermeable rock, water nonetheless can percolate very quickly through the fractured or weathered zones.

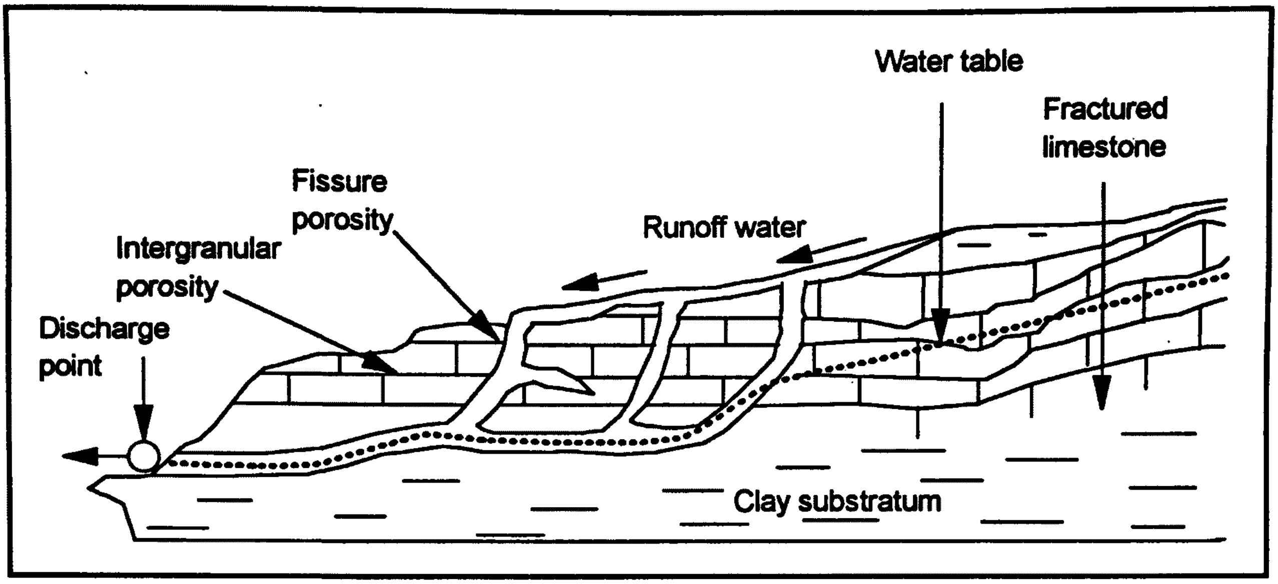


Figure 6-6. Karstic Aquifer

Configurations of Aquifers

Aquifers are classified as unconfined or confined, depending on the conditions at the boundary of the formation.

A confined aquifer is bound by two impermeable layers. The water is under pressure and, consequently, the water level will rise in a bore hole sunk into the aquifer. The level to which the water rises in a bore hole is called the piezometric level. A schematic diagram of a confined aquifer is presented in Figure 6-7.

An unconfined aquifer is one in which the water table (or piezometric level) is not constrained, and therefore the water level is free to fluctuate up and down, generally seasonally (see Figure 6-7).

Recharge and Discharge Zones

As seen in the water cycle (Figure 6-3), aquifers are filled (recharged) through the infiltration of rain water through permeable strata (Figure 6-8). Upon reaching the aquifer, the water flows

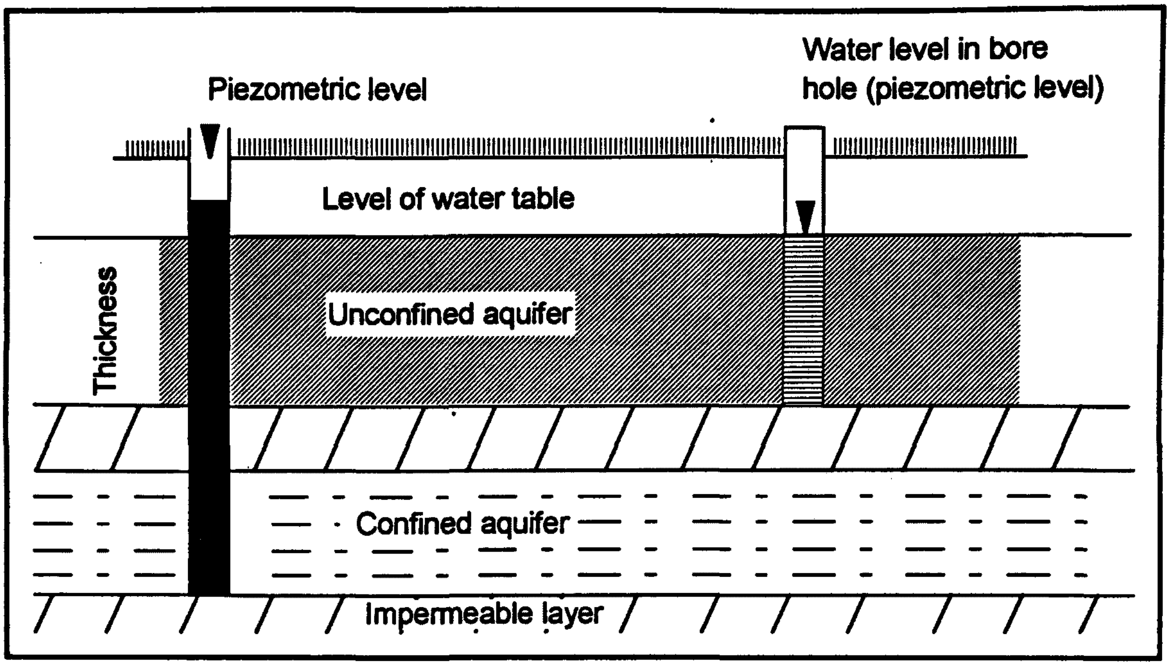


Figure 6-7. Schematic Example of Confined and Unconfined Aquifer

under the regional hydraulic gradient and is discharged to the surface environment again by way of springs, from seepages into rivers, and by means of pumped wells [3].

Water is not stagnant within an aquifer, but flows from the recharge to the discharge zone. Rates of flow vary according to the type of aquifer; for example, 1.5 km/yr in alluvium and 3.5 to 9 km/yr in a karstic system.

<u>Saturated/Unsaturated Zone</u>

In an unconfined aquifer, two successive zones are encountered by the water percolating downward from the surface:

The unsaturated zone is composed of rock interstices that are partially occupied by water and partially by a gaseous phase (air).

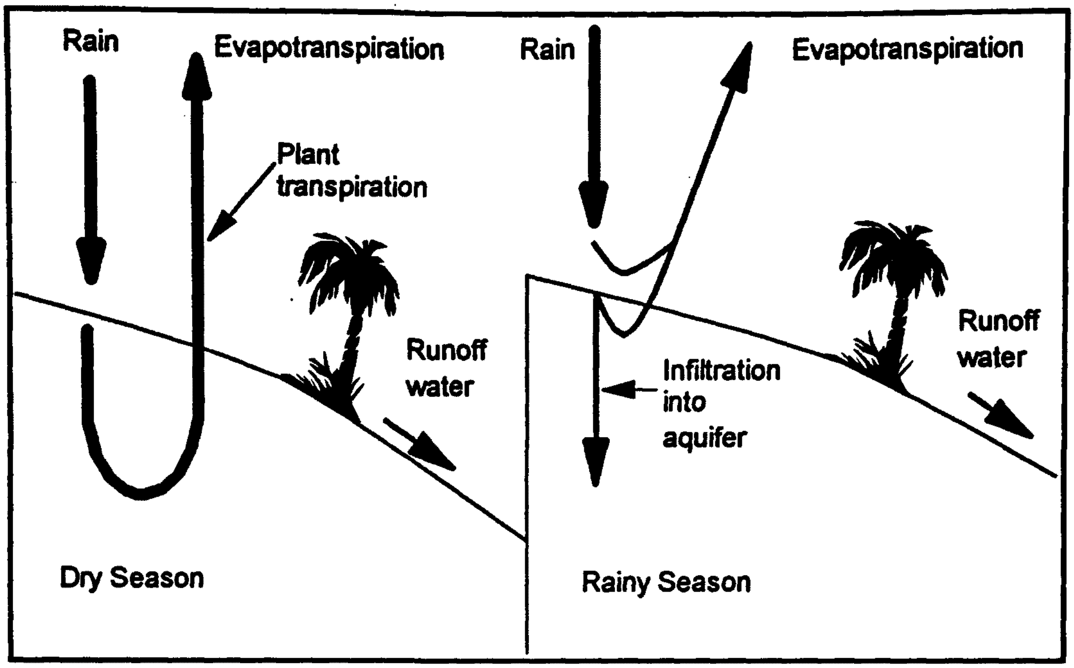


Figure 6-8. Recharge of Aquifers by Rain

The saturated zone starts at the level of the water table when the rock and soil interstices are entirely filled with water. In this zone, the groundwater flows under the regional hydraulic gradient to the discharge zone.

In both the unsaturated and the saturated zones, different complex mechanisms can interact with a percolating fluid (leachate or other pollutant): sorption, neutralization, precipitation, oxydo-reduction, and biodegradation. Although these mechanisms have been observed, they are yet to be precisely quantified and understood.

<u>Hydraulic Conductivity, Porosity, Velocity</u>

Hydraulic conductivity and porosity are commonly used to characterize soils, and all three of these terms are used to characterize aquifers. Before defining them, one must, first of all, understand the most important law governing the transmission of fluids through soils -- Darcy's law. Darcy's law allows the calculation of the rate of flow of a fluid (Q) through a given cross-sectional area of a soil, as depicted in Figure 6-9.

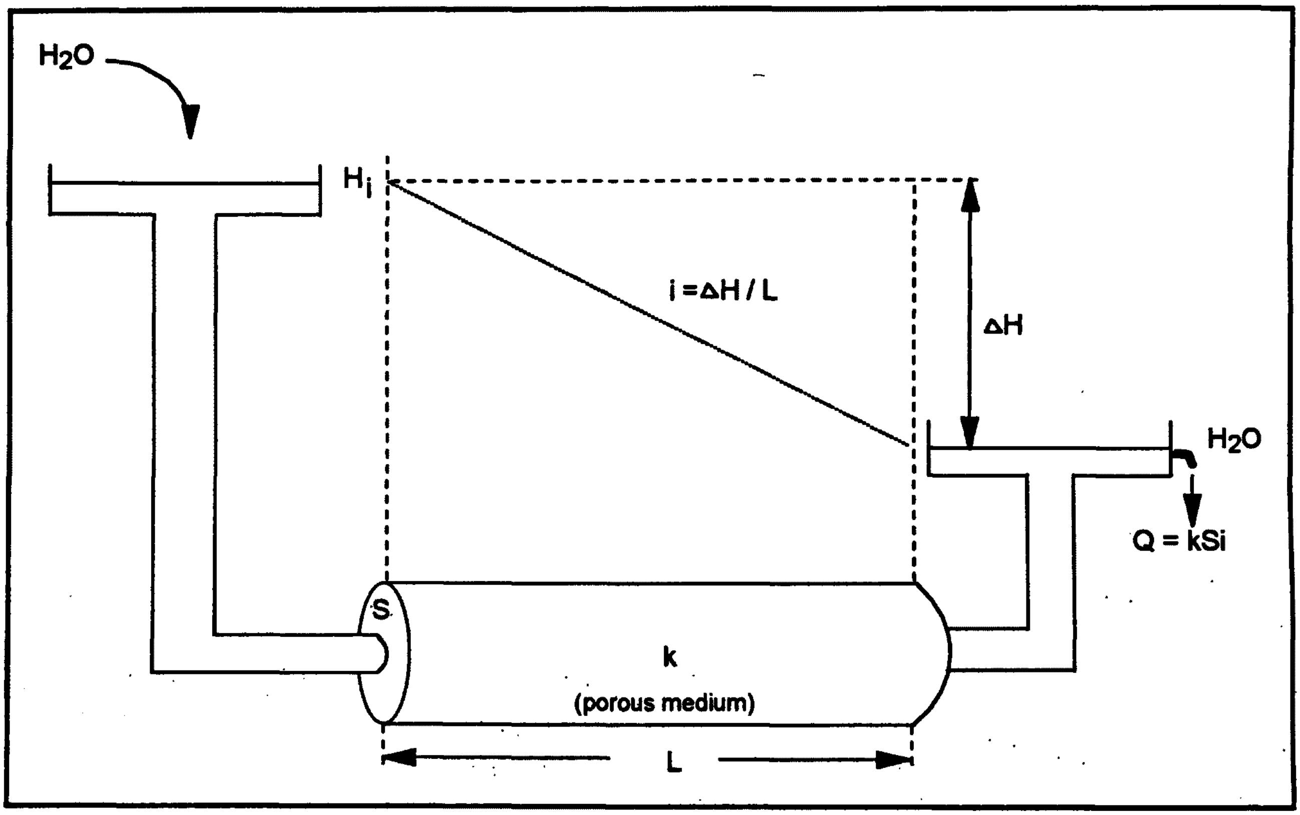


Figure 6-9. Depiction of Fluid Flow in a Porous Medium

The equation of Darcy's law is as follows:

$$Q = k \cdot S \cdot i$$

where:

Q = discharge (m^3/s),

k = permeability or hydraulic conductivity (m/s),

S = cross-sectional area, and

i = hydraulic gradient.

An example of the method of applying Darcy's law is given in Figure 6-10. Assume that there are 2 m of water-logged waste over a surface of 1 km^2 (i.e., 10^6 m^2) overlying 5 m of clay with a permeability of $k = 10^{-12}$ m/s. The flow of water through the "impermeable" layer can be described as follows:

$$Q = 10^{-12} \text{ m/s} \times 10^6 \text{ m}^2 \times 7/5 = 1.4 \times 10^{-6} \text{ m}^3/\text{s} = 44 \text{ m}^3/\text{yr}$$

Hydraulic conductivity is synonymous to permeability (k) previously defined.

Porosity is the measure of the interstitial pore space, expressed as the relative volume (in %) of rock or soil occupied by voids. In actuality, part of the water present in the voids is retained by forces of molecular attraction, adhesion, and cohesion and, therefore, is unavailable to store "free" water. Thus, in terms of actual storage potential, the use of effective porosity (n), i.e., the free storage space, is more appropriate. For example, while clay has a high total porosity, it has a low effective porosity (see Table 6-1).

6.2.3 Risks of Water Contamination by Waste

6.2.3.1 Surface Water Contamination

The main risks of surface water contamination (see Figure 6-11) are listed below:

1. If a land disposal facility is located below flood level, each flood will penetrate the waste, flow across the landfill, and disseminate polluted water. In some cases, flooding will carry the waste into the river system and surrounding area. Consequently, flood plain areas must be identified and generally avoided.

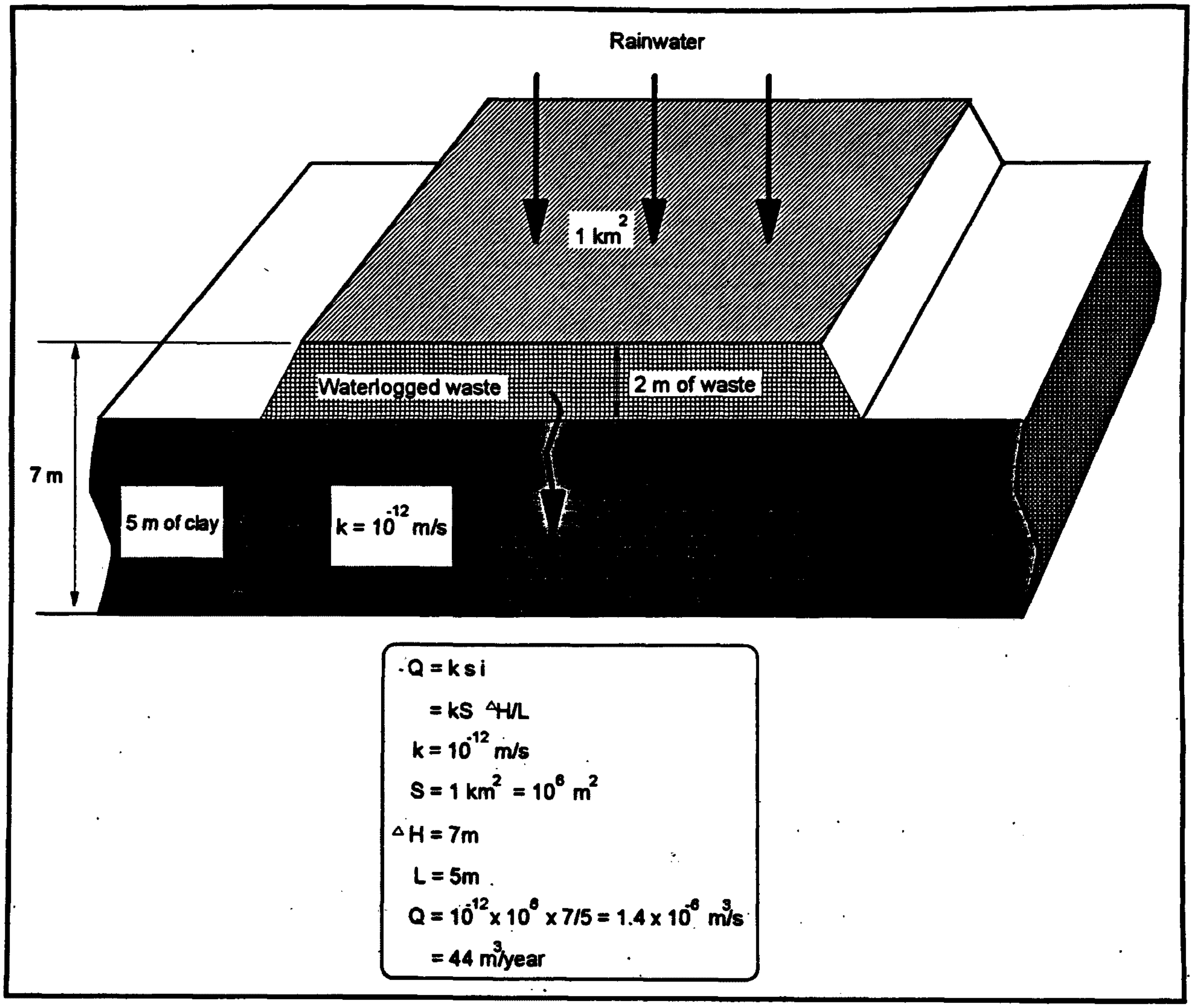


Figure 6-10. Application of Darcy's Law

2. Similarly, a disposal facility in close proximity to the sea represents a potential source of pollution to the sea water and to nearby beaches during high tides.

3. A disposal facility in close proximity to a source of surface water, e.g., a river or lake, represents a source of pollution as a consequence of the potential of seepage of leachate from the base of the landfill to the body of water.

Table 6-1. Porosity Ranges, Flow Types, and Saturated Hydraulic Conductivities of Various Soil Types

Soil Type	Total Porosity Range %	Effective Porosity Range %	Flow Type	Saturated Hydraulic Conductivity Range m/d
Clay	45 to 55	1 to 10	I	10^{-2} to 10^{-5}
Chalk	35 to 50	0.5 to 5	F + I	10 to 10^{-3}
Sand	35 to 40	10 to 30	I	10 to 1
Gravel	30 to 40	15 to 30	I	10^{2} to 10
Sandstone	10 to 20	5 to 15	F + I	10 to 10^{-1}
Shale	1 to 10	0.5 to 5	F + I	10^{-1} to 10^{-7}
Limestone	1 to 10	0.5 to 5	F (+I)	wide
Igneous and Metamorphic	(probably less than 1)		F (+I)	wide

F = fissure flow
I = intergranular flow

6.2.3.2 Groundwater Contamination

Several types of situations can result in groundwater contamination:

1. A landfill with a permeable base located in the water table -- the unsaturated zone is non-existent, and the leachate percolates directly into the aquifer, creating a plume of pollution that can diffuse widely.

2. A landfill with a permeable base located above a fractured zone of permeable soils such as sand or gravels -- leachate will reach the aquifer directly and quickly through the fractures or the permeable soils.

3. Leachate can reach an aquifer through heterogeneities and discontinuities in an otherwise impermeable zone (for example, along a fault zone, or along a thin limestone layer within a clay horizon).

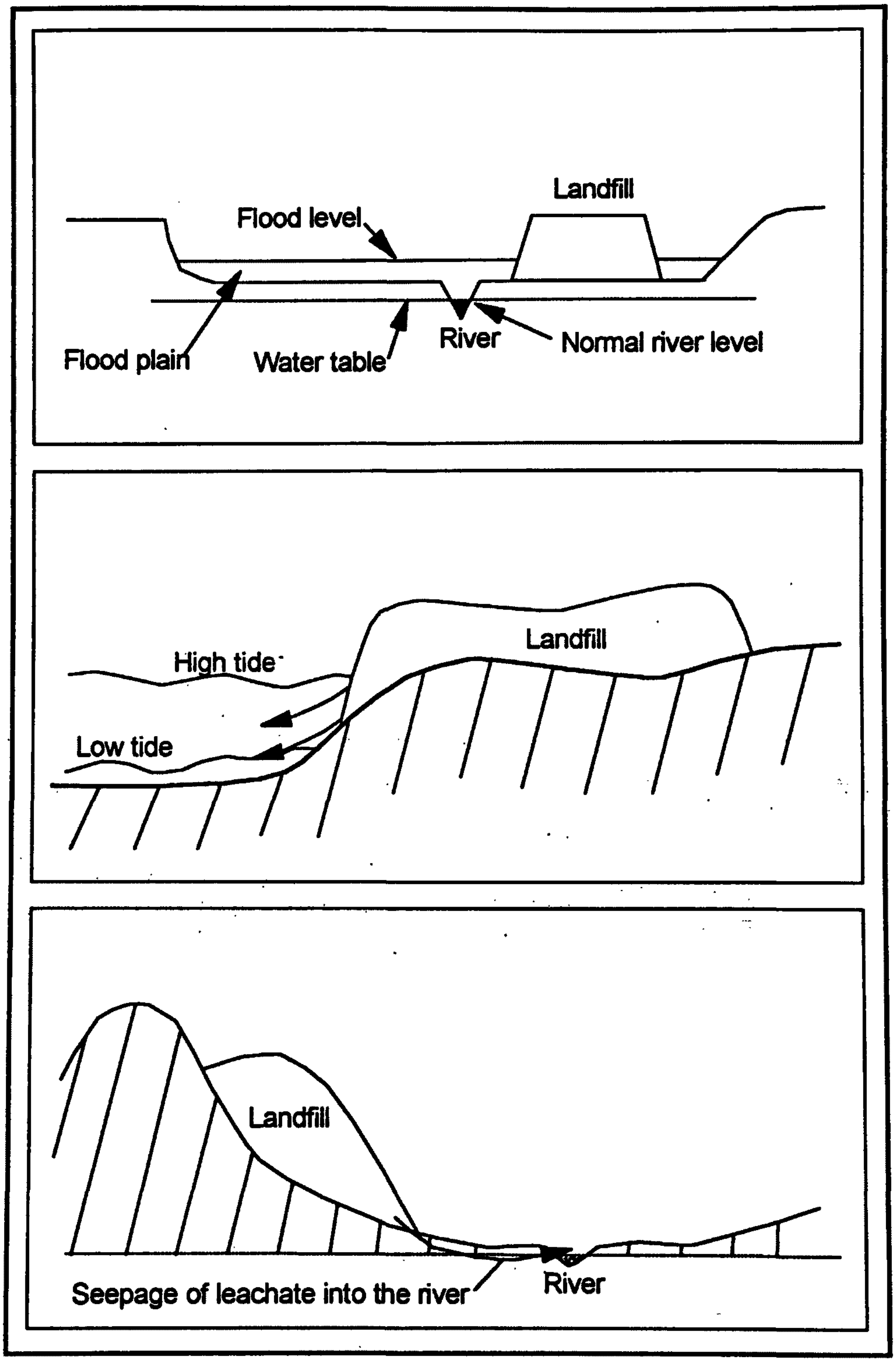


Figure 6-11. Risks of Surface Water Contamination

6.2.4 Procedure for Conducting a Geological/Hydrogeological Study

6.2.4.1 Regional Study

In order to conduct a regional study, the following information should be collected:

- the geology of the area in order to identify fault zones, impermeable areas, heterogeneities, and others;
- the geomorphology of the area, to identify geological hazards such as flood plains and to delineate the water basins; and
- the hydrology of the zone so that all of the aquifers can be identified together with the surface water network and the water flowing direction.

The above information can be gathered from existing maps, aerial photos, boreholes, and field work.

6.2.4.2 Local Study

The following data should be obtained during the conduct of a study of local conditions:

- detailed geology (including the availability of on- or off-site soils for construction and maintenance of the landfill),
- an inventory of springs and water boreholes,
- detailed hydrogeology (depth to aquifers, piezometric levels, water quality), and
- permeability of the different formations.

The above data can be obtained by using the following methods:

- detailed geological mapping;
- drilling and careful logging of the core;

- installing "piezometers" in several boreholes and monitoring the water movement (existing piezometers can also be used if they are operational);

- analyzing the water in the piezometer -- the drilling and installing of a piezometer requires the skill or supervision of a trained specialist. Incorrectly installed and monitored piezometers can result in costly mistakes (for example, missing an aquifer altogether or tapping the wrong aquifer); and

- measuring the permeability *in situ* of the surface and subsurface soils -- these measurements should be made and interpreted by specialists, and the interpretation should be linked to the geological mapping. An awareness should be had that permeability is potentially variable in a formation and the potential of variability is the reason that professional interpretation should be sought. For example: 1) layers of material with $k = 10^{-9}$ m/s can occur within a formation of siltstone ($k = 10^{-6}$ m/s), or 2) a thick clay formation ($k = 10^{-12}$ m/s) can be locally fractured, which increases k significantly, or it can contain sand lenses ($k = 10^{-4}$ m/s).

6.2.4.3 Best Case/Worse Case Scenario

One effective means of evaluating the data and information collected in the geological/hydrogeological study and of providing a context for selecting the optimum site is to define the ideal and the worse locations for a landfill.

<u>Best Case Scenario</u>

- geologically stable area (i.e., no active fault movement),

- impermeable strata at the base of the landfill,

- unsaturated layer below landfill base (more than 30 m),

- far from surface water bodies (more than 1,000 m),

- low hydraulic conductivity in the first underlying aquifer to minimize the migration of potential contamination, and
- nearest aquifer far below the landfill base and not used for drinking purposes.

<u>Worst Case Scenario</u>

- many permeable layers (gravel pits, fractured zone, fault zone);
- bottom of the landfill is close to the water table, or depth from ground surface to groundwater is less than 10 m;
- local groundwater is used for drinking; and
- close to surface water body or flood plain (within 100 m).

In reality, of course, compromises will have to be made in the selection of a site since all of the ideal conditions are seldom found at a given location [4]. However, the identification and assessment of all relevant factors will enable landfill developers and designers to take the factors into account and to include appropriate measures when the actual conditions fall short of the ideal.

6.2.4.4 Conclusion

An understanding of both regional and local geological conditions is a prerequisite to ensure the selection of the best available site in a given area and to assess the potential risks of water contamination from the landfill site. With such knowledge, it is then possible to minimize the risks with the design of the landfill. Consequently, geology and hydrogeology are part and parcel of the siting of a landfill and must be taken into account during the design phase as well.

Finally, the hydrogeological knowledge gathered during the siting phase will also be used when designing the groundwater monitoring system in place during and after the use of the landfill.

6.3 Proposed Classification System for Site Selection

Important factors that should be taken into consideration in the selection of a landfill site have been discussed in the previous sections. However, the degree of community development and, most certainly, affordability become important considerations in the process of selecting a site. By definition, communities in economically developing countries are poor. Large cities in an economically developing country, although poor, may have sufficiently large sources of revenue to enable them to apply high standards to solid waste disposal. On the other hand, small communities usually cannot afford to dispose of their wastes using the same set of high standards applied by large cities.

A number of reasons can be offered that support the concept that the standards for the development of landfills in economically developing countries do not necessarily have to be identical to those used by industrialized countries. Some of the more important arguments for this concept include the following:

1. The composition of the wastes generated in economically developing countries is substantially different from that generated in industrialized countries. As was shown in Table 4-3, some cities in economically developing countries generate municipal solid waste that has a relatively high concentration of food waste and has a high moisture content. On the other hand, low-economy communities which use either coal or wood for cooking and heating generate a waste that has a high concentration of ash. In some of these locations, much of the paper and vegetable matter is also used as a fuel.

2. The per capita quantity of refuse generated in some of the poorer economically developing countries may be smaller than that generated in industrialized countries by a factor of three to four. Consequently, a community of a certain size in an economically developing country may produce substantially less solid waste than a community of equal size in an industrialized country. Since less waste is produced, a landfill serving the same population would be smaller, or would have a longer life, and therefore would represent a smaller or less rapidly accumulating source of potential pollution.

3. The climate in many economically developing countries is humid and the potential for leachate production high. On the other hand, there are several economically developing countries that have arid climates or arid regions (e.g., parts of India, Africa, and South America), which have little potential for the production of leachate. Whereas, in industrialized countries, the same standards can be applied for landfilling regardless of climate, the standards may be relaxed in economically developing countries if little or no leachate is likely to be generated in the landfills. This relaxation can make landfilling more affordable, without unduly affecting environmental protection.

Consequently, a proposal for the classification of landfills in economically developing countries has been made by members of the ISWA Working Group on Sanitary Landfills [5]. The proposal aims at establishing graded standards without compromising environmental protection. The scheme of classification is considered suitable for either industrialized or economically developing countries. However, it probably will be more attractive in economically developing countries where affordability usually is a fundamental issue. The classification applies to landfills that receive only domestic and commercial refuse and dry, non-hazardous industrial wastes.

Since the classification can be used in site selection as well as site investigation and environmental impact assessment, it is presented in this section. Due to the importance of these aspects of the process for the establishment of a sanitary landfill, a brief description of the classification is presented herein.

6.3.1 Components of the Classification System

The proposed classification depends upon the evaluation of the following components: the type of waste, the size of the landfill, and the climatic conditions. A brief description of each of the three components follows.

6.3.1.1 Type of Waste

In the proposed classification, the composition of the waste is considered in terms of the relative concentration of organic matter. If the concentration of biodegradable matter exceeds 20% (dry mass), the waste is classified as type "B," or highly biodegradable waste. On the other hand, if the concentration of biodegradable matter is less than 20%, the waste is classified as type "b," or low biodegradable waste. At the present time, the division of less than and greater than 20% is arbitrary.

6.3.1.2 Size of Landfill

Obviously, the size of operating landfills increases as a function of time. One of the characteristics that has the biggest influence on the operation of the landfill, and consequently on the need for facilities, equipment, and operating skills, is the rate of deposition of the waste. Therefore, this classification is based on the Maximum Rate of Deposition (MRD) in Mg of waste deposited per year. The MRD is the projected rate of deposition at the end of the life of the fill. The MRD is calculated from the Initial Rate of Deposition (IRD) and the estimated annual rate of growth or development rate for the community that the landfill is intended to serve. The IRD can be estimated based on the amount of refuse entering the site at present or by using estimated per capita generation rates.

The MRD can be calculated as follows:

$$MRD = (IRD)\,(1+D)^t$$

where:

D is the annual development rate estimated for the landfill in %/yr, and

t is the estimated life of the landfill site in years.

Therefore, the mass of refuse deposited after t years of operation (M_t) can be calculated as follows:

$$M_t = \frac{(IRD)\,[(1+D)^t - 1]}{D}$$

Truck scales may not be available in many areas, particularly in small municipalities, to accurately determine the rate of deposition in mass units. In these cases, an estimation can be carried out by using volumetric estimates, number of vehicles entering the site, and bulk density of the waste.

The classification according to size is presented in Table 6-2. In the classification presented in the table, a "Communal" landfill would serve a village having a population of less than 1,500 inhabitants. A "Small" landfill would serve a town of up to 30,000 inhabitants. "Medium" and "Large" landfills would serve cities and large towns having populations greater than about 30,000 people. Actual per capita waste generation rates or total waste quantities from a given population vary, and should be used, if available, to arrive at the proper MRD classification.

6.3.1.3 Climate

It has been demonstrated that the quantity of leachate generated in a landfill depends upon the climatic conditions in which the landfill is located, the type of waste, the moisture content of

Table 6-2. Proposed Classification of Landfills in Economically Developing Countries According to Size

Landfill Size Class	Maximum Rate of Deposition (MRD) (Mg/yr)
Communal (C)	less than 250
Small (S)	up to 5,000
Medium (M)	up to 150,000
Large (L)	over 150,000

Source: Reference 5.

the waste at the time of deposition, and the design and operating conditions of the fill. The impact of climate on the landfill can be quantified by conducting a water balance on the fill. Basically, the difference between the net water input and the capacity of the refuse to store it will be available to form leachate.

Evaporation from a water surface can be measured by means of standard evaporation pans. In humid climates, the difference between net water input and water stored will be positive over a year or season. In arid climates, the difference will be negative, either over the entire year or over a particular season. Thus, in arid climates, landfills may not produce any significant quantities of leachate, produce leachate only seasonally, or produce leachate only as a result of the burden of the waste deposited in the fill.

In the situation where no significant quantities of leachate are produced, the proponents of this standard suggest that it may be possible to relax the standards required for the siting and the design of a landfill, by ignoring potential pollution due to the leachate and by omitting the leachate collection system and landfill liner. This situation, however, will depend on geological and groundwater conditions at the site.

However, even in an arid climate, there are occasional wet years. If extreme weather conditions occur, some leachate may be formed and may seep into the soil beneath the landfill. Provided that this does not occur more frequently than once in five years and if the foundation strata are relatively impervious, so that there is some degree of attenuation, the consequences of such an escape may not be serious and potentially may be ignored.

The proposed classification system uses a simple climatic water balance as a means of deciding whether or not a landfill will generate significant quantities of leachate and, therefore, whether or not a leachate collection system and bottom liner should be included in the facility. The climatic water balance can be expressed in the following manner:

$$W = R - E$$

where:

W is the quantity of moisture either lost or retained in the waste (mm),

R is the precipitation (mm), and

E is the evaporation from the landfill (mm).

In the above equation, runoff of precipitation has been ignored. According to the proponents of the classification, this approach is not only conservative, but is also realistic for most landfills in economically developing countries and in industrialized countries where the capping layers are semi-pervious. The lack of runoff occurs because, in many locations, about 85% of individual 24-hour rainfall events consist of less than 10 mm. This relatively small amount of rain can easily be absorbed into a semi-pervious layer of soil. Since the value of W is intended to represent the condition of the waste over the long term, the field capacity (i.e., moisture-holding capacity) of the waste does not appear in the climatic water balance. In order to allow for seasonal influences and variable weather patterns, W is calculated for the wet season of the wettest year on record. If the value of W is positive, the indication is that the landfill will generate leachate in a wet year. On the other hand, if W is negative, the indication is that the landfill will not generate leachate in even the wettest year.

Since the rainfall and evaporation in any one year do not necessarily correlate, W is recalculated for successively drier years to establish if: 1) W is positive in less than one in five years for which the data are available, or 2) if W is positive in more than one year in five. According to prevailing conditions, the value of one year in five can be modified to one year in ten or more, depending upon local climatic and hydrogeological conditions and environmental concerns. If W is positive in less than one in five years, the site is classified as W- (W negative) and a leachate collection system and bottom liner can be omitted. However, if W is positive in more than one year in five, the site is classified as W+. In this particular case, generation of leachate can be expected, and a leachate collection and extraction system, as well as a bottom liner, should be incorporated into the design.

6.3.2 Classification System

Use of this classification system would allow the determination of the need for liners, leachate collection systems, and leachate extraction and treatment systems. A complete description of the classification system can be found in References 5, 6, and 7.

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2. U.S. Environmental Protection Agency, *Guidelines for the Land Disposal of Solid Wastes*, Federal Register, 1985.
3. U.S. Environmental Protection Agency, *Design, Operation, and Closure of Municipal Solid Waste Landfills, Seminar Publication*, Office of Research and Development, Washington, DC, EPA/625/R-94/008, September 1994.
4. Attar, A.M., "Siting a Landfill: The First Step," *World Wastes*, 32(13):14-20, December 1989.

5. International Solid Waste Association, Working Group on Sanitary Landfills, *Graded Standards of Classification to Allow for Improved, Affordable Standards to be Introduced for Landfilling of Domestic Refuse in Developing Countries*, Copenhagen, Denmark, 1996.

6. Department of Water Affairs and Forestry, Republic of South Africa, *Waste Management Series: Minimum Requirements for Waste Disposal by Landfill, Volume 1*, ISBN 0621-16297-4, 1994.

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Chapter 7

Infrastructure

7.1 General

This chapter presents an overview and discussion of the various support facilities, or infrastructure, that should be considered during the planning of a landfill operation. Infrastructure may include the following:

- access roads,
- drainage facilities,
- scales,
- utilities,
- structures,
- fencing,
- vehicle washing facilities,
- hot load areas, and
- other support facilities (e.g., materials recovery, leachate management).

Many, if not all, of the above support facilities normally are present in a modern sanitary landfill for an efficient landfill operation. Many of the topics discussed in this chapter also are discussed in other chapters of the document.

7.2 Roads

Landfill access roads include permanent (all-weather) roads from the public road system to the site, permanent roads at the site, and temporary roads to the working face of the landfill.

If the public road system is paved, it also is a good idea to pave the permanent access road to the site. The paved road section should extend to just beyond the guardhouse or scales, as applicable. Beyond this point, permanent roads would extend to the vicinity of the working face, especially if the site is large. Where the terrain allows, a perimeter road encircling the entire site is advantageous. A perimeter access road facilitates maintenance of the site, engenders efficient traffic flow, and renders one-way traffic flow a practical option.

Permanent roads should be designed to support the anticipated volume and loading of vehicular traffic and pedestrians. In all cases, traffic flow patterns should be designed to minimize conflict between pedestrians and vehicles. Entry and exit turns against oncoming vehicles should be avoided as much as possible, and provision of safe sight distances should be considered in the layout of roads. The use of one-way traffic patterns can reduce the risk of collisions, while at the same time serving to aid the efficient flow of traffic.

Adequate roadway drainage should be provided to prevent the roads from flooding during wet seasons, and should be coordinated with the landfill drainage system design. Ideally, the roadway should consist of two lanes (minimum total width, 7.5 m) for two-way traffic. Grades should not exceed motorized equipment limitations (uphill grades, less than 7%; downhill grades, less than 10%). Although the initial cost of on-site permanent roads may be higher than that of temporary roads, the difference is more than compensated by savings in equipment repair, maintenance, and time.

If the expected delivery vehicle traffic is only 25 to 50 trips per day, a graded and compacted soil usually would suffice in dry conditions. Traffic consisting of more than 50 trips per day probably would justify the use of calcium chloride as a dust inhibitor, or of binder materials such as soil cement or asphalt. Traffic consisting of more than 100 to 150 round trips per day would indicate the need for a paved surface with a base course, binder, and wearing course.

Because the location of the working face is constantly changing, roads for the delivery of wastes from the permanent road system to the working face usually are temporary in terms of nature and construction. The relocation of temporary roads from time to time, over previously filled areas, generally is necessary and is desirable since the truck traffic helps to compact the landfill. Temporary roads may be constructed on the landfill by compacting the soil cover already present. The roads may be topped with a layer of tractive material (such as gravel, crushed stone, cinders, broken concrete, mortar, or bricks), as moisture conditions dictate. Lime, cement, or asphalt binders would increase the serviceability of the temporary roads.

The design of roadways for access to and about the site should be predicated upon the conditions peculiar to the level of local development, and more specifically to those of the community being served by the disposal site. For example, the construction of a large capacity, modern sanitary landfill in a developing country would be confined mostly to the relatively large urban communities, i.e., metropolitan areas and capital cities -- at least for the near future. The solid waste generated in many of the large urban communities is collected by conventional waste collection trucks. Thus, landfills serving these communities should accommodate these types of trucks. At the same time, since most large urban cities, even the more economically developed, have sizeable economically depressed areas, the traffic to, from, and on the landfill also will include a range of transport vehicles that extends from the very primitive (e.g., animal- and hand-drawn carts) to the relatively modern (e.g., automobiles and pickup trucks). This wide variation of types and number of vehicles contributes to the complexity of road planning, design, and regulation of traffic.

Since scavenging is an activity that usually would be present at a land disposal facility, the accommodation of the additional traffic from this activity also should be considered during the design of the roadway system. Scavenging is discussed in Chapter 15.

7.3 Drainage

Generally, water has a substantial adverse impact on landfills, at all stages of completion. Water interferes with construction and operation by reducing traction, particularly in rendering clays slippery and difficult to work. Water also promotes leachate generation. In the previous subsection, there was reference to roadway and landfill drainage. Generally, site drainage should be regarded as an integral part of landfill design. The facilities and structures needed for proper management of stormwater run-on and runoff must be correctly sized, constructed, and maintained for the duration of landfill operations [1].

The landfill site plan should include all essential features for drainage control: ditches, culverts, armored channels, retention ponds, outfall structures, etc. The location of these facilities requires careful consideration and will influence the layout of the landfill itself. Retention ponds or sediment basins, in particular, may have substantial areal requirements and must be provided in downgradient locations on the site. If the landfill property is of small size, it may be necessary to consider the use of adjacent land area for the purposes of stormwater management. Drainage facilities must be large enough to accommodate the design storm event, typically a 25-year, 24-hour rainfall. A more complete description of surface water management is presented in Chapter 8.

7.4 Measurement of Weight (Scales)

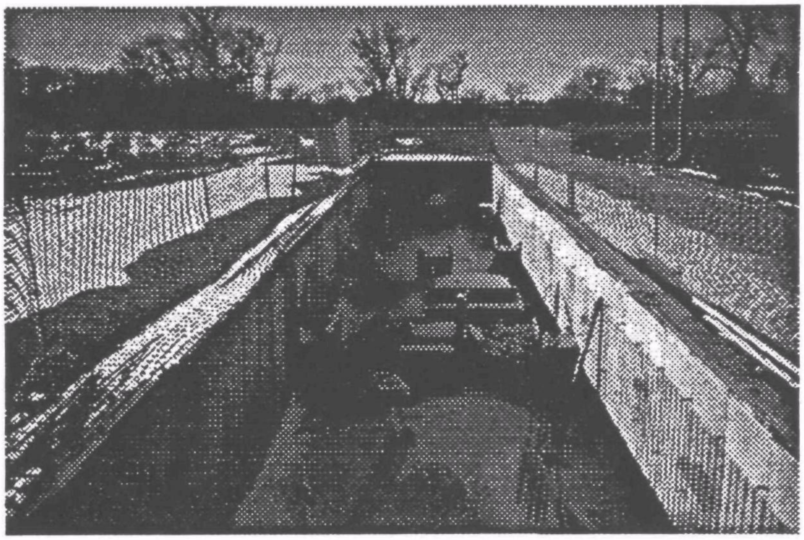
An accurate knowledge of the gravimetric and volumetric amounts of wastes delivered to the disposal site is an essential element in the development and implementation of solid waste collection and landfilling strategies, as well as in the regulation and control of the landfill operation. Volume estimation of incoming waste is subjective and as such is prone to significant inaccuracy; therefore, to the extent feasible, all incoming wastes should be weighed.

Types of scales range in complexity from highly automated electronic scales to simple, portable beam units. The platform, or scale deck, may be constructed of wood, steel, or concrete. The scale should be able to weigh the largest vehicle that will come to the landfill on a routine basis; 30 to 60 Mg would be adequate in most cases. Ideally, the platform should be sufficiently long to accommodate all axles of the vehicle simultaneously. An alternative, if financial resources are limited, is the use of a shorter scale in which the weight on the front axle and on the rear axle is measured. An example of a truck scale is presented in Figure 7-1.

Scales usually are located near the landfill entrance or the guardhouse, on a turn-out from the main access road. The location and design of this area should accommodate vehicles that are waiting in line to be weighed.

7.5 Utilities

Ideally, electric, water, communication, and sanitation services should be provided at the disposal site. However, the likelihood of all of these utilities being available at a disposal site in an economically developing country is unlikely. Electricity is to be used for illumination and power. These two uses are almost essential if equipment maintenance and repair are to be conducted at the site. Electricity can be generated at the site by means of a portable generator. Water should be available for drinking, firefighting, dust control, and employee sanitation. In the absence of access to a sewer, domestic wastewater can be discharged into a septic system with a leaching field. Where flush toilets are not practical, ventilated latrines should be constructed.



Scale Pit Under Construction

Completed Scale

Figure 7-1. Examples of Truck Scales

7.6 Structures

If technical and economic feasibility permit, a structure or structures should be erected to provide office space; to house employee facilities; to provide a sheltered area for equipment storage, maintenance, and repair; and to serve as a scalehouse. If these facilities are not provided, operation of the landfill will be impeded. The office space is needed for recordkeeping and for the conduct of clerical activities. The equipment structure serves as a garage and repair shop. Employee morale, well-being, and productivity would benefit if the structures also include a health clinic, personnel facilities (e.g., toilets, lockers), and a food service facility. Buildings that will be used for less than ten years should be of temporary construction and, preferably, be portable.

The design and construction of all buildings should take into consideration landfill gas movement and differential settlement of the fill. In general, construction on the landfill should be avoided. As the landfill ages, differential settlement can cause irreparable damage to building foundations. If it is necessary to place a permanent structure on a landfill, it will require special foundation design -- usually a pile foundation penetrating to firm subgrade soils or bedrock under the landfill.

Whether temporary or permanent, any structure on a landfill may be subject to the hazards of landfill gas. Gas emanating from the landfill may find its way into a building through cracks in the foundation or other openings. Even buildings outside of the waste boundary can be affected by landfill gas migration into these structures via pathways through the soil, utility trenches, etc. It is important, therefore, that any structure on or near the landfill have provisions for detecting and preventing/controlling the accumulation of landfill gas. Ignition sources, such as heaters and open flames, may cause gas explosions and must be restricted from any area where landfill gas may collect. The issue of landfill gas management is considered in greater detail in Chapters 8 and 14.

7.7 Fencing

Access to the landfill operation can be controlled by erecting a fence around the site. The fence does the following:

- keeps out children, as well as dogs and large animals;
- screens the landfill;
- delineates property lines; and
- helps to control wind-blown litter.

While a perimeter fence for a large site may not be practical, fencing should be considered for small landfills. The type and height of fencing are determined by the available resources and conditions prevailing at the site.

Litter fences may be erected in the immediate vicinity of the working face to control blowing paper and other litter. A low (about 1 m) fence usually suffices at a sheltered trench operation; whereas a 2 to 3 m height may be necessary at an operation located in a windy area. Litter fences placed near the working face are intended to be movable. Typical portable litter fence installations are presented in Figures 7-2 and 7-3.

Permanent litter fences are sometimes erected along the downwind side of the landfill to keep wind-blown materials from entering adjacent properties. An effective litter fence of this type can be constructed simply and economically with netting suspended between tall (5 to 10 m) vertical posts. Also, tall plants or trees and earth berms on the upwind side of the landfill may serve as both windbreaks and visual screens.

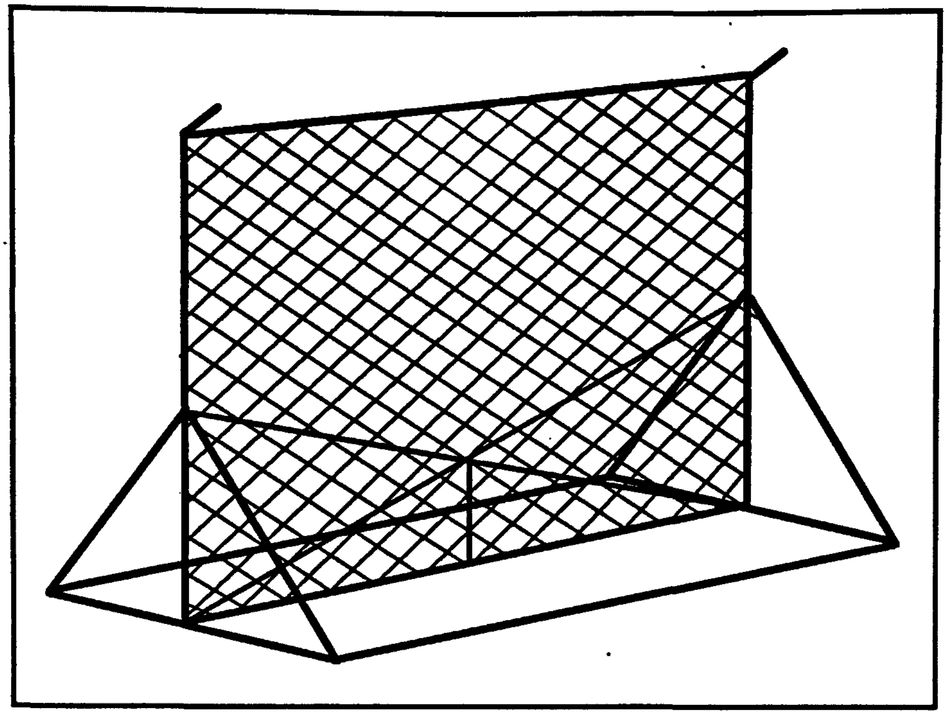


Figure 7-2. Portable Litter Control Fence

7.8 Vehicle Washing Facilities

Provisions for vehicle washing should be included in the facility design if the water supply is adequate to support such an operation. Vehicle washing refers to the general cleaning of dust and dirt from landfill equipment, and to the washing of collection truck wheels. The requirements for vehicle washing are: a reliable water source, a pump or other means of providing pressurized water spray, and a designated washing area (or areas) with runoff control.

The washing area should have a paved surface to prevent mud formation. The area should have curbing or berms to direct the runoff to a collection channel. As is the case in the design of all other drainage systems at the landfill, channels should be protected from erosion. The sediment-laden runoff should be directed to a sediment trap or basin. Often, it is possible to direct such runoff to the major landfill drainage and erosion control system. A stormwater

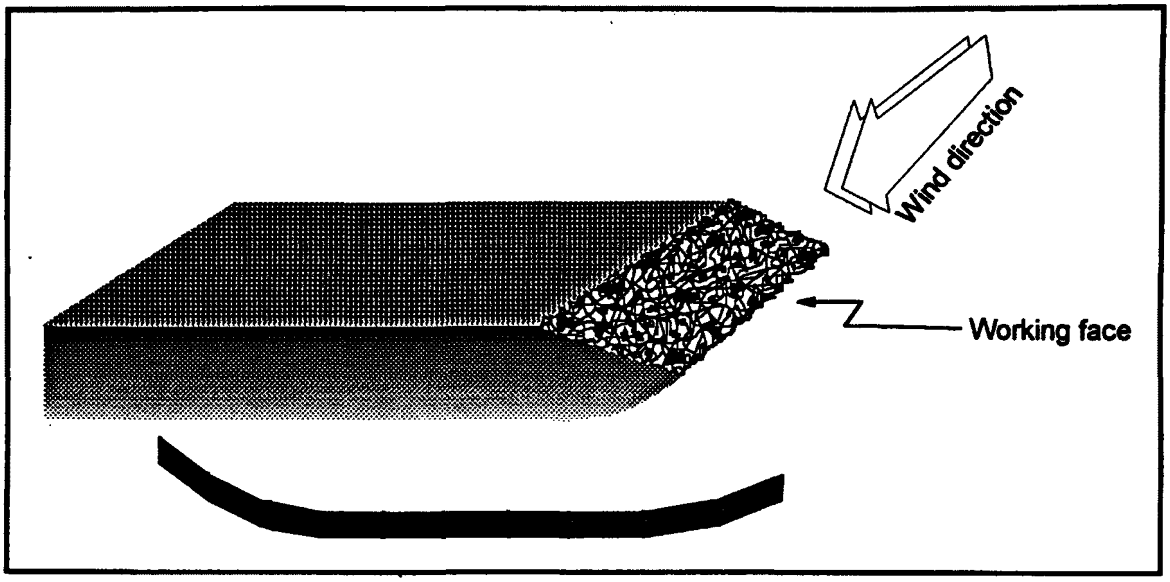


Figure 7-3. Correct Positioning of Litter Control Fencing in Accordance with Wind Direction

detention basin or a storage pond used for fire protection may serve double-duty as a water supply for vehicle washing.

Vehicle washing facilities normally are located near the equipment storage area and landfill exit. Wheel washing of refuse haul vehicles is desirable where the landfill access and public roads are paved, to keep the road surfaces clean. The areas for landfill equipment washing and collection vehicle wheel washing may be the same; if not, they should be adjoining. The logical location for wheel washing is on the exit side of the working face area and located on a paved area that is adjacent to the paved roadway that leaves the site property. Mechanical wheel washing devices are sometimes used at larger facilities.

7.9 Hot Load Areas

Good management practice dictates that all incoming loads of refuse be inspected on the truck before delivery to the working face. Any load that is smoldering or on fire, or that contains radioactive material, should be sent directly to a hot load area. In the hot load area, the material is dumped so that the fire can be extinguished or, in the case of radioactive material, left undisturbed until trained personnel arrive to handle the material. The hot load area should be located a short distance from the inspection checkpoint, but away from the area of high traffic frequency and away from personnel facilities. The hot load area should consist of bare ground stripped of all vegetation and combustible material, and should be a minimum of 10 m x 10 m in size. A hydrant and pressurized water delivery system should be provided at this location. A storage pond or other water source should be available at all times for fire protection.

7.10 Other Support Facilities

Other infrastructure may be provided at the landfill to support such operations as:

- materials recovery (scavenging, recycling),
- handling of special wastes,
- leachate management, and
- landfill gas management.

7.10.1 Materials Recovery

If a materials recovery operation is to be included at the landfill site, careful consideration should be given to traffic control and to the location of recycling or scavenging operations. The planning of a materials recovery operation should be developed from the outset of the project and incorporated into the overall facility site plan and operating plan. A detailed discussion of materials recovery is presented in Chapter 15.

7.10.2 *Special Wastes*

Special wastes referred to in this document include hazardous wastes and some types of sludges. These types of waste require special provisions for handling and disposal. In the case of hazardous wastes, disposal should be conducted in a hazardous waste landfill, if possible, separate from municipal solid waste. Hazardous waste landfills are considered at greater length in Chapter 8.

7.10.3 *Leachate Management*

The management of landfill leachate is an issue for all landfills, but is most relevant to facilities that are constructed with bottom liners. Lined landfills must have provisions for collecting and treating the leachate. At such facilities, the landfill infrastructure typically will include leachate pumping stations and treatment works. In heavily urbanized areas, a public sewer may be available near the landfill; in which case, the leachate might be discharged to the municipal wastewater treatment system. Pre-treatment of the leachate before discharge to the public sewer might be necessary in order to protect the operation of the public treatment works.

The location of on-site leachate pumping and treatment facilities should be incorporated into the overall site development plan from the beginning of the project. Leachate treatment ponds, for example, may require a substantial land area. If such facilities are situated on the downgradient side of the site, it may be possible to reduce or even eliminate the need for leachate pumping.

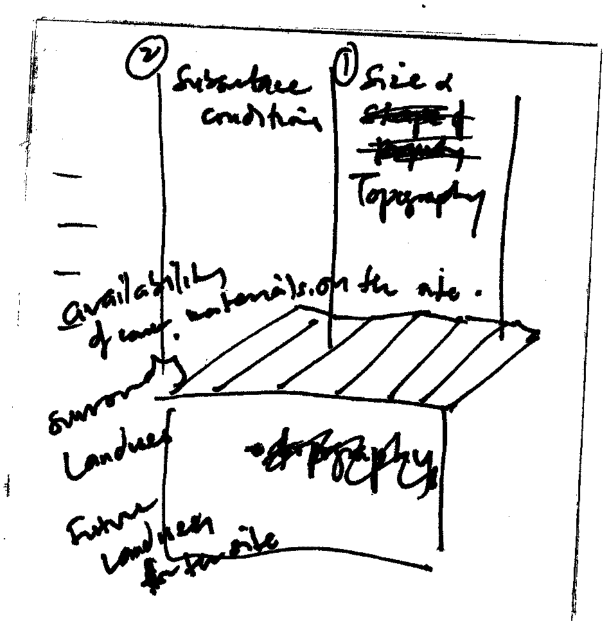
Leachate management is discussed in detail in Chapters 8 and 13.

7.10.4 *Landfill Gas Management*

Facilities for landfill gas management may include passive vents, trenches, extraction wells, collection piping, migration monitor probes, flares, or energy recovery devices. Vents, trenches, and extraction wells generally are located within the landfill area, while the other components would be outside the waste boundary. As with other infrastructure, facilities for landfill gas management should be integrated into the overall site design. Further discussion of landfill gas is presented in Chapters 8 and 14.

Reference

1. U.S. Environmental Protection Agency, *Design, Operation, and Closure of Municipal Solid Waste Landfills, Seminar Publication*, Office of Research and Development, Washington, DC, EPA/625/R-94/008, September 1994.



Subsurface conditions
Size &
Topography
availability of const. materials on the site.
surrounding
Landuses
Future Landuses for the site

Chapter 8

Design and Construction

8.1 Site Considerations

The methods and criteria for selecting a landfill site have been discussed in Chapter 6. However, landfill site considerations do not end once a site has been selected; site considerations also are important during the design of a landfill. The landfill should be designed to fit appropriately on the site and, where aesthetics are a concern, the facility should also be designed to blend into the surroundings. Since no two sites are identical, landfill designs can vary substantially, even if the sites are to provide the same disposal capacity. Site factors that may affect landfill design are topography, subsurface conditions, size and shape of the property, surrounding land use, availability of cover materials on the site, aesthetics, future land use for the site and surrounding properties, as well as other considerations. While the possible variations and combinations of site factors influencing the design of a disposal site are too numerous to describe here, of relevance and prime importance to the landfill designer is an awareness and accounting of all of the local site factors as they relate to the development of the landfill.

The following subsections present the key considerations associated with site characteristics which are also related to the design and construction of a landfill.

8.1.1 Site Preparation

Site preparation refers to the various procedures associated with the modification of the terrain in preparation for the construction of the landfill. Depending upon the characteristics of the site, this may be minor or major work. Site preparation would be minor, for example, at a site that is relatively flat, devoid of vegetation, and upon which all filling would occur above the existing grade. An example of major site preparation is one in which extensive excavation into the suborder is required or redirection of surface waters is necessary. Site preparation may include the following activities in advance of landfilling:

- clearing and grubbing;
- provisions for drainage, erosion and sedimentation control, and site access;
- excavation and stockpiling of soil; and
- grading.

8.1.1.1 Clearing and Grubbing

Clearing involves the removal of trees, brush and vines, fallen trees, and other matter such as boulders or refuse. Grubbing involves the removal of tree stumps and roots. Root removal typically is performed to a depth of 15 to 50 cm. Clearing should be performed in any area of the site that would otherwise impede the free movement and operation of vehicles and equipment, or would hinder the performance of the landfill.

All stumps should be removed from cleared areas, an operation that may require the use of heavy equipment. Grubbing of roots may not be necessary in all areas. Some of the areas that may not require grubbing include those assigned for material stockpile, gravel-topped roads, or areas that will receive the landfilled waste. However, any area that will have a landfill bottom liner should be thoroughly grubbed to ensure the long-term stability and integrity of the liner system.

The relative amount of land area cleared should be kept to the practical minimum to facilitate supervision of the site and to minimize environmental damage. At larger sites, clearing done in increments will reduce erosion, dust generation, sedimentation, and will help to prevent excessive scarring of the land. It may be necessary to avoid clearing and grubbing activities altogether during wet periods. Trees and shrubs at the periphery of the landfill should be retained to the maximum possible extent.

In some developing countries, because of chronic shortages of household fuel, a landfill site may already have been stripped of combustible vegetation long before it was considered for landfilling. Clearing is likely to be irrelevant in such cases. On the other hand, in other economically developing countries, substantial clearing and grubbing may be required for some landfill facilities in order to take advantage of an otherwise ideal landfill location.

8.1.1.2 Provisions for Drainage, Erosion and Sedimentation Control, and Site Access

Adequate provisions for drainage, erosion and sedimentation control, as well as site access will be required for the duration of site preparation activities. These provisions may be of a temporary nature, as in the case of a temporary haul road to an on-site borrow pit; or they may be developed as permanent support facilities for the landfill operation. Discussion of drainage, erosion and sedimentation control, and site access can be found elsewhere in the subsections that follow, as well as in Chapter 7.

8.1.1.3 Earth Excavation and Stockpiling

The majority of landfill sites require substantial excavation of earth materials in preparation for landfilling. The excavated materials generally are used in the construction and subsequent operation of the landfill. The volume of the excavation, when backfilled with waste, may represent a significant percentage of the landfill's design capacity.

Because there may be a lapse of several months or even years between the time of excavation and the time of use of the materials, a stockpile area of sufficient size must be provided for these materials. The physical characteristics of the excavated soils may vary to a considerable degree from different parts of the landfill site. Therefore, it may be desirable to establish separate stockpiles for the different types of materials extracted from the site. Similarly, separate stockpile areas should be provided for any earth materials imported to the site for the construction or operation of the landfill. Excavated soils that will not be used onsite (i.e., excess materials) potentially may be sold for other purposes, and the revenue from the sales used to defray landfill costs.

Topsoil should be stripped from all areas of the site that will be excavated, or filled with waste and covered. The topsoil, which is a valuable resource, will be needed later for final cover and restoration of disturbed areas. The removed topsoil should be carefully stockpiled at the site. Precautions should be taken to prevent mixing the topsoil with other soil materials, and to prevent the washing of topsoil into excavations or drainage ways.

In developing the landfill site, consideration should be given to the sequence of events involved in site preparation. It is a common practice to be filling in one phase of the landfill while excavating for the next. The timing of these operations is of critical importance in order to operate the landfill efficiently and economically. Furthermore, the sequence of excavation should be included in the overall plan for managing surface waters at the site, to avoid ponding, to minimize erosion, and to avoid disturbance to the active landfill operation.

8.1.1.4 Grading

Preparatory grading is the process of contouring the land to create the required base grades for the landfill once the processes for clearing, grubbing, and bulk excavation of earth materials have been completed. Grading also is performed in the construction of roads, drainage systems, and other landfill support facilities.

Preparatory grading plans should be developed in concert with the design of site drainage, erosion control measures, and access roads. The preparatory grading plans should show contour elevations for all disturbed areas of the landfill site and should establish minimum and maximum slope criteria for all cut and fill areas. Most importantly, the base grades and slopes for the landfill bottom should be developed only after careful consideration of subsurface conditions (e.g., soil type and depth to water table) and of the manner in which the area will be drained.

In the case of constructing a landfill with an impervious bottom liner and provisions for leachate management, the landfill base must be sloped to facilitate leachate collection. A minimum base slope of 2% is recommended. For unlined landfills, the preparatory grading is less critical but should still be done in accordance with a design plan that eliminates surface irregularities, controls runoff, and prevents ponding.

8.1.2 Location of Facilities

The site plan for the landfill should include a detailed layout of the initial and future landfill areas and of all major support facilities. The specific items to be covered in the site plan will depend greatly on the physical nature of the site and on the services to be provided at the landfill. A detailed discussion of the development and design of site plans is provided in Chapter 7.

8.1.3 Buffers

Buffers, or buffer strips, are corridors of land outside of the boundary of the solid waste, but usually within the landfill property, that are left in a natural-looking state to provide an aesthetically pleasing transition between the landfill site and the adjacent property. Buffers may be established from undisturbed natural areas or from disturbed areas that have been restored to a natural appearance. Enhancements may include tall or dense trees to provide visual screening of the landfill from its surroundings. Occasionally, screening berms with a vegetative cover are constructed for the same purpose. If the surrounding area is populated, screening berms may also help in controlling nuisance noise from landfill operations.

The wider the buffer zone, the more effective it will be in isolating the landfill from bordering property. In the United States, for example, it is common to establish required setback distances from the landfill to the property line. At the time of this writing, most economically developing countries lack specific regulations of this type, and the provision of buffers around the landfill typically is a matter of judgement. An adequate buffer zone will greatly improve public acceptance of the landfill and its operation, and usually is a wise investment to minimize future problems regarding groundwater quality and gas migration. Note that, if desired, buffer areas can be sold for compatible land uses once the landfill is completed and monitoring of the area indicates the absence of groundwater and gas problems.

8.2 General Design Criteria

The criteria for landfill design should be developed specifically to meet the particular requirements of a country or region. Local factors affecting the appropriateness of certain design criteria include climate, characteristics of the waste stream, availability of construction materials, economic resources of the population, and educational level of the workforce. However, several general criteria would apply to the design and construction of landfills at all locations. These criteria relate to the primary purpose of establishing the landfill, which is to protect human health and the environment. Consequently, these criteria may be regarded as universal standards. A brief description of the key criteria is presented in the following paragraphs.

8.2.1 Groundwater Protection

Water resources should be protected by locating the landfill downgradient from major aquifers and drinking water supplies. Where climatic conditions require, and the economic situation allows, the landfill should be provided with an impermeable bottom liner to reduce the risk of contaminating the underlying groundwater. It may be possible to construct the landfill within a naturally occurring low-permeability soil layer, which would avoid the high cost of installing an artificial liner. If the landfill is constructed without a liner, a minimum separation of 3 m should be maintained between the bottom of the landfill (and sidewalls in cases where the water table has been artificially lowered and an inward hydraulic pressure gradient exists on the sidewalls) and the high groundwater table and bedrock surface wherever possible, and no water supply wells should be located within 2 km or so downgradient of the site. An even greater distance of vertical separation is desirable.

8.2.2 Surface Water Protection

Surface water resources should be protected by preventing contact between surface water and the wastes in the landfill wherever possible. Run-on should be diverted from upgradient areas so that it flows around, rather than through, the landfill. The landfill also should be contoured such that runoff does not drain into the area of the working face or form pools on the landfill. All runoff from the landfill should be directed to appropriate sediment control devices, such as basins or traps, to allow suspended solids to settle out before the runoff enters natural drainage courses.

8.2.3 Spatial Efficiency

Cuts and fills should be balanced so that adequate quantities of soil from on-site locations will be available for construction, operation, and closure of the landfill. The need to import soil materials for these purposes should be avoided whenever possible. Deeper and taller landfills generally will be more efficient in terms of space utilization and cost than shallower and wider landfills of equal capacity.

8.2.4 Slope Stability

Whether during the initial preparation of the site or during operation of the landfill, slopes should be designed and established such that they are stable. The stability of the natural terrain, of cut slopes, of disposed wastes, and of mixtures and layered structures of waste and soil and synthetic materials must all be considered, analyzed, and assured by the facility design plan. The analysis must consider that while the properties of soils generally are invariant over the lifetime of a land disposal facility, the properties of the disposed wastes change because of the effect of landfill processes on them. The changes in some of these properties influence the stability of disposed wastes and, equally important, can influence the stability of structures composed of layers of waste, soil, and synthetic materials. Failures of land disposal facilities due to the instability of soil, waste, or both can be catastrophic if the quantities involved are large. Open dumps are particularly susceptible to, and candidates for, failures involving waste and soil since, by definition, they are not engineered facilities. Two examples of stability failures of open dumps are those that occurred in Sarajevo (formerly, Yugoslavia) in 1977 and in Istanbul, Turkey in 1993; the latter failure resulted in extensive damage to property and 39 human casualties [1].

The fundamental material properties that govern the stability of sloped structures of waste, soils, and synthetic materials are in-place bulk density, friction angle, and intercept cohesion [2]. These properties are, in turn, influenced by the moisture content of the materials and by other conditions, e.g., compactive effort (for instance, that exerted mechanically and that due to the overburden), porosity. Suggested values of friction angle and intercept cohesion for municipal solid wastes based on limited data are approximately 25 degrees and 30 kPa, respectively. If the in-place bulk density, friction angle, and intercept cohesion are known or determined, a qualified and trained professional can safely design the heights and slopes of a landfill facility.

In the design and construction of slopes, the natural angles of repose of the materials used should not be exceeded under any circumstance. On slopes where liner systems or final cover systems are to be placed, global and veneer stability (the ability of the installed materials to resist sliding) should be considered. Under typical conditions, soil slopes are stable at 1 vertical:3 horizontal. In addition, slope stability analyses should be performed, as necessary, to determine factors of safety.

8.3 Types of Landfills

Under the conditions prevalent in most economically developing countries, landfills may either be lined or unlined. They may also be classified by the types of waste they receive.

8.3.1 Landfills

Landfills generally refer to landfills that accept household or municipal solid waste. These facilities may either be lined or unlined, based on criteria presented elsewhere. A lined landfill has a natural or synthetic low-permeability barrier installed at its base. The purpose of the liner is to prevent the movement of leachate and gas into the surrounding soil and groundwater. With a liner in place, provisions must be made to remove and properly treat or dispose of the leachate that accumulates above the liner. The implementation of sophisticated synthetic bottom liners, combined with leachate collection and treatment systems, may be prohibitive for a number of developing countries. For this reason, landfills in economically developing countries are more likely to be either unlined, or lined with natural soils having a low permeability. In order to protect the groundwater resources, the design of landfills should stress good siting, careful regulation of wastes accepted at the facility, attention to overall landfill operations, diversion and/or control of water from entering the buried wastes, and periodic groundwater monitoring.

8.3.2 Hazardous Waste Landfills

Hazardous waste landfills refer to those which are provided with bottom liners and with all of the controls necessary to allow receipt of most types of wastes, including hazardous wastes. In developing countries, hazardous waste landfills are most likely to be used for the disposal of selected hazardous wastes.

8.3.3 Special Landfills

Special landfills (e.g., construction and demolition waste/industrial waste landfills) sometimes are designed and developed for the final disposition of special types of waste or residues, such as construction and demolition debris or some industrial products. Depending upon the characteristics of the wastes, these facilities may be lined or unlined. Demolition debris often consists of inert materials, and this type of waste typically may be disposed safely in a landfill. However, this practice of disposal may represent an unnecessary expense. Not only do the handling characteristics of demolition wastes usually differ from those of household refuse, but a large fraction of the demolition materials are recyclable and should be monitored and processed for materials recovery and, thus, diverted from land disposal.

8.4 Cell Design and Construction

Experience has shown that no one method of landfilling is best suited for all sites, and a single method is not necessarily the best solution for any given site [3]. The selection of a particular method should depend upon the physical characteristics of the site, climatic conditions, amount and types of solid waste to be accommodated, and the relative costs of the various options. The two basic types of landfill methods are the trench (Figure 8-1) and the area (Figure 8-2). In the trench method, the landfill airspace (or volume) and cover are obtained primarily from excavation within the eventual footprint of the waste. On the other hand, in the case of the area method, excavation for landfill volume and cover material within the eventual waste footprint is minimal, and cover material is obtained primarily from outside the waste footprint. The choice of trench versus area method is primarily based on topography, geology, and depth to groundwater. Most sites are a combination of trench and area.

8.4.1 Definition of Cell

All true sanitary landfills consist of basic elements commonly termed "cells." The cell forms an enclosed volume, more or less, and is intended to mitigate the more immediate public health and safety and environmental impact on a regular basis. The more immediate problems are those associated with vector attraction, odor, potential fires, and aesthetics.

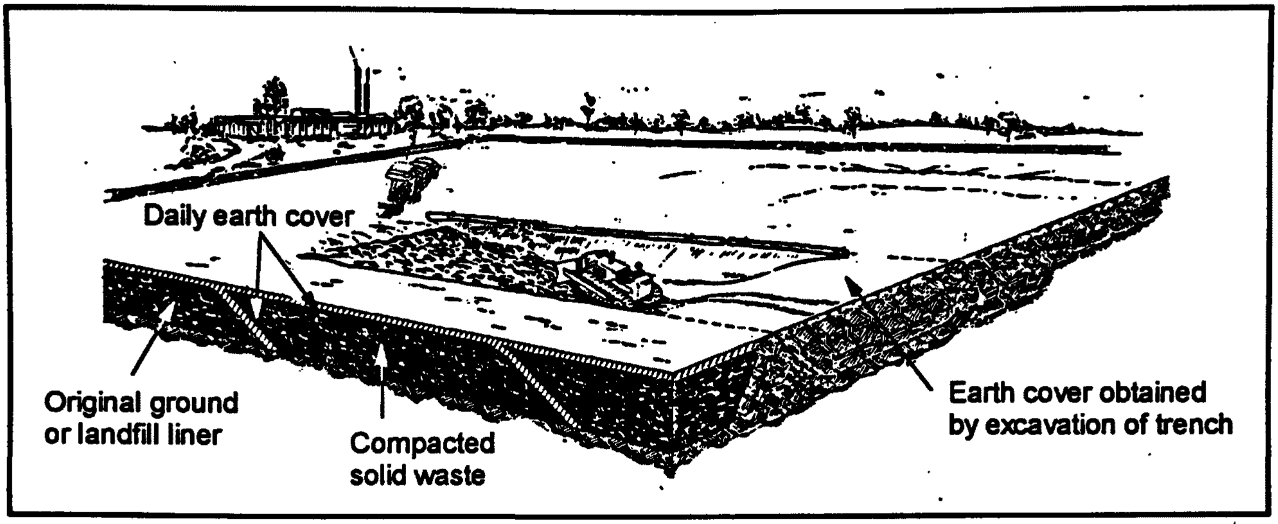


Figure 8-1. Trench Method of Landfilling

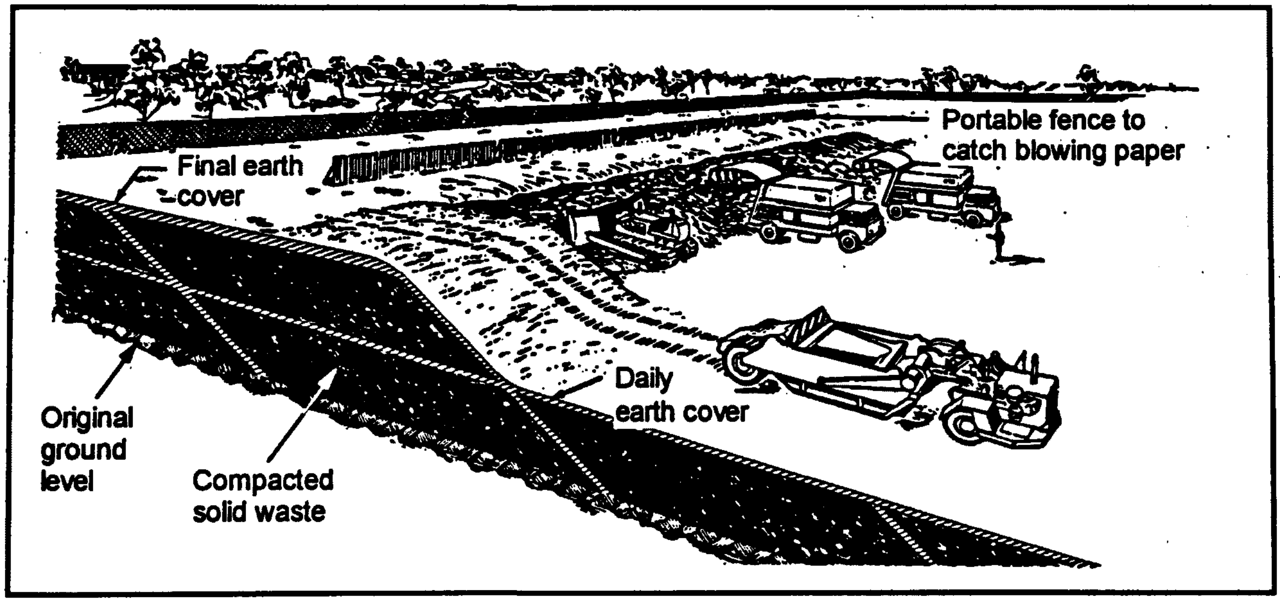


Figure 8-2. Area Method of Landfilling

A cell is formed by spreading and compacting the incoming solid waste in layers within a confined area. At the end of each working day, or during the working day as well, the compacted refuse (including the working face) is covered completely with a thin, continuous layer of soil, which is then compacted. The thickness of the soil cover typically is about 15 cm. The volume of compacted waste and its daily soil cover comprise a "cell."

The individual daily cells of refuse are placed in a sequential manner, side-by-side and row-by-row, to fill the area. A series of adjoining cells at the same height constitute a "lift." A complete area fill may consist of several lifts. The structures of cells and lifts are presented in Figures 8-3 and 8-4.

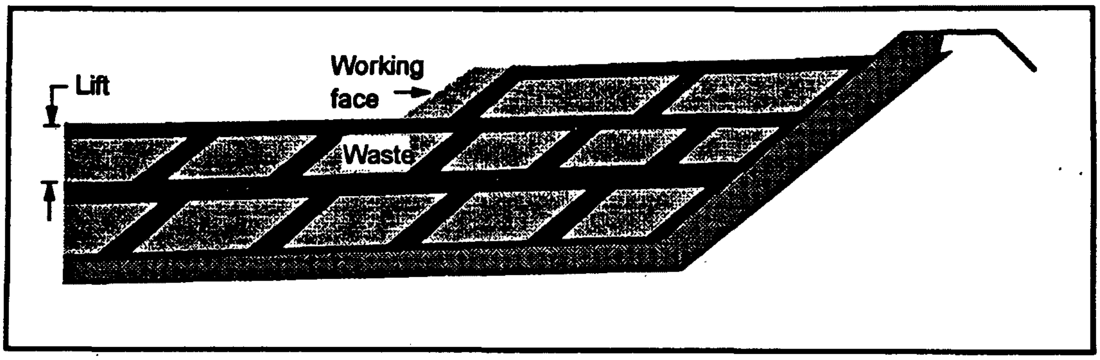


Figure 8-3. Illustration of Lift and Cell Structure of a Landfill

The cells should be designed and sized for quantities of waste requiring disposal. The basic elements of a cell are: height, length, width of working face, slope of cell, and sidewalls.

The factors that affect the dimensions of a cell are: the quantity of waste, thickness of daily cover, stability of slopes, and degree of compaction. As the cell height increases, the relative quantity of cover material (the soil-to-waste ratio) is reduced. The height of a typical cell varies between 2 and 4 m. Thinner lifts than the aforementioned range may have some benefit in

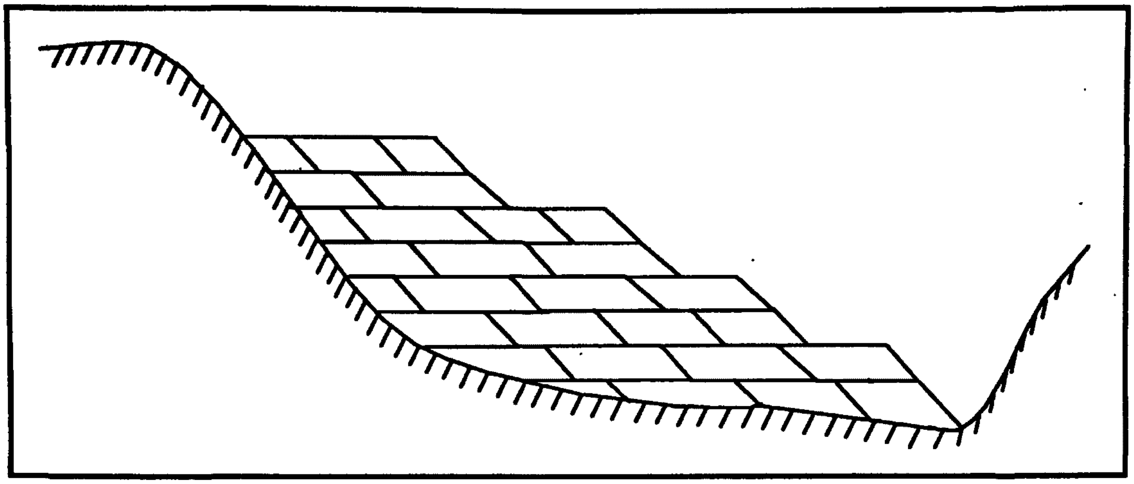


Figure 8-4. Example Illustration of a Canyon Fill

terms of avoidance or control of fires and in speeding the initiation of the methanogenic phase; however, a disadvantage is a higher cover-to-waste ratio.

Another important parameter is the width of the cell or width of the working face. The width of the working face dictates the degree to which the disposal operation can be managed. In most economically developing countries, the working face either is much too wide or there is not a clearly delineated working face. The minimum width of the working face depends upon two key factors: 1) the type of equipment used to distribute and compact the waste, and 2) the maximum number of vehicles arriving at the peak hour. Typically, it is recommended that the minimum width of the cell be on the order of 2 to 2.5 times the width of the blade of the equipment used for building the cell. Suggestions for cell widths as a function of quantity of waste are given in Table 8-1.

With respect to the number of vehicles, it is advisable to reach a practical and adequate balance between the width of the cell and the maximum number of vehicles arriving at the

Table 8-1. Suggested Minimum Cell Widths as a Function of Daily Waste Quantities

Quantity of Width Wastes (Mg/d)	Minimum Width Cell (m)
20 to 50	8
25 to 130	10
130 to 250	12
250 to 500	15

peak hour. The required width of the working face (in meters) can be estimated by multiplying the maximum number of vehicles arriving at the peak hour by four.

The slope of the cell is the inclined plane upon which the wastes are distributed. The maximum recommended slope is 1:4 (vertical:horizontal). However, slopes of lesser steepness are preferred, e.g., maximum compaction is achieved when the angle of the working face is close to horizontal. Outside slopes of the completed cell, if they represent the finished landfill surface, should not exceed 1:3. Depending upon slope stability and erosion protection analyses, outside slopes of 1:4 or even 1:5 may be required to avoid potential slope failure and to minimize long-term maintenance.

8.4.2 Trench Method

As the name implies, in this method, a trench is excavated. The excavation usually is sized to receive a specified quantity of waste. Depending on the local circumstances (e.g., availability of equipment), the excavation can be sized to receive several days of waste or more, e.g., a year's volume. Once the waste is discharged into the trench, the material is compacted and covered (Figure 8-1). Thus, each trench can be considered a cell.

In the process of disposal, the waste is deposited on the slope of the trench (maximum slope, 1:4). The excavated material, or spoil, serves as cover material. Spoil not used for the daily cover is stockpiled for later use in a subsequent area fill that might be constructed on top of the completed trench fill.

Stability of the sidewall is a very important factor in trench designs. Sidewall stability is a function of the characteristic strength of the soil, depth of the trench, distance between trenches, and slope of the sidewall. Maximum depth and steepness of sidewall slope are achievable when the soils are clays, glacial till, or other fine-grained, well-graded, consolidated soils. Weaker soils require gentler sidewall slopes to preserve stability. Other factors that may affect soil stability and permissible steepness of sidewall slope are climatic conditions and the length of time the trench is to remain open. In all cases, sidewall slopes should be designed so as to avoid imperiling the workers and equipment operating in and near the trench. As previously indicated, a suitable distance should be maintained between the bottom of the fill and the groundwater table. Consequently, groundwater protection places another constraint on trench depth.

The width of the trench should be sufficiently wide to accommodate the unloading of wastes from vehicles and the maneuvering of the compaction equipment. The width should be determined based on the number and types of vehicles that will use the landfill. Generally, practicality dictates that the width should be at least twice that of the largest piece of equipment that is expected to work in the trench.

Depending on the size of the landfill operation, excavation of the trenches may either be carried out on a continuous basis at a rate adjusted to meet landfilling requirements, or periodically. If periodic excavation is required, it may be possible to contract the operation to an entity which has specialized equipment. Greatest efficiency is likely to be achieved if, as one trench is being filled, another one is being excavated to receive the next day's waste.

Alignment of the trenches relative to the prevailing wind direction will influence the amount of blowing litter. The alignment most effective in terms of reducing wind-blown litter is one that is perpendicular to the prevailing wind.

The bottom of the trench should be sloped away from the working face to ensure drainage. During wet weather, water that may accumulate at the bottom of the trench should be pumped out. Surface water can be diverted from the trench by constructing temporary berms on the sides of the excavation.

8.4.3 Area Method

The area method involves placing the waste on a surface that has been previously prepared for that purpose (Figure 8-2). In this method, a layer of waste is spread and compacted on the surface of the ground (on the inclined slope) or, in the case of a lined landfill, on top of the liner system (Figure 8-3). Cover material is then distributed and compacted over the waste. This method can be adapted for use for land disposal of waste in quarries, strip mines, ravines, valleys, canyons, and other types of land depressions (Figure 8-4).

8.4.4 Ramp Method

The ramp, or progressive slope, method is a variation of the area fill. It consists of spreading and compacting the solid waste on a slope, as illustrated in Figure 8-5. Cover material obtained directly in front of the working face is spread and compacted over the waste. Since, in this method, no importation of cover material is needed, the ramp method promotes greater efficiency of site usage only when a single lift is built.

8.4.5 Combination

The area and trench methods can be combined in the construction and operation of a landfill. For example, if the site has varying depths of workable soil, the trench method could be used

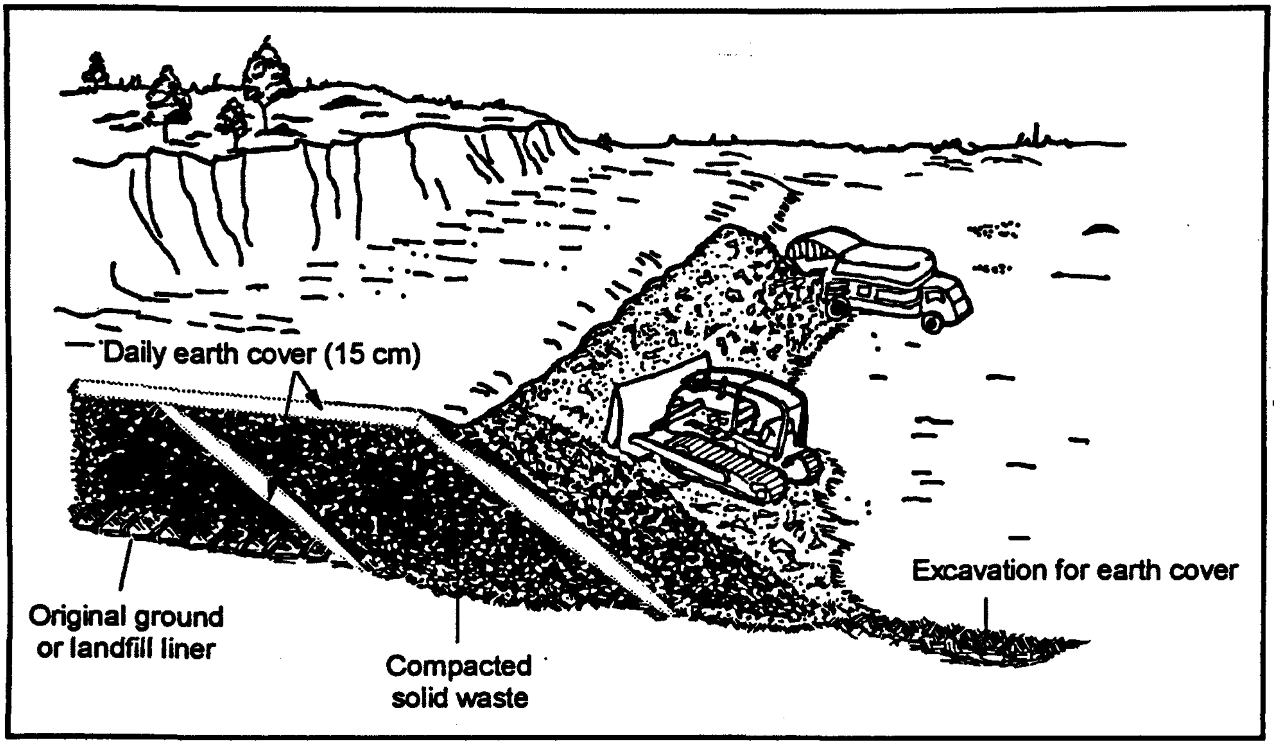


Figure 8-5. Ramp Method of Landfilling

where soil depth is greatest. Spoil not used for cover on the trench fill would be reserved for the sections of the site that are most applicable to the area fill method.

Through the use of the area method and stockpiled cover material, additional lifts could be constructed upon a completed lift.

8.5 Landfill Contouring

In the preceding subsections, it was explained that the construction of a landfill can take place either below ground or above ground. In addition, the size and shape of the landfill will be site-dependent. Topographical contouring involves the shaping of a site through controlled filling and grading. Determination of the desired size, shape, slope configuration, and final height of the landfill is an essential step in the design. The elevation contours to achieve the required dimensional aspects of the landfill should be established in the form of final grading plans as part of the original design. Since it is generally advantageous to build a landfill in stages, the grading plans should consist of a series of drawings corresponding to the different stages of construction. Needless to say, the contouring of the landfill must reflect the eventual intended land use of the fill. Land use of completed fills is discussed in other chapters of the guidance document, including Chapter 17.

An example of topographical contouring is landfilling above grade, such that a hill is formed. Landfill construction of this type can have a major impact on any landscape that is otherwise relatively flat. Another example of topographical contouring is filling against the natural slope of a hillside in order to extend the hill in an outward direction. The appearance will be more natural if the finished landfill is gently contoured with sweeping lines and smooth transitions to existing grade, rather than abrupt changes in slope. The construction of a hill from compacted solid waste is a difficult undertaking. The design of slopes should be based on analyses of slope stability and professional engineering judgement, not on general rules.

8.6 Bottom Liners

Liners are used in modern landfills to protect groundwater from contamination by landfill leachate. Based upon the limitations of economic resources and on the availability of materials of low permeability that exist among a number of economically developing countries, the installation of bottom liners may not be feasible. The need for the installation of a bottom liner depends upon a number of factors. Two of the more important factors are the hydrogeological conditions beneath the potential landfill site and local climatic conditions. Bottom liners may be considered for omission from the design of a landfill if the site is located in an arid or semi-arid region, where precipitation is 25 cm or less per annum, and the evaporation rate is greater than 50 cm. If the above climatic conditions are met and engineering calculations show that the potential for generation of leachate is very low, the omission of a bottom liner may be justifiable provided that surface water and groundwater sources are located remotely from the disposal site. An adequate engineering analysis of the potential impact of an unlined facility on surface water and groundwater resources would include the identification and consideration of the maximum design precipitation or inundation event.

If the conditions warrant the implementation of a bottom liner, the design should be such that materials used for the liner, as well as the facilities for leachate collection and treatment, be carefully selected and designed since their inclusion in the facility plan could represent a substantial economic hardship.

Bottom liners for landfills include those constructed from earth materials (soil and clay liners) and those that are anthropogenic. Synthetic liners include those constructed solely of polymeric materials (such as HDPE) and geosynthetic clay liners (GCLs), which are prefabricated bentonitic blankets. Anthropogenic, or synthetic, liners may not be readily available or secured, even if an economically developing country has the economic resources to construct a lined landfill. On the other hand, it also is to be expected that many locations will not have readily available sources of clay or other low-permeability soils for liner construction. The application of liners, therefore, will be sensitive to both cost considerations and the availability of materials.

Liner systems may be single, double, or composite. As its name implies, a single-liner system consists of only one impervious or low-permeability component. The liner may be either a natural soil material or a synthetic material. A leachate collection system is placed above the liner (Figure 8-6). A double-liner system consists of two liner components, which may be of the same or different materials. Above the top, or primary, liner is a leachate collection system. A leak detection system is placed between the primary and secondary liners (Figure 8-7). A

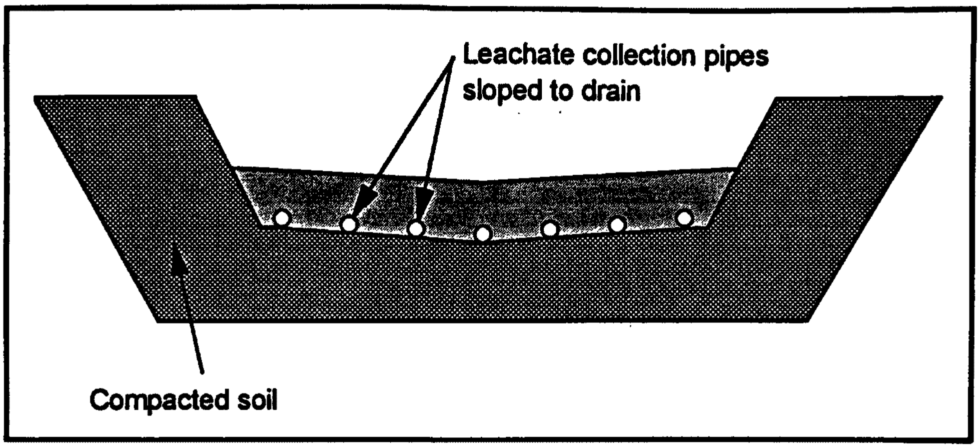


Figure 8-6. Example of a Single-Liner System with Leachate Collection System Also Shown

composite liner is one that is composed of two dissimilar materials. Usually, such liners employ a synthetic geomembrane liner directly on top of clay or other low-permeability soil.

8.6.1 Soil (Clay) Liners

Soil liners are used in both single-liner systems and composite-liner systems. Because of the relative availability of soil in general, compared to anthropogenic materials, soil liners would be the liner of choice for most applications in economically developing countries. Occasionally, soil liners are used as one component of double-liner systems. In situations that require secure containment, such as hazardous waste containment, double and composite liners should be used. A soil liner may be either the sole liner (single-liner system) or the lower component of a composite-liner system. Used as a single liner, a soil liner reduces, and may even prevent, leachate from migrating from the fill into the subsurface environment. As the lower component of a composite liner, a soil liner constitutes a protective bedding for the overlying geomembrane liner and serves as a backup for breaches in the geomembrane. A useful function of all soil liners is to serve as a long-term, structurally stable base for overlying facility components.

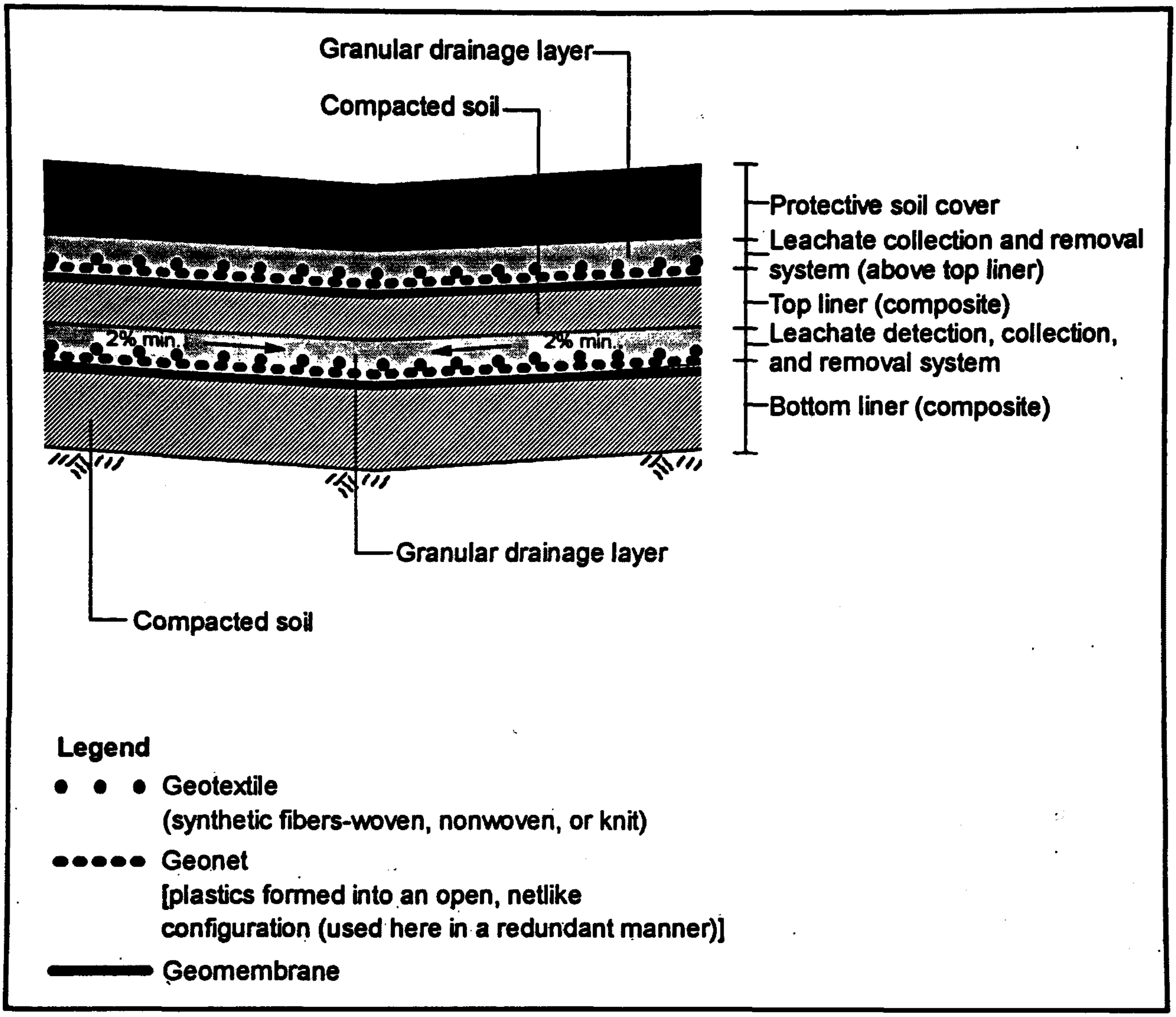


Figure 8-7. Example of a Double-Liner System with a Leak Detection System

8.6.1.1 Materials

To adequately serve as a liner, a soil must have a low permeability (hydraulic conductivity, k). The ideal k is equal to or less than 1 x 10^{-7} cm/sec when compacted under field conditions. After compaction, the liner should be able to support its own weight as well as that of the overlying facility components. The liner material should yield to handling by construction equipment. Finally, a liner constructed of soil material should suffer no significant loss in permeability or strength when exposed to waste or leachate from the waste. A soil that is deficient in a particular characteristic may be rendered suitable by blending it with another soil or with a soil additive. An example is the addition of bentonite to decrease permeability. Ideally, the compaction and permeability characteristics of the selected soil liner material should be determined by laboratory tests, so as to provide necessary information regarding the interrelationship between moisture content, density, compactive effort, and permeability. In addition, it is recommended that a test pad be built in order to verify the results of the laboratory analyses, as well as to evaluate the performance of the liner material under field conditions.

Of the available materials, well-compacted clay soil is most commonly used because of its properties and general availability. However, some locations do not have sufficient deposits of clay, e.g., desert areas and islands of volcanic origin. A clay liner usually is constructed as a compacted layer, 0.3 to 1 m thick. To function as a liner, the clay must be kept moist. If sufficient clay is not available locally, natural clay additives (e.g., montmorillonite) may be disked into it to form an effective liner material. The use of additives also requires evaluation in a laboratory, as well as controlled field testing to determine optimum types, amounts, and installation procedures.

If it meets the necessary specifications, use of the native soil at the facility site would be the most convenient and cost-effective approach. Otherwise, a suitable soil must be imported. Obviously, cost becomes an important consideration when off-site material is used. In economically developing countries, the feasible economic distance would depend upon local conditions, such as costs associated with excavation and transport. In most cases, a haul of any appreciable distance would be impractical. The soil liner material, whether excavated locally or imported, usually is stored as a borrow pile established at the site.

8.6.1.2 Design

Standard geotechnical practices adjusted to the local geology and landfill operational requirements should be followed in the design of the landfill liner. The soil liner should be underneath the entire area of the landfill that is covered with solid waste. The liner should also be sufficiently impermeable in order to impede leachate flow and thick enough to provide a structurally stable base for overlying components. The liner should have a uniform thickness and its design and placement should make allowances for leachate collection pipes and sumps.

Prior to installation of the liner, the base and sidewalls of the site must be prepared. The preparation usually consists of excavating and grading. Suggested sidewall slopes for liner placement are about 1:4 (vertical height:horizontal height). Suggested slopes to the leachate piping system are 2 to 5%, and 1 to 3% for the pipe.

In general, soil liners are constructed of compacted soils installed in a series of layers (lifts) of specified thickness. Although the use of thinner lifts facilitates compaction, it adds to construction costs because the number of lifts per unit of liner thickness is increased. Generally, the thickness of a liner lift prior to compaction is on the order of 15 to 20 cm. Some compaction equipment has compaction components (i.e., "feet") of dimension longer than 15 to 20 cm. Thus, the height of a compactor lift must be consistent with the equipment that is used to compact the soil.

8.6.1.3 Installation

The liner is installed by placing the liner material on the bottom of the fill with the use of scraper pans or trucks. The material is spread evenly over the site and then is broken up and homogenized through the use of disk harrows, rotary tillers, or manual implements to facilitate compaction. If soil additives are used, they are applied evenly over the site and then are thoroughly mixed into the soil.

The liner may be constructed in sections or in one piece. For a small facility, the entire liner may be constructed in one piece. Sectional or segmented installation would be more suitable for large landfills. In the latter operations, the wastes are placed on completed portions of the liner while the following portions of the liner are built. It is important that the sections be installed such that no breaks occur between them. This can be done by beveling or step-cutting the edge of a section as soon as it is installed, so that the succeeding section can be tied in with the previously installed section (Figure 8-8).

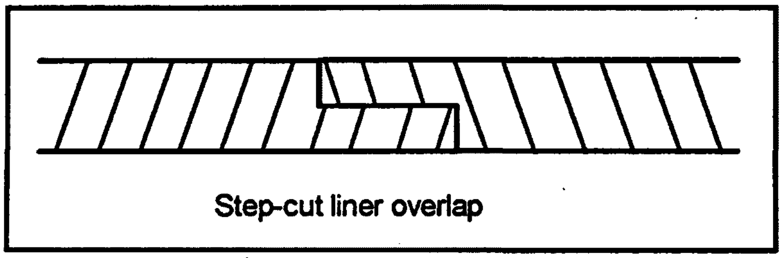


Figure 8-8. Example of a Segmented Liner Installation

The attainment of a high degree of compaction (and, therefore, of a low permeability) of the liner depends upon a proper moisture content of the soil. Any adjustment of the moisture content (e.g., through evaporation or through addition of moisture) should be made prior to placement of the liner. Care should be taken to achieve a uniform distribution of moisture throughout the soil. Uniformity of moisture distribution is achieved through mixing and by allowing adequate equilibration time after the moisture addition. The required time may be days or even weeks if the soil is very dry or certain additives are used. If the soil is too wet, it should be spread in layers, without compaction, until sufficiently dry and then mixed and placed and compacted on the liner. Moisture control is critical to the successful performance of a liner. If the soil is too wet (muddy) it cannot be worked, and if it is too dry, it cannot be compacted sufficiently.

The use of on-site clays for a liner generally will require recompaction and moisture adjustment of the soil in order to achieve a satisfactory liner. Recompaction generally is needed also to ensure that there are no lenses, cracks, and fractures which would compromise the performance of the liner system.

Practices followed and equipment used in earthwork construction generally are suitable for compacting a liner. Heavy compaction equipment fitted with sheep's foot rollers are ideal. The success of the compaction effort depends upon the individual soil liner layers being properly joined together. Joining the layers can be accomplished by scarifying the surface of the last installed lift prior to adding the next one and ensuring that the moisture content of adjacent lifts is similar. If sidewall slopes are not very steep, they can be compacted in lifts which are continuous with the layers for the bottom liner. Steeply sloped sidewalls may have to be compacted in horizontal lifts because compaction equipment cannot operate on steep slopes. Joining is especially important for steep sidewalls, because separation between lifts can serve as pathways for the migration of leachate through the liner. In general, horizontal lifts on steep side slopes should be avoided, and the side slopes should not exceed 1:4 unless special measures for steep slopes have been fully considered in the design.

Because climatic conditions strongly influence activities related to soil liner construction, steps must be taken to minimize impacts associated with climatic conditions. For example, precipitation may interfere with construction operations by eroding or flooding the site or by over-moistening the liner material. A preventive step would be to seal-roll the compacted layer so that the water will drain and not puddle or pond on the liner surface. Conversely, drying of the liner material can lead to the formation of cracks and, thereby, seriously increase the permeability of the liner. Cracks due to excessive drying can be remedied only by disking, adjusting the moisture content, and recompacting the affected portion of the liner. Liners must not be constructed by using frozen soils and must be protected from below-freezing temperatures.

With regard to the proper placement of soil-type bottom liners in economically developing countries, the availability and commonly used types of heavy construction equipment must be borne in mind. Tracked dozers (i.e., track-type tractors) are the dominant heavy equipment available in economically developing countries for performing the function of compacting soil. Generally, due to reasons of cost containment, of competition for funds, or of having to borrow equipment from other departments, the dozers tend to be the smaller models (i.e., those of lesser production capacity and lighter gross weights). Unfortunately, tracked dozers are not the ideal equipment for compacting clay soils for the purpose of achieving a hydraulic conductivity of 10^{-7} cm/s or less. Field studies [4] have shown that the achievement of this level of permeability for clay soils requires a grain size of 50% (by weight) cumulative passing 200 mesh and a clay content greater than 25%. On the other hand, tracked dozers are best suited for the compaction of coarse-grained soils with less than 4 to 8% passing 200 mesh. Consequently, for the successful placement of a bottom liner, the designers and installers of bottom liners must be cognizant of the need for the proper type of heavy equipment, as well as the availability of suitable soils.

8.6.2 Geomembrane Liners

The constituent material of a geomembrane liner is prefabricated polymeric sheeting. The terms "liner" and "geomembrane" are sometimes used interchangeably. Another, and lesser used, name for geomembrane is flexible membrane liner (FML).

A geomembrane liner may be used in several ways. For example, it may be used as a single liner installed directly over the foundation (soil) of the landfill, or it may be part of a composite liner placed upon a soil liner. Finally, it may be placed above or below a leak detection system in a double-lined landfill.

The design of a liner system that utilizes a geomembrane has many of the general features of a soil-liner system, namely an impermeable base, a collection and drainage system, and a piping system for transport of the collected leachate.

Geomembranes may not be available in economically developing countries. Should they be available, attention must be given to cost, as well as to the practicality of their installation.

The major steps to be taken in the use of a geomembrane liner are: 1) selection of the material, 2) design of the subgrade, and 3) planning of the installation. Planning involves the design of subcomponents, such as sealing and anchoring systems and vents. Among the types of membranes commonly used for lining landfills are high-density polyethylene, chlorinated polyethylene, and chlorosulfonated polyethylene [5,6]. Important criteria to follow in selecting a geomembrane include:

- chemical compatibility with the leachate to be contained;
- possession of appropriate physical properties such as thickness, flexibility, strength, and degree of elongation;
- long-term stability; and
- availability and cost.

One of the more important criteria in the selection of a geomembrane liner for a community in an economically developing country would be that of availability and cost. Another important criterion closely related to cost is availability of equipment and properly trained personnel for the adequate installation of the synthetic liner.

In the absence of testing facilities, judgements related to chemical compatibility should be made on the basis of specifications listed by the manufacturer. Regarding mechanical properties, geomembrane liners having high strength and low elongation are best suited where high stresses are expected (e.g., sidewalls steeper than 1:3). Lower strength and higher elongation geomembranes (e.g., high-density polyethylene, chlorosulfonated polyethylene, rubbers) are most appropriate for applications likely to involve large deformations, such as differential settlement and local subsidence. Other physical properties to be considered are:

- resistance to puncture,
- thermal expansion,
- characteristics for making joints or seams,
- resistance to weathering, and
- resistance to biological attack.

Weathering may take the form of deterioration by ultraviolet light, ozone reactions, and plasticizer migration. Agents of biological attack include bacteria, fungi, and rodents. In this particular case, it is necessary to rely on data provided by the manufacturer and advice by trained professionals. Although some published literature is available, such information typically is very difficult to obtain in an economically developing country.

The subgrade upon which a geomembrane liner rests is a key factor in the maintenance of its integrity. The subgrade should serve as a supporting structure and should prevent the accumulation of gas and liquid beneath the liner. Surface preparation should include removal of stones (larger than 2.5 cm), roots, and other debris from the surface. Organic material should be removed in order to reduce settlement and gas production from the decomposing organic matter under the liner. Soils that expand or shrink excessively should be avoided because of the repeated stresses imposed on the liner by the shrinking and swelling. Finally, the substrate soil surface should be compacted to provide a firm and unyielding base for the liner.

Gas can be produced below the liner by microbes in the underlying soil. It could result from air entrapped during liner installation or that which is being forced through the soil by a rising groundwater table. Regardless of its origin, the gas could lift up the membrane, thus imposing a stress on it. Liquid may accumulate as a consequence of leaks in the liner or infiltration of groundwater from surrounding soils. Consequences of the accumulation can be uplift stress and reduction of the strength of underlying soils. Leachate that escapes from the landfill through breaks in the membrane can contaminate surrounding soils.

In addition to mechanical stresses resulting from gas and liquid accumulation, such stresses may be caused by subsidence beneath the liner. Other mechanical stresses may take the form of: 1) tangential stresses due to differential movements of the subgrade, 2) concentrated stresses that lead to punctures and tears, and 3) repeated stresses that fatigue or abrade the liner. All of these failure mechanisms can be prevented or minimized by:

- taking general foundation design measures to prevent settlement, subsidence, slope failure, and other undesirable occurrences;
- determining foundation configuration;
- appropriately designing protective bedding layers; and
- specifying proper surface preparation measures.

Among the foundation design measures that can be adopted are configuration of the subgrade to be free of abrupt changes in grade (i.e., to be on a smooth plane or as regular as possible). Sidewall slopes should be such that tangential stresses do not exceed the tensile strength of the liner. Important design features of protective bedding layers are the provision of drainage to prevent the accumulation of gas or liquid and the protection of the liner from being punctured. The drainage layer may consist of sand, gravel, or other comparable granular material. Alternatively, it may take the form of a geotextile (a fabric designed to provide tensile strength and serve as a filter).

Some of the problems associated with granular drainage layers are:

- difficult installation on slopes,
- instability on steep slopes, and
- vulnerability to disturbance by workers during construction.

These problems are avoided by resorting to geotextiles. Moreover, geotextiles protect the liner from mechanical stresses. However, geotextiles in contact with liners may present another set of difficulties, especially with respect to slippage on steeper slopes. The need for a drainage layer below the liner may be avoided altogether if there is adequate vertical separation between liner and groundwater, and if perimeter drainage controls are effective.

As the discussion presented in the preceding paragraphs indicates, the design of any landfill-liner system is a complex and critical task, and the variables are many. Liner system design should be performed by qualified and competent engineers only. Similarly, the installation of a geomembrane liner is a complex and critical undertaking, and should be done by a qualified and competent company under the supervision of the manufacturer or an installer designated by the manufacturer, with third-party oversight by a trained engineer.

8.7 Final Covers

With regard to the landfilled wastes, the final cover is the only method to limit leachate generation and, hence, potential contamination of groundwater for sites not located in groundwater. The final cover serves to limit the inflow of water into the fill from outside ambient sources, e.g., precipitation. A good final cover system also serves to reduce the time and expense of long-term care and to reduce long-term adverse environmental impacts, while at the same time promoting productive use of the closed landfill and its surroundings.

Final covers for landfills (also called landfill caps) serve several purposes; namely, they:

- provide a physical barrier over the buried refuse, thus preventing human contact, minimizing problems with vectors (disease carriers), and serving to control odors;
- prevent erosion that could expose the waste materials;
- reduce the amount of infiltration that contributes to the generation of leachate; and
- provide for a good foundation for possible reuse of the landfill area.

Final cover systems in some industrialized countries are designed with multiple layers and range from the simple to the complex. In a developing country, the simpler designs are more likely to be affordable (one reason is the general scarcity and expense of securing appropriate cover soil), but may not offer entirely satisfactory performance. Where compromises in design and construction are made, the likely tradeoff will be greater maintenance requirements during the post-closure period.

The most basic design of a final cover contains two layers: 1) the surface (or vegetative support) layer, and 2) the hydraulic barrier layer (Figure 8-9). The surface, or vegetation, layer supports a cover crop of hardy, perennial grasses that promote evapotranspiration and help to control erosion by wind and water. Below the surface layer is the hydraulic barrier layer, consisting of a soil of low permeability, which impedes the infiltration of any water from the surface layer that was not lost to runoff or to evapotranspiration, and also holds water for later evapotranspiration.

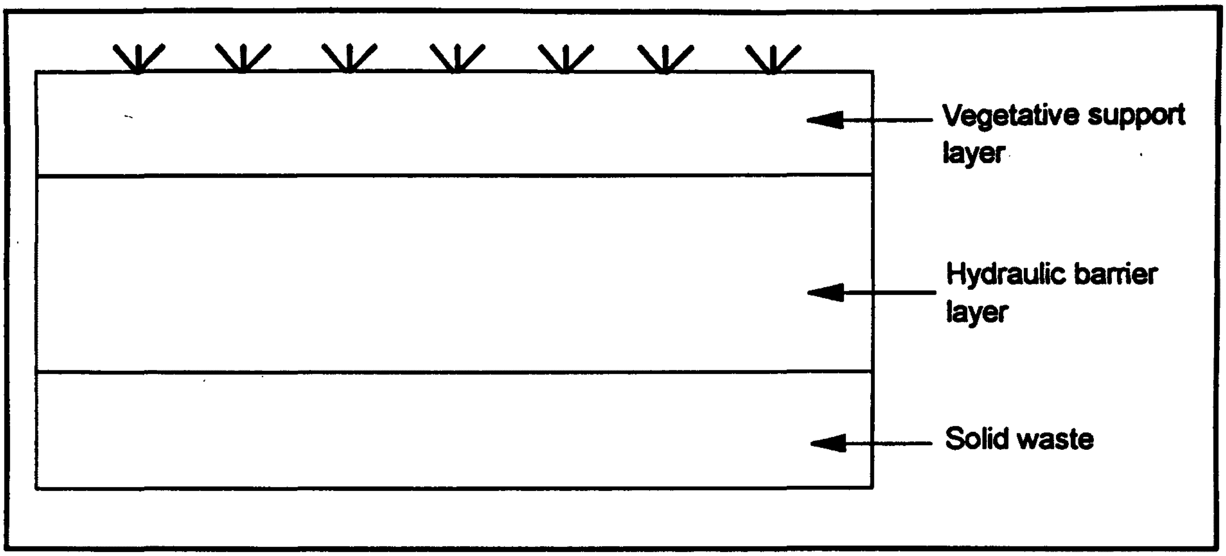


Figure 8-9. Basic Final Cover Design

In an economically developing country, it is advisable to use a thickness of about 60 cm for the surface layer and 30 cm for the hydraulic barrier. This design would be acceptable in areas with high evaporation and low rainfall (i.e., arid and semi-arid regions).

In other climates, and where situations demand additional protection, it may be necessary to include thicker layers or other layers in the final cover system design. For example, in humid climates, the basic 2-layer design may be incapable of controlling the quantity of water infiltration without causing saturation and sloughing of the overlying soil layer.

As described above, the three routes for reducing infiltration into the landfill are:

1. promotion and facilitation of runoff,
2. enhancement of evapotranspiration, and
3. reducing the passage of water through the barrier layer.

In order to promote runoff, the finished surface of the landfill should have a recommended minimum slope of 5%. A slope of this magnitude will provide good drainage, while allowing for differential settlement of the landfill over time. Establishment of a vigorous cover crop will help to prevent erosion, while removing a large fraction of the water budget through evapotranspiration. The hydraulic barrier layer will be most effective if it is comprised of a very low-permeability material -- the lower the hydraulic conductivity the better, with the best being 10^{-7} cm/sec or less.

A substantial buildup of moisture above the barrier layer, as already mentioned, could lead to problems in the performance of the final cover system. The addition of a drainage layer above the barrier layer would contribute to the solution of this problem. The drainage layer represents an increase in the complexity of the landfill cap, but is just one example of the more elaborate designs that are possible in multi-layer landfill cover systems. As shown in Figure 8-10, there are eight different layers that can be considered in the design of a final cover. The layers are as follows:

1. surface (vegetative support) layer,
2. filter layer (upper),
3. biotic barrier,
4. drainage layer,
5. hydraulic barrier,
6. foundation layer (buffer),
7. filter layer (lower), and
8. gas ventilation layer.

The function and essential criteria for each layer are summarized below.

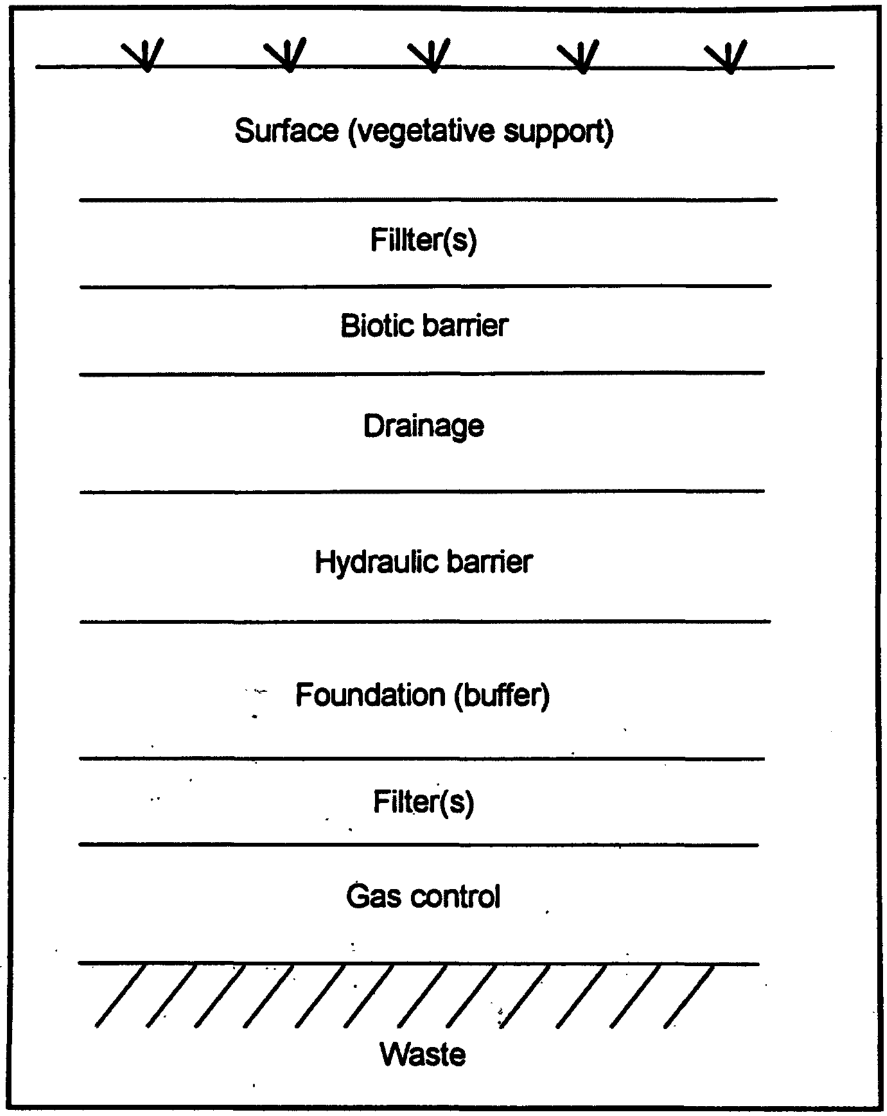


Figure 8-10. Components of a Complex Final Cover System

8.7.1 Surface (Vegetation) Layer

The surface layer is needed to protect the cover from erosion due to wind and water flow. It also serves to reduce infiltration through evapotranspiration. This layer should be about 60 cm, composed of nutritive and dense topsoil in order to support plant growth, and be sloped to prevent water accumulation. This material can be mixed with composted yard debris, sludge, or animal manures.

8.7.2 *Filter Layer*

Any time that fine soils are placed above coarse soils, there is potential for the migration of the fine soils into the voids of the layer of coarse grains. This phenomenon results in the plugging of the coarse layer. Filter layers are used to remove fine particles from infiltration and to allow upward flow of landfill gases. A graduated soil layer of finer to coarser particles (top to bottom) may be used as the filter layer. Granular filter sand can also be used as the filtering media. Synthetic filter fabrics (geotextiles) can also serve this function if they are available locally.

8.7.3 *Biotic Barrier*

The integrity of the hydraulic barrier must be maintained throughout its design life. Plants and animals can perforate the hydraulic barrier and, thus, ruin its performance. One method of controlling this potential problem is through frequent mowing and pruning of the plant growth. Rodenticide can be used, but sparingly, since it may contaminate surface or groundwater. Another method of control is through the installation of a biotic barrier. A biotic barrier consists of a layer of construction debris or crushed rock, of a size that will prevent the advance of plants and animals into the underlying layers. Biotic layers can range from 30 to 90 cm, depending on site-specific conditions.

8.7.4 *Drainage Layer*

The design of final covers should, in most cases, incorporate the design of a drainage layer. The few exceptions would be in arid areas, where precipitation is very low. The only purpose of this layer is to intercept the downward flow of infiltration and to redirect it laterally (to the landfill perimeter) before it can penetrate the hydraulic barrier.

A schematic of a drainage layer system is presented in Figure 8-11. As shown in the figure, the layer must slope in the direction of collection points on the perimeter of the landfill. The layer should be composed of porous material, having a hydraulic conductivity of 10^{-2} cm/sec or

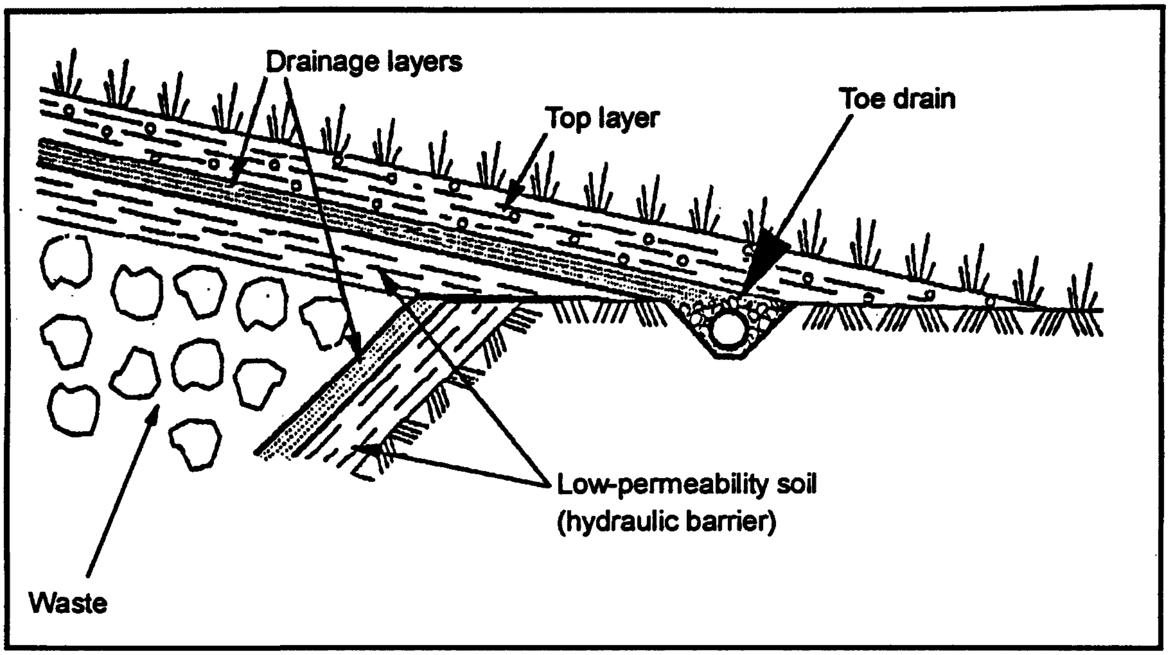


Figure 8-11. Illustration of a Drainage Layer Sloping to the Collection System

greater, and the thickness of the layer should be at least 30 cm. Appropriate materials include medium-to-coarse sands, gravel, and synthetic drainage media (geonets).

8.7.5 Hydraulic Barrier

The hydraulic barrier is probably the most important layer of a final cover system. The main function of the hydraulic barrier is to prevent infiltration of precipitation into the solid waste. In industrialized countries, these barriers are made up of geomembrane liners, or of fine-grained, low-permeability soil, carefully compacted. In economically developing countries, soil barrier layers should be the first choice as hydraulic barriers. The thickness of the layer depends on site conditions, but should be at least 30 cm, with the goal being 60 cm. The soil can be admixed with other materials such as bentonite clay and fly ash in order to achieve as low a permeability as is feasible, with the goal being the achievement of a permeability of less than or equal to 10^{-7} cm/sec. The success of the final cover depends upon the maintenance of the hydraulic barrier's integrity.

The integrity of the hydraulic barrier layer can be adversely affected by three mechanisms of degradation: chemical, mechanical, and environmental. Of the three mechanisms, chemical degradation occurs as a result of reactions between vapors and gases and the barrier material, and is the least troublesome. Mechanical degradation results mainly from construction-related factors such as excessive overburden, high compaction, the presence of clods, improper moisture content at the time of compaction, and punctures by coarse materials. Environmental degradation is caused by drying, wetting, freezing, thawing, and root penetration. Even where available, the use of synthetic membranes in liner construction can be relatively expensive in some economically developing countries. If synthetic membranes are used, they must be properly protected from mechanical damage (during both construction and post-closure maintenance) by installing them with an adequate underlayment and an overlaying protective layer such as sand, which may also serve as the drainage layer.

8.7.6 Foundation Layer (Buffer)

The foundation layer is designed to serve as a protective buffer between the barrier layer and the landfilled waste, and to support the load from the cover. It is installed directly under the barrier layer. This layer usually is made up of compacted medium-to-coarse grained soil. A geotextile may also be used for this purpose.

Installation of a foundation layer is not the only consideration in foundation design for landfill cover systems. Since one of the main concerns is the control and accommodation of settlement of the cover system due to decomposition of the underlying wastes, a particularly effective means of protecting the capping system is to provide a well-designed and properly constructed subgrade. The longevity of the cap components will be enhanced if the subgrade is graded smoothly and is properly compacted before the final cover materials are placed.

8.7.7 Gas Ventilation Layer

Landfill gas (biogas) is a product of decomposition of organic matter in the landfill (see Subsection 8.13 and Chapters 11 and 14). The final cover system must provide a means for releasing the gases generated after the cap has been placed. The gas ventilation layer provides the mechanism and pathway for gas release. Gas venting mechanisms typically utilize a porous layer of at least 30 cm, placed as close to the waste as possible. The layer may be part of a static or dynamic gas collection system (see Chapter 14). An effective means of gas ventilation is to install the porous layer directly above the waste and below the hydraulic barrier layer. It would probably be most economical to combine the functions of the ventilation and foundation layers into one layer. A typical design would include a 15 to 30 cm layer of highly permeable soil (k greater than 10^{-2} cm/sec, similar to that of a drainage layer) or the equivalent permeability using geotextiles.

8.8 Use of Earth Materials

An efficient and economical landfill operation is one that makes productive use of on-site and locally available earth materials, to the maximum practical extent. Using local materials will reduce the costs of material hauling, construction, and operation of the landfill. A list of some possible uses of different earth materials that may be readily available to a particular landfill project is presented in Table 8-2.

8.9 Construction Quality Assurance

This section presents a series of recommendations to follow in order to achieve a proper and reliable design of a landfill. It is recognized that in some locations, it may very difficult to comply with all of the recommendations. However, it is also recognized that there are several areas within economically developing countries which have reached a very sophisticated level of landfill design and operation. Furthermore, the recommendations are presented so that those communities which, due to present circumstances, are not able to comply with the

Table 8-2. Typical Uses of Earth Materials for Landfill Construction and Operation

Material	Uses
Clay, Silty Clay ($k=10^{-7}$ cm/sec after compaction)	Bottom liners, barrier layers
Dense Till ($k=10^{-7}$ cm/sec after compaction) (no stones larger than 10 cm)	Bottom liners, barrier layers
Silt, Silty Sand, Fine Sand	General site filling and grading, daily and intermediate cover
Medium-to-Coarse Sand	Drainage, gas ventilation, and buffer layers; general site filling and grading; pipe bedding
Gravel	Drainage and gas ventilation layers; road and embankment fills; pipe bedding; subdrain trenches
Stones (crushed rock up to 4 cm in size)	Leachate collection drains; subdrains; gas collection vents, trenches, and wells; road bases and surfaces (angular rock only)
Stones (rock fragments from 4 to 40 cm in size)	Rip-rap for channel protection and slope stabilization
Stones (rock fragments larger than 40 cm)	Rip-rap for protection and stabilization of major slopes and drainage ways
Common Borrow (no stones larger than 15 cm)	General site filling and grading
Topsoil	Surface (vegetation) layers

suggestions are aware of the intricacies associated with a sound program for construction quality assurance.

The design engineer is responsible for ensuring that the materials specified for the landfill construction have the proper size, quality, durability, and performance characteristics for the intended function. The responsibility of the installer (e.g., municipal crew or construction contractor) is to obtain the specified materials and to install them in accordance with the engineer's drawings and specifications. Finally, it is the responsibility of the owner's supervising agent (usually the engineer) to make certain that the installer documents the specifications of the materials and performs the required field tests of the installed components as set forth in the engineer's construction specifications.

Modern sanitary landfill practice entails the presentation of laboratory test reports or manufacturer's written certifications to show that the more important landfill construction materials meet the physical properties stated in the specifications. Some of the important construction materials include earth materials and manufactured products. The owner, or the owner's agent, should receive these certifications and reports for approval before the materials are installed, and preferably before they are delivered to the jobsite, or are excavated if obtained on-site.

Laboratory test reports or certificates, as relevant, should be presented for the following construction materials:

- low-permeability soils for liners or barrier layers;
- soils for drainage, gas ventilation, or buffer layers;
- any other soils having a specified permeability or gradation requirement;
- stone for leachate collectors; subdrains; gas vents, trenches, or wells;
- topsoil for final cover systems;
- geotextiles for any specified application;
- geomembrane liners; and
- any other specified geosynthetic material.

Typical laboratory tests on proposed soil materials include natural moisture content, particle size distribution, Atterburg limits, and Modified Proctor compaction. Hydraulic conductivity testing is performed on low-permeability soils, as well as drainage and gas ventilation media. As stated previously, special attention must be paid to the moisture content and to the proper compaction of clays during preparation and installation of clays as hydraulic barrier layers.

In the United States, it is common to require testing of samples taken from the borrow pit before delivery, then subsequent testing of the delivered material at a specified sampling frequency. It is recommended that installed earth materials be field tested for in-place compacted dry density and moisture content after each completed lift. Structural fill for landfill foundations, earth berms, and others should be compacted to a relative density of 90%. Non-structural fill and soil layers within final cover systems may be compacted to 75% relative density.

Manufactured products for which certificates are normally required in industrialized countries include: all pipe and fittings, geomembrane liners, geotextiles, and other geosynthetic materials. In addition, the specifications should require the contractor to submit shop drawings for any special fabrications. In the example of a geomembrane liner to be installed, the contractor's submittals would typically include the following:

- manufacturer's certification of compliance to specified physical properties;
- laboratory test results demonstrating conformance to selected physical property requirements;
- manufacturer's warranty;
- manufacturer's recommended installation and repair procedures;
- contractor's workplan and detailed sequence of installation;

- shop drawings showing proposed layout of geomembrane panels and location of field seams; and
- manufacturer's non-destructive and destructive seam testing procedures to be used in the field, and the criteria for accepting or rejecting tested seams.

During the installation, the contractor should be required to maintain a quality control log to document the progress of the work, including the location and results of all field tests. Laboratory test results on any samples taken for destructive field seam tests should be submitted to the owner as soon as they are available. Upon completion of the installation, the contractor should submit bound copies of all certificates, test results, logs, and field notes to the owner. Record ("as-built") drawings of the completed installation should also be included in the documentation.

8.10 Groundwater Controls

As discussed in Subsections 8.2 and 8.6, in the event that conditions are such that an unlined landfill can be implemented, it is important to provide a vertical separation between the bottom of the landfill and the underlying aquifer (e.g., 3 m). The requirement for separation also pertains to situations wherein the aquifer has been artificially lowered and the sidewalls of the landfill are potentially subject to groundwater intrusion. In the case of lined landfills, the separation is less critical; but it is still good practice to provide at least some nominal distance between the liner and the highest known water table elevation.

To achieve an adequate separation between the water table and the landfill, in some cases lowering of the water level by pumping or lateral diversion of the water may be possible. When positioned within an aquifer, the fill is subject to an inward pressure gradient effected by the water. If the source and flow of the water is artificially modified, an adequate separation can be achieved between the fill and the water.

Lowering of the groundwater table, coupled with the excavation of the soil, can also be used in some cases to generate cover soil and landfill capacity. However, it is generally impractical in an economically developing country to lower the water table by pumping because of the required effort and expense of operation and maintenance. Consequently, in most cases, any groundwater table modification would have to be performed by means of gravity drainage. The ability to collect and drain groundwater will depend on the transmissivity of the groundwater through the soil, which is a function of available hydraulic pressure and the permeability of the soil. Attempts to modify the groundwater table will be possible only where the soils are reasonably permeable and there is sufficient topographic relief to allow free drainage of collected groundwater to a surface outlet at some lower elevation.

The usual method employed for diverting groundwater is to install an interceptor trench(es) on the upgradient side(s) of the landfill. This concept is illustrated in Figure 8-12. The high permeability material for the interceptor can be locally available aggregate or alternatives such as coarsely crushed glass from resource recovery operations if conventional aggregate is not locally available. The design of the groundwater control system must be carefully considered, as it must perform reliably and virtually without maintenance for the duration of landfilling and the subsequent post-closure period.

8.11 Surface Water Management

Surface water management consists generally of:

- preventing run-on (from upland areas) from flowing onto the landfill site and contacting the waste fill,
- controlling runoff so that it is diverted from the active landfill area and does not create pools or saturated soil conditions on the landfill and peripheral areas, and

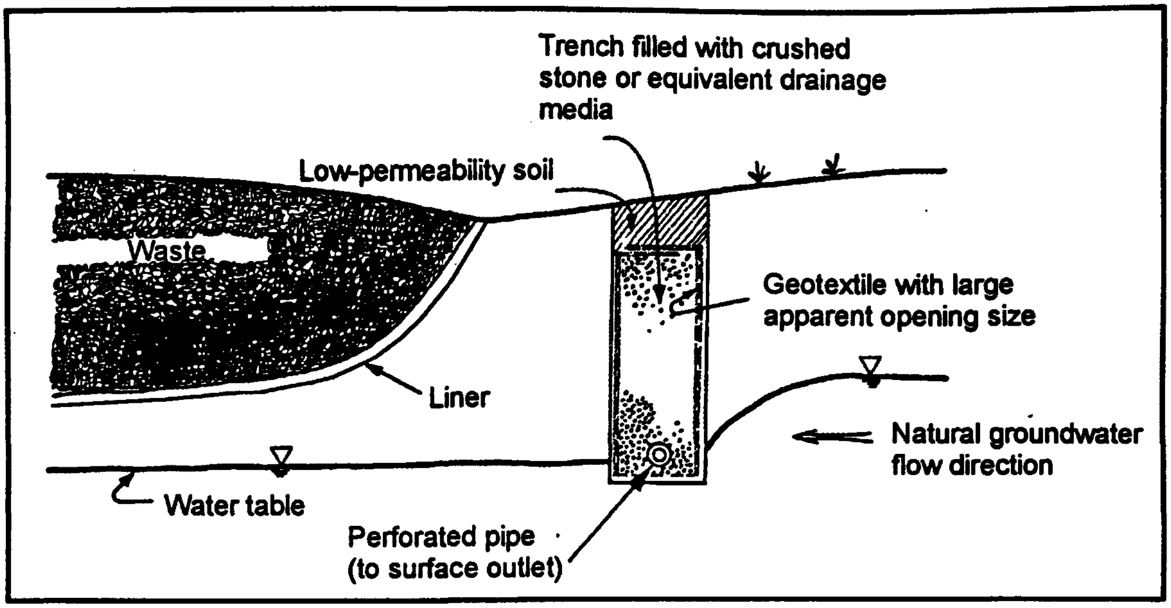


Figure 8-12. Groundwater Interceptor Trench

- providing erosion and sedimentation control measures to prevent sediment deposition in drainage ways and low-lying areas on the site and to protect downstream water resources.

The significance and methods of surface water management have been previously mentioned in this chapter, as well as in Chapter 7.

8.12 Leachate Management

The purpose of leachate management is to prevent contaminants in the leachate from entering the underlying aquifer and any connected surface water body. The three tenets of leachate management are minimization, prevention, and containment.

8.12.1 Minimization

The first rule is to minimize the quantity of leachate generated by considering the manner in which the landfill design and operation influence leachate formation. As previously indicated, infiltration of precipitation and surface water is the major pathway for the generation of leachate. Therefore, steps should be taken in the design and operation of the facility to minimize infiltration. This goal is achieved by:

- keeping the active area of the landfill as small as practical;
- segregating the active landfill from unfilled (future) stages by means of berms and separate leachate collection systems;
- placing low-permeability soil cover on inactive areas, and final cover on areas that have reached final grades (in other words, providing for sequential closure of the landfill in planned stages); and
- ensuring that the final cover system design incorporates an effective hydraulic barrier layer, as discussed previously.

8.12.2 Prevention

Ideally, the landfill should be constructed entirely above the water table. The fulfillment of this condition will prevent the formation of leachate through contact between the waste and groundwater. Although to be avoided if possible, where a landfill is located within groundwater and therefore subject to an inward hydraulic pressure gradient, contact between the waste and the water is to prevented by proper design of the liner system.

8.12.3 Containment

Containment of leachate is possible only in lined landfills or in those landfills built in a naturally occurring clay or dense till subgrade soil. The contained leachate must be collected in a leachate collection system above the landfill liner, then removed for subsequent treatment or disposal. Removal of leachate from the system usually is accomplished by pumping. The alternative to the collection and treatment of the leachate that is produced is a steadily rising level of leachate within the fill, which has led to substantial problems and costs at disposal sites in the past. The costs of containing, collecting, removing, and treating leachate are relatively high. Where collection or containment is not feasible, the strategy for leachate management must be effective application of the concepts of prevention and minimization.

Detailed discussions on leachate generation and the systems for collecting and treating leachate are presented in Chapters 12 and 13.

8.13 Landfill Gas Management

The management of landfill gas includes:

- prevention of gas migration to off-site properties or landfill structures,
- passive venting of gas through the landfill cover system, and/or
- extraction of landfill gas for the purpose of emissions control or energy recovery.

Prevention of gas migration is achieved by providing zones of high permeability within the landfill into which the gas will flow preferentially. This commonly is done by installing a permeable gas ventilation layer and collection system in capped areas of the landfill (see Subsection 8.7). The ventilation layer exhausts into vertical gas vents (Figure 8-13), which penetrate the final cover system to release the gas into the atmosphere. Typical spacing for surface vents is one per 4,000 m^2, assuming good movement of gas and high permeability layers, or one per 1,000 m^2 if gas movement to the collection points is slow.

Inexpensive gas venting systems in use in some economically developing countries include the use of columns of rocks as the porous media, constrained to a columnar shape by using stiff wire mesh or 200-liter drums with the ends cut out. The wire mesh or drum columns are extended vertically as the height of the fill rises.

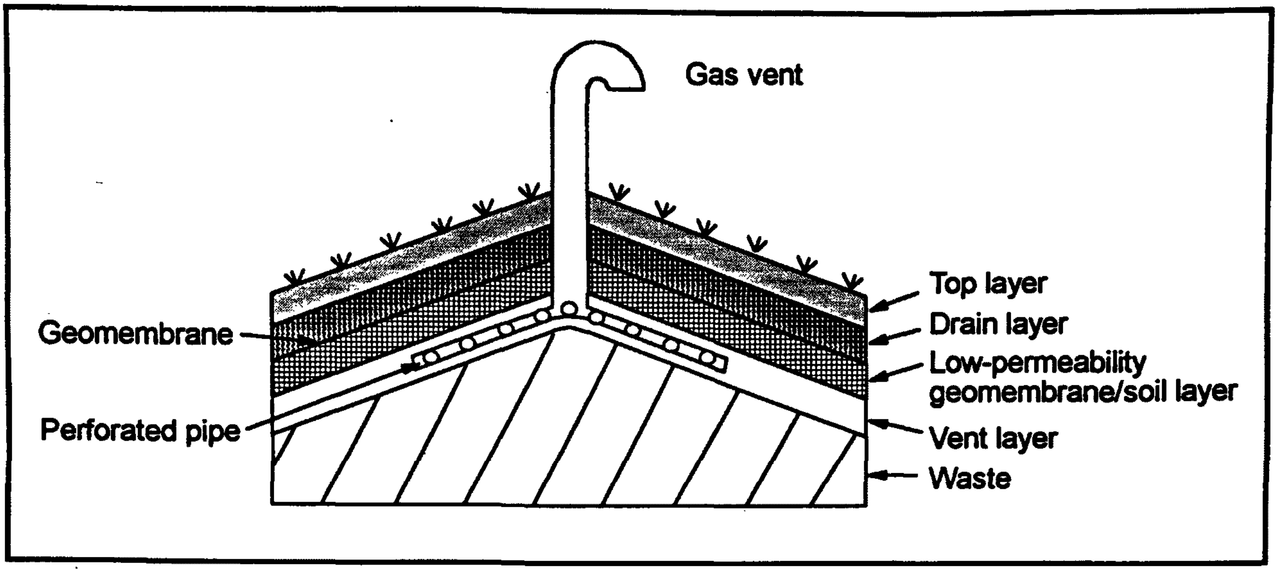


Figure 8-13. Ventilation Layer and Vertical Gas Vent

Occasionally, passive control measures may not be sufficient to stop all lateral migration of gas. In such cases, additional perimeter controls may be installed; for example, permeable layers under the cover or within the fill to facilitate lateral movement and venting of gas or high permeability gravel-filled trenches with an outer low permeability barrier wall located just outside the waste boundary and extending from ground surface to below the level of the landfill base. In extreme cases, active ventilation systems may be necessary.

Active gas extraction systems for the purposes of emissions control or energy recovery are likely to be feasible only at large urban landfills. The topic of gas extraction and utilization is considered at length in Chapter 14.

8.14 Provisions for Materials Recovery

Recovery (i.e., salvaging) of materials from mixed solid wastes delivered to land disposal facilities is practiced and generally accepted at many land disposal sites in economically developing countries. The salvaging operations can involve a high or low number of scavengers, depending on local conditions. Regardless of the number, scavengers, if present at all, represent an aspect of the waste disposal process that must be managed and controlled if they are to be allowed to ply their trade at the disposal site. The importance of scavengers with respect to the design and operation of disposal sites is sufficient to warrant separate treatment of the subject in Chapter 15.

8.15 Land Disposal of Hazardous Waste (Hazardous Waste Landfill)

8.15.1 General

A variety of hazardous wastes also are generated in economically developing countries, regardless of degree of development, and require disposal in a safe and environmentally acceptable manner. In many economically developing countries and in some industrialized countries, legal definitions, standards, safeguards, practices, or enforcement procedures pertaining to the protection of the public health and of the environment are inadequate. One result of this circumstance is that solid and hazardous wastes often are mixed and delivered in combined form to land disposal sites.

However, in those cases where the collection of hazardous wastes is separate from that of municipal solid wastes, the disposal of the hazardous wastes in dedicated containment facilities (i.e., hazardous waste landfills) offers an added measure of protection to human health and safety and to the environment in comparison to their disposal in a facility with a lower degree of management and containment, e.g., a solid waste landfill.

Since the characteristics of hazardous wastes which make them dangerous are universal, the measures required for the disposal of hazardous wastes in economically developing countries should not differ materially from those imposed in industrialized countries. While the main focus of the guidance document is municipal solid waste, the fact that, in some locations, hazardous wastes can comprise a substantial portion of some mixed solid wastes streams is a strong reason to dedicate a portion of the document to acceptable methods of their disposal on land.

8.15.2 Definition and Basic Criteria

A hazardous waste landfill is a complex, engineered system specially designed to contain hazardous wastes such that they cannot escape into the environment. Therefore, this type of landfill must meet the following important criteria:

1. Waste disposed in the landfill must be completely contained by a naturally occurring low-permeability soil layer (e.g., clay) or an installed liner of impervious material.

2. The distance between the bottom of the liner and the groundwater shall be sufficient to prevent contact between the two under all conditions.

3. Leachate and all other liquids must not be allowed to accumulate inside or outside of the containment.

4. The containment system must include a system to detect leaks in the containment.

5. Groundwater must be monitored in such a way that any leakage from the landfill can be detected.

6. The landfill is located such that it is isolated from surface and subsurface water supplies; will be free from flooding, earthquake, or other natural disturbances; and its site will not be needed for other uses after the facility is closed.

8.15.3 Hazardous Waste Landfill Design

Any landfill that will contain significant concentrations of hazardous wastes and that will represent a threat to the quality of surface water or groundwater should be constructed with a composite or double-liner system (see Subsection 8.6). As with all landfills, the design will depend in large part on the hydrogeological characteristics of the site. In an ideal setting, there will be adequate distance to the water table, and the underlying soils will have very low permeability. If the natural soils have a hydraulic conductivity of 10^{-7} cm/sec or less after compaction, they may serve as the lower component of a composite liner. If conditions are not ideal but do meet minimum siting criteria, a composite- or double-liner system can be installed following suitable preparation of the site.

A leachate collection system must be installed directly above the liner. Provisions must be made for withdrawing the leachate as it accumulates, and for properly treating or disposing of this liquid.

The design of the hazardous waste landfill should provide for the segregation of incompatible constituents of the hazardous wastes, including separation of solid wastes from liquid wastes if necessary. Otherwise, mixing of incompatible wastes could result in adverse chemical reactions, which may result in explosions or other dangerous effects (e.g., the mixing of a highly caustic waste with a strongly acidic waste). Separation of incompatible wastes is accomplished by subdividing the hazardous waste landfill facility with lined dikes, or berms. The leachate collection system design should also provide for separation of chemically incompatible forms of leachate.

As a general rule, the hazardous waste landfill should accept only wastes that are in solid form, i.e., waste from which there is no drainage of free liquid when the waste is placed on a filter cloth. Appropriate bulking agents may be added to liquid hazardous waste so that they conform to the above condition of moisture content and, therefore, the mixture may be handled as a solid. The placement of liquid wastes within the landfill should be avoided if the liquid waste will cause an adverse reaction or create problems with respect to leachate generation, collection, containment, or treatment.

Groundwater monitoring wells are another important aspect of the hazardous waste landfill design. Wells should be placed both upgradient and downgradient of the facility, beyond the limits of the liner. If the facility has a double liner, provisions should also allow for the detection of leaks between the two liners. The horizontal location of wells and the vertical intervals over which they are screened should be carefully considered. The design of the groundwater monitoring system should be performed by a qualified and experienced hydrogeolgist or engineer.

The design, operation, and monitoring of a hazardous waste landfill is a highly sophisticated undertaking and requires the participation of skilled professionals. The various elements of a hazardous waste fill are shown diagrammatically in Figures 8-14 and 8-15.

8.15.4 Closure of the Hazardous Waste Landfill

Obviously, the operation of the landfill is terminated when its capacity has been exhausted. The closure operation must be designed such that total and complete decontamination of the facility is ensured and such that the closed facility does not pose a threat to public safety and the environment. These objectives are met by installing a high-quality final cover system and providing for leachate management, gas management, site maintenance, and monitoring in the post-closure period. The design of final cover systems is described in Subsection 8.7. General requirements for landfill closure and post-closure are discussed below (in Subsection 8.17), as well as in Chapter 17.

Post-closure use of a hazardous waste landfill should not be considered viable. The closed landfill should not be excavated or disturbed in any way, since most buried hazardous wastes continue to be dangerous long after their initial burial.

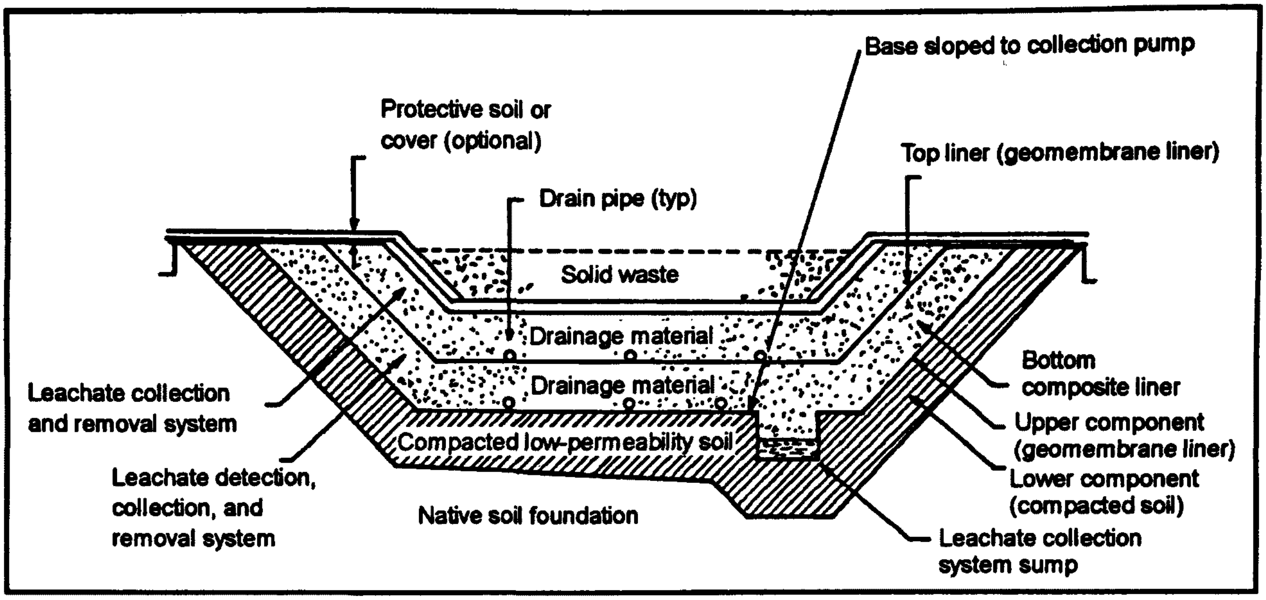


Figure 8-14. Cross-Section of a Hazardous Waste Landfill System

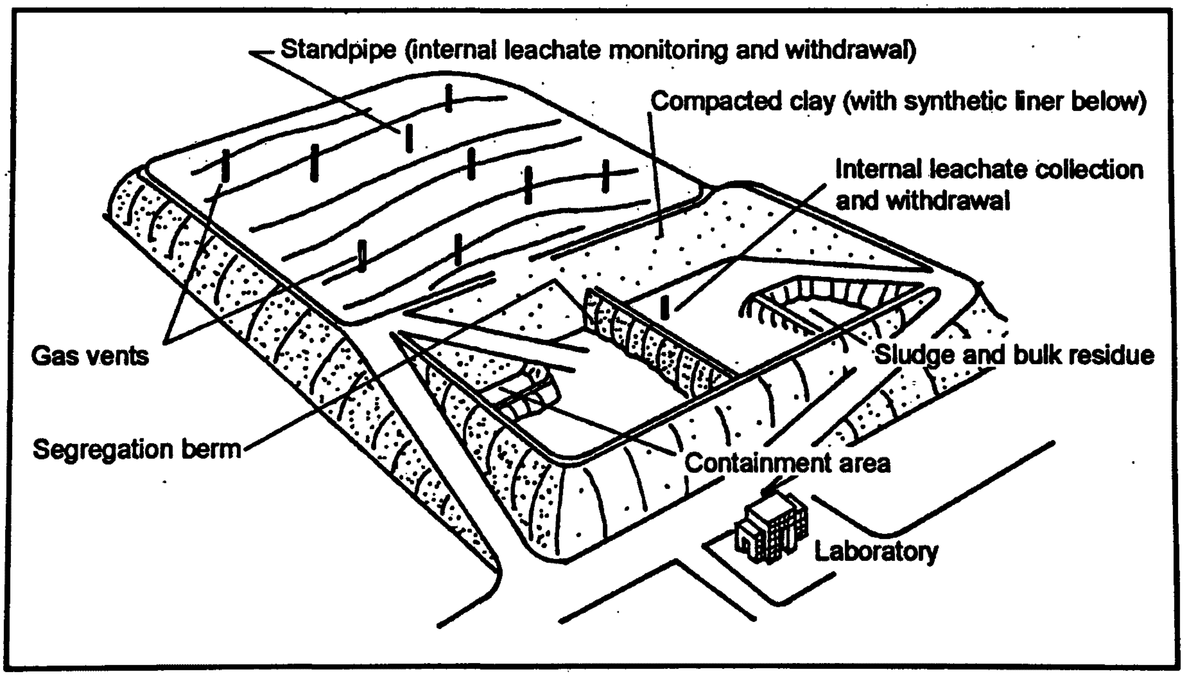


Figure 8-15. Illustration of a Hazardous Waste Landfill Facility

8.16 Combined Disposal of Different Types of Wastes

Combined disposal refers to the practice of mixing one type of waste with another and subsequently disposing of the mixture. Although the combined disposal described in this section applies to most types of non-industrial sludges, the discussion is directed primarily to sludges associated with the storage, treatment, and disposal of human body wastes (primarily, the fecal wastes). Examples of the latter sludges are: those produced by a conventional wastewater (sewage) treatment facility, septic tank pumpings, sludge from the storage pits of unsewered public toilets, and nightsoil in general.

Despite the many hazards to the public health and nuisances attributed to the practice, in several economically developing countries, untreated nightsoil frequently is disposed with municipal solid wastes. These hazards and nuisances are amplified by the prevalence of the open dump method of disposal. Although perhaps not as pronounced, the same hazards attend the open dumping of municipal solid waste and primary (i.e., raw) sewage sludge from a sewage treatment facility. The hazards can be substantially reduced by resorting to landfilling.

In an operation involving combined disposal by landfilling, an effective approach is to deposit the sludge on top of the refuse at the working face of the landfill. The sludge and refuse are thoroughly mixed. The mixture is then spread, compacted, and covered in the manner usual to the landfilling of solid waste.

In order for this approach to work effectively, the applied sludge must behave more like a liquid than a solid. Ideally, the solids content of the sludge should be a minimum of 20 to 30%, wet-weight basis. Liquid in the sludge is absorbed by the solid waste. In the United States, municipal solid waste has a considerable moisture absorption capacity, as much as 60 to 120 kg of moisture per 100 kg of solid waste (wet weight), due to the large concentration of paper. With such waste, the weight of water in the sludge should not exceed about 50% of the weight of the solid waste to which it is applied. Because the moisture and putrescible contents of solid waste generated in economically developing countries tend to be much higher than those characteristic of solid wastes in industrialized countries, the absorption capacity of a developing country's refuse would be correspondingly lower. Hence, the maximum weight of the water in the applied sludge should be considerably less than 50% of the weight of the solid waste.

In those situations where the sludge cannot be or is not dewatered to about 20 to 30% (for example, primary sludges with a moisture content of 2 to 4%), they can be spray-applied from a tank truck to a layer of solid waste at the working face, wherein the solid waste serves as a bulking agent. For example, the bulking ratio for a sludge with a solids content of 3% should be at least 7 Mg of solid waste to 1 Mg of sludge. If the solids content of the sludge were 20% or more, the bulking ratio of solid waste to sludge could be as low as 4 to 1. In practice, application of sludges having a solids content approaching 3% should be avoided because of the probability of operational problems and adverse health and environmental consequences. If combined disposal is practiced and scavengers normally would be present, they should be restrained from coming into contact with the sludges or mixed wastes in order to protect their health and safety.

A different concept of combined disposal of wastes involves the use of a sludge/soil mixture as an interim or final cover material over completed areas of the solid waste landfill. The approach has the following potential advantages:

1. The quantity of sludge being disposed at the working face of the landfill is reduced or eliminated by the alternative use of the sludge.

2. Due to the nitrogen and phosphorus contents of the sludge, the mixture promotes the growth of vegetation in the areas where the sludge is applied, thereby reducing fertilizer requirements.

3. Problems associated with poor sanitary conditions at the disposal area, and with erosion, may be mitigated through the alternative use of the sludge in a sludge/soil mixture.

A major disadvantage of the practice of combined disposal, as described above, is its general limitation to well-stabilized (i.e., digested) sludge. The limitation arises from the fact that the land-applied sludge is not completely buried. A potential nuisance and human health hazard exists when unstabilized sludge is left exposed to humans, vectors, and the elements.

8.17 Landfill Closure

The closing of a landfill requires the design and construction of the following elements:

- final cover system (cap),
- leachate management system, and
- gas management system.

8.17.1 Final Cover System

The performance criteria and design guidelines for final cover systems have previously been described in Subsection 8.7. The final cover system design must be integrated with the overall site drainage and erosion control plan to ensure effective long-term post-closure performance of these systems. The final grading plan, showing the finished contours of the landfill, should include benches or diversion channels at regular intervals to minimize erosion of the cover system and to control runoff from the slopes of the landfill. The recommended maximum spacing of diversion channels is one per 8 m of elevation gain.

8.17.2 *Leachate Management System*

The design of leachate management facilities would normally be completed as part of the initial design effort. However, prior to closure, the system should be re-examined to ascertain that it is fully functional and appropriate to the service conditions under which it must perform in the post-closure period. Design modifications to leachate pumping or storage facilities, for example, may be indicated by such an analysis.

8.17.3 *Gas Management System*

If landfill gas management is to occur by means of passive venting, the venting system should be designed in conjunction with the final cover system design (see Subsections 8.7 and 8.13). If the gas management system is an active (dynamic) one, it was probably constructed and operated during the active life of the landfill, and system modifications are likely to be needed at the time of closure. These modifications may include additional extraction wells and gas collection piping in previously unserved portions of the landfill. Any penetrations of the landfill cap by gas vents or wells should be carefully detailed in the design to ensure an effective, permanent seal. The method of sealing penetrations should allow for relative movement of the components resulting from settlement of the landfill. The seal must be effective against water infiltration and, in the case of active gas collection systems, against air intrusion into the landfill.

Other considerations for closure design include the dismantling of temporary structures and the restoration of peripheral areas that supported facility operations but were not part of the actual landfill area. Such areas should, at a minimum, be properly graded, covered with topsoil, and revegetated -- unless they have been designated for some other productive reuse of the land.

8.18 Post-Closure Use of Site

If any portion of the landfill site is envisioned to be used after closure, the closure design should take into account the specific intended reuse. For example, the provision of recreational playing fields would affect the final contouring of the site, as well as the design of the gas management and site drainage systems. The nature of closed landfills is such that they present many obstacles and limitations to site reuse. The issues surrounding redevelopment of landfill sites are considered in Chapter 17.

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Chapter 9
Equipment Selection

9.1 Fundamental Considerations

The construction and operation of a landfill requires proper equipment. Unless much of the required equipment can be borrowed from other activities or uses, the acquisition of equipment accounts for a large fraction of the total capital investment of a landfill. Furthermore, equipment operation and maintenance usually accounts for a large portion of the annual operating budget. Improperly sized equipment and equipment in poor condition usually result in capital and operating costs in excess of the optimum. Consequently, in order for a landfill operation to be optimum, the selection and specification of equipment must be in accordance with the type and method of landfilling chosen for implementation. The requirements of the equipment must take into account the handling, compaction, and covering of the solid waste, as well as the construction of cells and the completion of general earth work.

The discussion in this chapter considers that the availability of equipment may be limited in many cases and that equipment may have to be borrowed (e.g., from another municipal department) to conduct a landfilling operation. Thus, scheduling and multiple-use of equipment are of general relevance and importance.

The following fundamental items are discussed below: 1) spare equipment, 2) multi-purpose equipment, and 3) maintenance and repair of equipment.

9.1.1 Spare Equipment

A landfill operation should have spare equipment in order to optimize the cost of landfill operations and to provide continuous operations. The recommended redundancy factor for large rolling equipment for a specified task is 0.3. The redundancy factor itself is applied to the number of hours of operation. A maximum potential of 20 hours of continuous duty per day for heavy equipment (4 hours are reserved for fueling, maintenance, and repair) is a reasonable availability for landfill equipment.

To calculate the number of spare pieces of equipment, the redundancy factor is added to 1.0, the sum is multiplied by the total number of working hours (not exceeding 20 hours per piece of equipment) specified by the design and operational plan of the landfill, and the resulting product is divided by 20 hours per machine and rounded up to the nearest whole piece of equipment. For instance, if the design specifies two machines operating a total of 36 hours per day (i.e., 18 hours each), using a redundancy factor of 0.3, the total hour requirement is 46.8 hours per day. As a consequence of the daily limitation of 20 hours of operation for each piece of equipment, three machines are required when the result of the calculation (i.e., 2.34) is rounded up.

Although the purchase of spare equipment will increase the capital budget, the extra equipment will assure continuity of service and normally will extend the useful life of the machines. The level (i.e., the magnitude) of backup capacity chosen for a particular work function affects the type and frequency of the maintenance and repair operations. For example, a system with an adequate backup factor can be expected to keep its equipment in better repair than a system with an inadequate factor, all other conditions being the same. The expectation results from the fact that adequate redundancy of equipment results in the ability of the user to service equipment needing repair and maintenance at the time that the service is needed, thus avoiding the risk and eventuality of major repairs if simple repairs and preventive maintenance are delayed because substitute equipment is not readily available.

9.1.2 Multi-Purpose Equipment

The use of multi-purpose equipment, i.e., equipment that is capable of performing more than one function, is one means of meeting the redundancy offered by the alternative of spare equipment. The use of multi-purpose equipment also represents a means of optimizing the utilization of equipment and capital equipment expenditures.

Two examples of multi-purpose equipment are: 1) a landfill compactor which can be utilized for compaction, for covering of solid waste, and to build roads on the site; and 2) a tracked loader equipped with a multi-purpose bucket, which can be used for moving and spreading cover soil and to push and compact solid waste. The strategy of multiple use demands that the time requirement for each particular activity and that the associated pieces of equipment be carefully planned during the design of the landfill operation and monitored after implementation so that the useful hours for each piece of equipment are optimized for each specific activity.

The incorporation, or potential of incorporation, of multi-purpose equipment into a landfill operation requires that a schedule and description of the major work activities (e.g., spreading and compaction of wastes, covering of compacted wastes with soil) be carefully prepared early in the planning stages of the landfill. Subsequently, the major activities and the schedule of the landfill operation are compared to the function and availability of equipment from other equipment-related activities (e.g., road construction). The uses of the multi-purpose equipment subsequently are identified and incorporated into the landfill operational plan. The portions of the landfill operational activities that cannot be satisfied by multi-purpose equipment must be fulfilled by purchased or loaned equipment.

9.1.3 Maintenance and Repair

The maintenance and repair of equipment requires detailed planning in order to satisfy one of the primary missions of the landfill: continuous and satisfactory waste disposal service. It is recommended that preventive maintenance and most repairs be performed in the field in order to avoid the inconvenience of transporting the equipment to a remote workshop. An accommodation for the performance of major maintenance and repair in the form of a protected enclosure is a worthy design goal and instills a sense of the importance of these functions to the successful operation of the landfill. Frequent washing of all rolling stock assigned to the handling of solid waste is an aid in maintaining the equipment in good repair. Washing will help increase the useful life of that equipment and decrease potential frictional wear resulting from the buildup of dust and particles in the different mechanical components of the equipment (e.g., bearings). Regular and frequent inspection and cleaning (including washing, if necessary) of the machines' radiators is another task that should be scheduled and enforced for all equipment that comes into direct contact with solid waste. This operation must be performed at least daily. The other maintenance operations, described in the operating and maintenance manuals for the equipment, catalogs, or both that are supplied by the manufacturers must be programmed into the plan of operations in advance and be performed according to the manufacturers' specifications.

The operators of the landfill should be prepared to perform light mechanical repairs (i.e., those that require no more than two days to complete). To accomplish these types of repairs, it is very important that all of the necessary tools and an adequate supply of spare parts be readily available at the site. The need for an adequate supply of spare parts is reduced if a reliable supplier is able to provide the required parts within a reasonable period of time.

9.2 Selection Factors

Three important factors must be considered when selecting equipment:

1. amount of waste to be landfilled and the type of materials to be handled,

2. economic feasibility, and

3. availability of adequate maintenance and repair facilities and skilled personnel.

The issues of economic feasibility and of adequacy of maintenance and repair are especially important in developing countries. However, failure to take into account any of the three factors makes the operation of a landfill a virtual impossibility.

The importance of the ability of the equipment to accommodate the steady flow of waste into the disposal site is obvious. Maintenance and repair are important as well, since landfill operations place great reliance on large pieces of equipment operating under severe conditions of duty.

With the exception of the smallest of operations, a landfill involves the movement of large quantities of materials (soil and solid waste). The handling of materials begins with site preparation, continues through operation of the fill, and ends with the closing of the fill. Because of the limitations of human performance and productivity and other practical considerations, the rates of manually moving wastes and soils and of exercising environmental control are small compared to the typical quantities of wastes entering the majority of disposal sites. Thus, most land disposal operations must rely on mechanization. Under certain conditions, it is possible to rely on manual labor and on suitably modified farming equipment (e.g., tractors).

Under the rigorous conditions characteristic of landfill operations, even the most rugged equipment breaks down frequently unless it is conscientiously maintained. The need for conscientious maintenance takes on added significance in economically developing countries because replacement parts often are very difficult to obtain, especially in a timely manner. The problem of the performance of maintenance is increased further due to scarcity of personnel skilled in the maintenance of heavy equipment.

9.3 Key Usage Categories for Equipment

The major areas of usage of landfill equipment can be differentiated into the following three categories:

1. those activities related to soil (excavation, handling, compaction);

2. those activities related to wastes (handling, compaction); and

3. other (i.e., supporting) functions.

Depending on the size of the disposal operation (i.e., quantity of wastes requiring disposal) and other operational conditions, one piece of equipment may have the ability to perform several activities among the three major categories of usage, i.e., serve as multi-purpose equipment. Versatility is an essential consideration in equipment selection for situations, or locations, in which equipment is likely to be used for more than a single use and in which the availability of some or all of the necessary pieces of equipment is limited.

9.3.1 Soil-Related Usage

The excavation, handling, and compaction of soils for liner and cover material are key considerations when selecting and specifying landfill equipment. Procedures and equipment for accomplishing the soil-related function tasks differ only slightly from those used in other earth-moving operations. Consequently, the degree of mechanization and sophistication of equipment suitable for landfilling in a given location would not differ markedly from that which is characteristic of earth-moving operations in nearby areas. This criterion extends as well to modifications and variations in equipment, procedures, or both that may be needed to meet specific requirements due to local topographic and soil conditions. For example, wheeled equipment usually is satisfactory for excavating soils in which sand, gravel, clay loams, and silt loams are the predominant constituents. On the other hand, tracked equipment would be indicated for the less workable soils. Other variations and modifications may also be required to accommodate seasonal changes in soil properties.

If soil is to be moved over distances shorter than about 100 m, loaders, dozers, etc. used to move waste in the fill can serve the purpose. Other types of equipment should be used for hauling soil distances greater than 100 m.

Spreading and compaction of soil are discussed elsewhere in the document. Types of equipment are discussed in Section 9.4.

9.3.2 Solid Waste-Related Usage

Equipment is used at a landfill to distribute, spread, and compact solid waste. For small-scale landfill operations, and those locations with limited economic resources, equipment used for soil-related functions can substitute for those related to solid waste handling. The spreading and compaction of wastes discharged from the collection vehicles can be optimized by confining the unloading of collection vehicles to the immediate vicinity of the working face. Thus, spreading and compaction of the wastes are effectively integrated and the overall efficiency and productivity of the operations are high (minimizing the size of the working face also is beneficial in terms of controlling environmental impacts). Additionally, the dual activity of spreading and compacting the wastes conceivably could be conducted by the same bulldozer that might be used to move and spread soil.

The compaction of wastes demands careful attention because of its many short- and long-term effects on the operation of the landfill, and rate and extent of settling. One of the more important effects is the influence of compaction on the in-place density of the wastes and therefore on the quantities of waste that can be disposed in a particular volume of air space.

Heavy equipment specifically designed for compaction of mixed solid waste is more effective and efficient for this type of application than is lightweight equipment designed primarily for earth-moving, all other conditions being equal. However, since in-place density of waste is also a function of number of passes of the equipment over the waste, increasing the number of passes can be used to compensate for lesser machine weights, up to a certain point. Spreading the waste in thin layers, in addition to increasing the number of times the machine passes over the layers, also compensates for lesser machine weights. The number of passes required to attain sufficient compaction also depends upon the moisture content, composition, and other properties of the waste. Additional discussion of the relation between equipment specifications and compaction performance is presented in Chapter 10.

Landfill equipment must be rugged because operating conditions in a landfill environment are harsh. Radiators tend to become clogged and damaged, and the body and operating parts of the equipment can be damaged by protruding or dislodged wastes. Tires, even of heavy-duty construction, frequently can be punctured or cut. These circumstances demonstrate the necessity of maintaining a parts inventory and an adequate repair and maintenance facility convenient to the fill.

9.3.3 Supporting Functions

With respect to the initial and subsequent construction phases of a landfill, equipment may be needed for the installation of roadways and of environmental control measures such as geomembrane liners and covers, monitoring wells, leachate collection facilities, and gas vents.

Support functions during the operational phase include extension and maintenance of roads to the working face of the fill, dust control, and fire protection. Unless the collection and transport vehicles delivering waste to the site are equipped with self-unloading features, support equipment might be needed to assist in the unloading of waste. This situation exists especially in those locations with primitive and poorly maintained collection vehicles. Generally, some of the support functions (such as road extension and maintenance) during the operational phase can be supplied by the machine used for spreading and compaction of soil and solid wastes.

9.4 Types of Equipment

The selection of equipment should be based upon the primary use, and the ability of the equipment to accommodate successfully the conditions peculiar to the site. A secondary consideration is the ability of equipment to meet multiple uses. The considerations related to the primary use include those imposed by the soil; topographical and climatic characteristics of the site; waste characteristics, quantity, and delivery rates; and budgetary constraints. Possible off-site use is another consideration.

The main uses and characteristics of the different types of equipment used at landfills are discussed below.

9.4.1 Track-Type (Tracked) Tractors with Push-Blades (Bulldozers)

9.4.1.1 Use

Bulldozers are used to distribute and compact solid waste, as well as to perform site preparation, distribute daily and final cover, and conduct general earth work. A photograph showing a bulldozer is presented in Figure 9-1.

9.4.1.2 Characteristics

Bulldozers are equipped with metal tracks having variable standard widths, such as 460, 510, 560, and 610 mm. The tracks must have cleats that are sufficiently high to size reduce (i.e., crush and tear) the solid waste and to prevent slippage and sliding of the equipment down the working face or other slopes. The pressure exerted on the solid waste is achieved by distributing the weight of the machine over the contact surface. The following table presents some typical values for these machines.

Power (kW)	Weight (kg)	Area of Contact with Refuse (m^2)	Pressure (kg/cm^2)
100	11,750	2.16	0.54
150	16,100	2.76	0.58
220	24,800	3.19	0.78

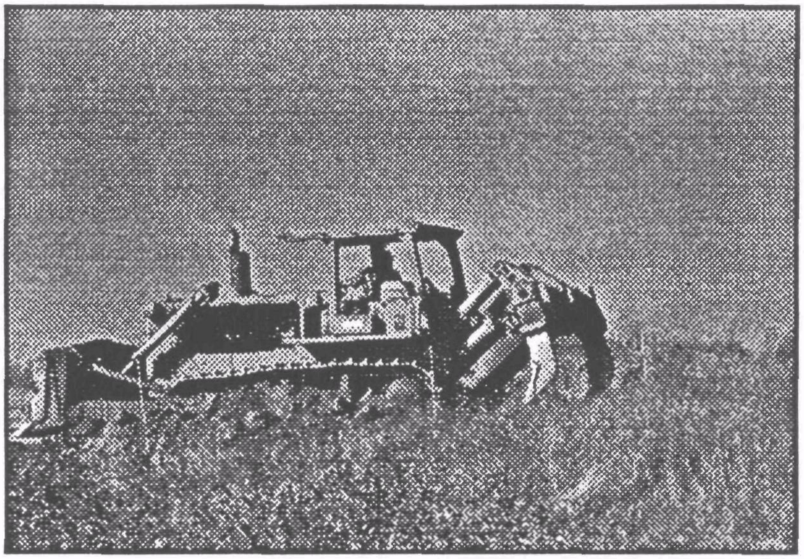

Figure 9-1. Bulldozer

The degree of compaction of the solid waste depends on the pressure exerted. As mentioned before, the thinner the layer of refuse, the more effective the pressure applied to the bottom of the layer. Tracked machines are not very efficient at compacting solid wastes due to their low ground pressure.

In order to obtain maximum efficiency from a track-type machine, it should be equipped with an adequate blade to push the material. The density of solid waste discharged from a collection vehicle is about one-third that of soil; therefore, the physical size of the blade can be increased without overloading of the equipment. The capacity of a blade can be increased by increasing its height. A steel screen can be used to increase the height of the blade without interfering with the operator's visibility, as would be the case of a solid plate used as an extension. The dimensions of the blades vary with each model. For example, a typical 100 kW machine would have a blade with the following dimensions:

- width (straight): 3.2 m,
- height (without screen): 1.1 m, and
- height (with screen): 1.8 m.

The push-blade is controlled through a hydraulic mechanism. The estimated productivity for a typical 100 kW model, on flat surfaces, is on the order of 50 Mg of solid waste per productive workhour. On sloped surfaces, the production will be less: in the case of a slope of 20°, production will be reduced to about 40 Mg/hr for the 100 kW model mentioned above.

9.4.2 Steel-Wheeled (Landfill) Compactors

9.4.2.1 Use

Compactors are used for spreading and compacting the incoming solid waste. A photograph of a steel-wheeled compactor is presented in Figure 9-2.

Figure 9-2. Steel-Wheeled Landfill Compactor

9.4.2.2 Characteristics

Compactors are typically equipped with either a standard or turbo diesel engine. The metal wheels usually have alternated, inverted, V-shaped teeth that allow them to concentrate the weight of the machine on a smaller contact surface than that characteristic of a track-type machine and, consequently, to exert a greater pressure on the solid waste. The following table indicates the average pressure for two types of compactors based on the area of contact.

Power (kW)	Weight (kg)	Average Pressure (kg/cm^2)
110	16,000	75
130	26,000	120

Operating under similar conditions, compactors are in general more versatile and faster than bulldozers in the spreading and compacting of solid waste. A typical 110 kW model will have a productivity of approximately 75 Mg/hr on flat surfaces. The productivity decreases to about 60 Mg/hr if the working slope is 20°.

Steel-wheeled compactors are equipped with a hydraulically controlled blade. The blade has an additional metal screen to increase its capacity. The common dimensions of the blade are as follows:

- width: 3.0 m, and
- height (with screen): 1.9 m.

9.4.3 Wheel Loaders

9.4.3.1 Use

Wheel loaders are used to excavate soft soil (i.e., soil offering little resistance), load excavated material onto trucks, and transport material over distances not greater than 50 to 60 m (for optimum efficiency). A photograph of a wheel loader is presented in Figure 9-3.

9.4.3.2 Characteristics

Wheel loaders generally are equipped with a diesel engine and four-wheel drive. The units can be equipped with solid, pneumatic, or foam-filled tires. The type of tire selected depends on the application and on the working conditions. Solid and foam-filled tires are favored in those applications where the tires are exposed to sharp objects that can cut and puncture the tread or sidewall. The front axis is fixed and the rear axis can oscillate. Models vary in power, ranging from 50 to 370 kW. The capacity of the bucket varies from 0.8 to 6 m^3. The most

Figure 9-3. Wheel Loader

commonly used models are those falling in the range of 75 to 110 kW. Some characteristics of wheel loaders are presented in the following table:

Power (kW)	Weight (kg)	Bucket Capacity (m^3)
75	9,280	1.34 - 1.72
100	11,550	1.72 - 2.68

If the soil is soft, a 100 kW wheel loader with a bucket capacity of 1.9 m^3 would be able to excavate and load a dump truck at a rate of about 160 m^3/hr. If the ground is firmer (i.e., offers more resistance to penetration by the bucket), the productivity would decrease. To maintain the same productivity, a more suitable piece of equipment would be needed to perform the excavation work.

Wheel loaders also possess the capability to perform efficient earth work with clay-like soil, such as the covering of waste, and to prepare sites for landfilling.

9.4.4 Track-Type (Tracked) Loaders

9.4.4.1 Use

These machines can perform similar functions as the wheel loaders. Track-type loaders are also able to excavate well-compacted and tough soil. Their optimum material transport distance usually does not exceed 30 m. Their low bearing pressure is beneficial and in fact necessary in a number of landfill operations, e.g., carrying soil on a muddy or soft surface.

In emergency situations and in cases where the daily deliveries of quantities are small, track-type loaders can be used to handle (i.e., to spread and compact) solid waste. They can also be utilized to contour and level the cover material. In some cases, the track-type loader may be more efficient and flexible than a track-type machine equipped with a push-blade.

9.4.4.2 Characteristics

Tracked loaders are equipped with 50 to 200 kW diesel engines. The following table describes some parameters and typical values for this type of equipment.

Power (kW)	Weight (kg)	Area of Contact with Refuse (m^2)	Bucket Capacity (m^3)
70	12,340	1.54	1.34
100	13,700	1.79	1.34 to 1.74
140	21,300	2.48	1.90 to 2.48

The bucket in track-type loaders is operated through a hydraulic mechanism. In many cases, better efficiency and flexibility in operational activities can be achieved when this equipment is equipped with a multi-purpose bucket. This type of bucket performs four different operations, according to the position in which the bucket is operated.

The bucket has a stationary section and a moving section. Movement can be controlled by the operator with the same lever control. With a multi-purpose bucket, a track-type loader can serve as the following types of equipment:

1. Loader -- Opening the grapple will allow the material within the bucket to be totally discharged.

2. Dozer -- Lifting the moving section will allow pushing and leveling of the material.

3. Scraper -- In soft and/or clay-like soils the cutting action can be controlled with the grapple opening.

4. Clamp Bucket -- The loader can be used to lift materials like trunks and branches of trees. This can be accomplished by holding the material between the grapple and the edge of the bottom part of the bucket.

The versatility of a track-type loader is beneficial in applications such as landfills, especially when the availability of equipment in general is limited or when financial resources are limited.

9.4.5 Track-Type (Tracked) Excavators

9.4.5.1 Use

Two types of excavators are relevant to heavy landfill work: 1) the common track-type excavator in which the bucket and excavating motion are toward the cab, and 2) the front-shovel model in which the excavating motion is away from the cab. Common excavators are used to excavate soil and load hauling equipment, and to apply the daily or primary cover to solid waste (e.g., in the trench method). This equipment can also be used for certain tasks in earth work operations. As with all tracked equipment, the load (vehicle and working load) is distributed over a large track area, thus minimizing the bearing pressure on the soil. This feature is important in some landfill operations, e.g., in muddy or soft soil conditions. This equipment has the capability of digging deep excavations at high rates of productivity (the smaller tractor-type excavators, e.g., backhoes, have a more limited depth of reach and a lower productivity than track-type excavators).

9.4.5.2 Characteristics

The excavator is equipped with a diesel engine and a hydraulic system to control the movement of the loading arms and that of the bucket. Typical engine sizes are in the range of 100 to 500 kW. As mentioned above, the bucket of the common excavator faces the cab and the excavating movement of the arm is toward the operator.

The excavation cycle is composed of four phases:

1. loading of the bucket,

2. rotation when loaded,

3. opening of the bucket and discharge of material, and

4. rotation when unloaded.

The length of time of the excavation cycle depends on the size of the equipment and on the site conditions. When the excavation is difficult or the trench is deep, the time to excavate will be slower than for a set of less difficult conditions. The manufacturers' literature on the market typically describes the cycle time, or its method of calculation, according to the equipment model and particular types of site conditions (e.g., type of soil, excavation depth). The excavation depth (measured from the ground level) depends on the reach of the loading arms. The following table provides some typical specifications for excavators:

Power (kW)	Weight (kg)	Length of Loading Arm (m)	Bucket Capacity (m^3)	Maximum Depth of Excavation (m)
100	22,680	2.44	0.75	6.4
145	34,020	2.90	1.18	7.3
240	56,200	3.20	1.94	8.5

9.4.6 Front-Shovel Excavators

9.4.6.1 Use

Front-shovel excavators are used to excavate trenches for the placement of solid waste, to load soil and rock into hauling vehicles, and to perform the daily or primary covering of landfill cells (without compaction or leveling of the solid waste). As mentioned previously, front-shovel excavators differ from the more conventionally observed excavator in that the bucket opening faces opposite the cab and the articulated motion of the bucket is outward from the cab. Thus, the front-shovel unit is limited mechanically to digging near the surface and moving piles of material at surface level and does not have the excavation reach of the common excavator. This equipment is unsuited to the digging of deep excavations.

9.4.6.2 Characteristics

Front-shovel excavators are mounted on tracks and equipped with a diesel engine having power ranging from about 300 to 600 kW. The tracks are formed by shoes typically having a width of 600 to 700 mm. These machines are equipped with a boom that is operated mechanically. The length of the boom can vary from 10 to 15 m. The operational turning radius varies, according to the equipment, from 6 to 13 m. Depending on the type of soil and on the size and use of the bucket, this type of excavator can reach to depths up to 4 m. The buckets generally have a capacity of either 0.6 or 0.8 m^3. The weight of a 100 kW front-shovel excavator is about 20,500 kg.

9.4.7 *Motor Grader*

9.4.7.1 Use

Motor graders are used in the construction and maintenance of hauling roads, embankments, and drainage ditches, and the profiling and leveling of cover material. A photograph of a grader is shown in Figure 9-4.

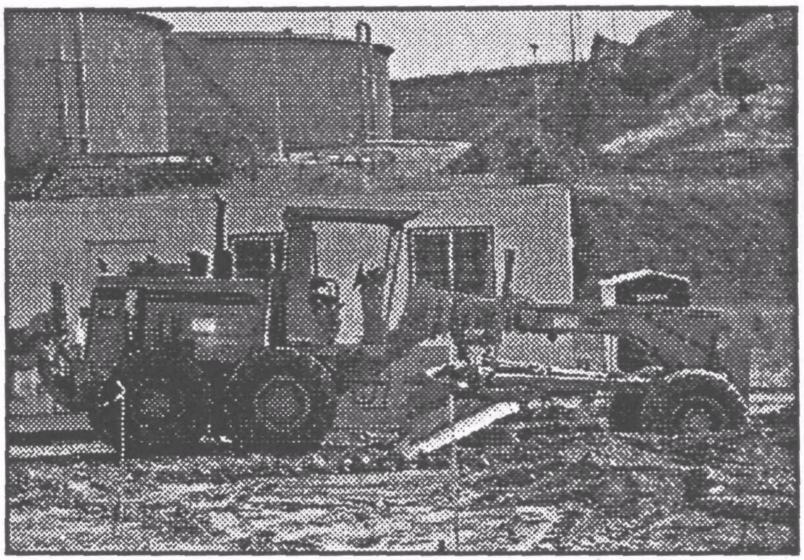

Figure 9-4. Grader

9.4.7.2 Characteristics

Graders are equipped with a diesel engine, rubber wheels, and power steering. Typical weights and power for this type of equipment are presented in the following table:

Power (kW)	Weight (kg)
90	12,000
165	18,280

The standard blade for these machines has the following dimensions:

- length: 4.0 m,
- height: 0.7 m, and

- thickness: 25 mm.

The blade can reach a maximum slope of 90° and is able to adopt different axial positions.

These machines can carry a scraper as additional equipment. The scraper is used to rip the ground or to mix soils. A typical scraper attachment has 11 teeth shaped as hooks, with replaceable ends. The scraping depth varies according to the model, generally in the range of 0.2 to 0.4 m.

9.4.8. Scrapers

9.4.8.1 Use

Scrapers are used to excavate, haul, and distribute large volumes of soil at high rates of productivity on relatively flat or moderately hilly soil surfaces. Because of their high rate of productivity, they are commonly used at large landfills to excavate and distribute soils for cover and for liners. A photograph of a wheeled scraper is presented in Figure 9-5.

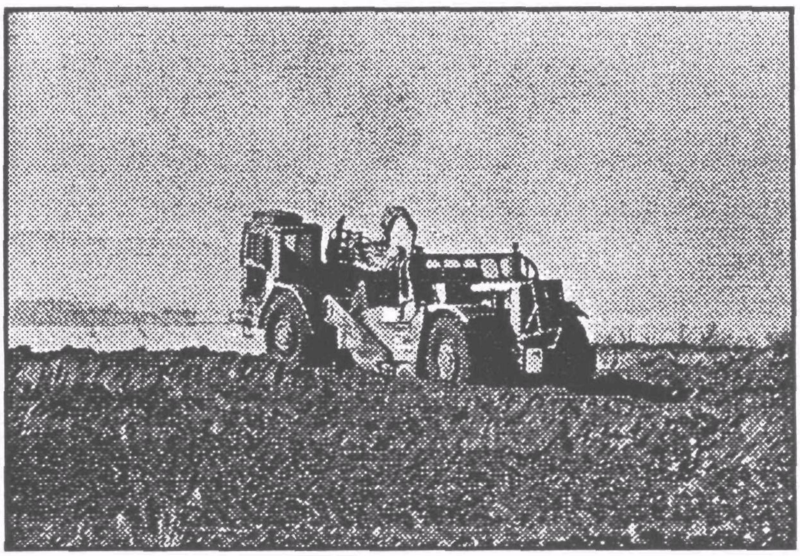

Figure 9-5. Scaper

9.4.8.2 Characteristics

Scrapers can be self-propelled or towed by separate equipment, e.g., by a bulldozer; they are relatively maneuverable. They are equipped with a cutting blade or elevating conveyance system that cuts and directs the excavated soil into a storage unit. The volumetric storage capacities are in the range of 10 to 40 m^3.

The approximate earth-moving capacities for loaders and scrapers are presented in Table 9-1.

Table 9-1. Approximate Earth Moving Capacities for Average Soils (m^3/hr)

Capacity of Units (m^3)	One-Way Haul Distance (m) 0	30	60	90	120	150	180	240	300
Tracked Loader									
1¼	40	30	25	20	15	-			
1½	50	35	30	25	20	15			
2	80	60	45	40	35	30			
Pulled Scrapers									
14					190	170	150	125	100
12					165	145	125	100	75
7					90	80	75	60	55
Self-Propelled Scrapers									
20						400	380	340	300
14						250	240	210	180
11						170	160	140	120

9.4.9 Sheeps Foot Compactors

9.4.9.1 Use

Sheeps foot compactors are used to compact soils and embankments.

9.4.9.2 Characteristics

A sheeps foot compactor can be either self-propelled or pulled by a tractor. Basically, it is composed of two cylindrical drums with "feet" that convey pressure to the soil to be compacted. The drums can be ballasted with water. The average pressure depends on the type of "foot" used. There are several designs. A compactor composed of two cylindrical drums has the following specifications:

- diameter: 1.53 m,
- rolling width (2): 3.4 m,
- number of feet per drum: 120,
- weight of drum with water ballast: 12,600 kg, and
- pressure exerted on the ground: about 27 to 82 kg/cm^2.

Since these machines have a mechanism that allows articulation of the drums, uniform compaction can be achieved even on irregular layers of soil.

9.4.10 Pneumatic Tire Compactors

9.4.10.1 Use

Pneumatic tire compactors are used in the compaction of topsoils and sublayers, especially when loamy material is present. High and uniform densities can be obtained throughout the thickness of the layers.

9.4.10.2 Characteristics

These machines can be either self-propelled or pulled by tractors. The load is transmitted to the ground through the contact surface of the tires, which form the rolling unit. Typically, these compactors have seven tires.

The ballasting of the equipment is accomplished using wet sand (density = 2,000 kg/m^3), which results in working weights in the range of about 13,000 to 35,000 kg. The operation is as follows:

- Initially during the rolling of the soil, low tire pressures are used in order to produce sufficient pressure to somewhat compact the soil without the tires sinking into and rutting the soil. Low tire pressures result in a large contact area of the tires, and therefore low vertical pressure applied to the soil.

- As the rolling and compaction process progresses, the tire pressures are gradually increased, thus reducing the contact area and therefore increasing the pressure applied to the soil.

These machines have a system that controls the pressure of the tires to the proper level.

9.4.11 Self-Propelled Vibratory Drum Compactors

9.4.11.1 Use

Vibratory drum compactors are used to compact soils and cover material formed by normal, granulated, or clay-like soils.

9.4.11.2 Characteristics

This category of machine is specially designed and constructed to effectively produce compaction of the type of soils mentioned above. Vibratory drum compactors have a metal drum on the front. The approximate dimensions of the drum are:

- width: 2.2 m, and
- diameter: 1.5 m.

The compactors have pneumatic tires on the back. The vibration system is operated by a hydrostatic engine directly connected to the vibrator, allowing variations in amplitude and frequency, independent from the speed of the propelling engine. The vibration frequency can be regulated to reach a maximum of up to 2,000 vibrations/min. The weight of the equipment varies according to the model (9,000 to 12,000 kg).

9.4.12 Drainage of Ditches

There are two types of equipment that can be used to perform this task:

1. Centrifugal pumps driven by internal combustion engines -- The power rating of engines for this type of pump is typically in the range of 6 to 10 kW. In this range of power, pumping capacities of 6 to 30 m^3/hr usually can be achieved, depending on the efficiency of the system, the line losses, and the gravitational head.

2. Submersible pumps with electric motors -- These types of pumps are recommended for the handling of leachate. The range of pumping capacities for these types of pumps is typically in the range of about 8 to 15 m^3/hr.

9.4.13 Rubble Shredders

The purpose of these machines is to shred large soil particles in order to obtain adequate size distribution of the cover material. The machines usually have a power rating of about 100 to 300 kW. These shredders usually are driven by an internal combustion engine or an electric motor.

9.5 Inspection and Maintenance

As previously indicated, the costs associated with operation and maintenance of the equipment used in landfills account for a major portion of total operating costs. Frequent inspection and a systematic maintenance program are necessary to keep equipment running productively. Conversely, the neglect of preventive maintenance can lead to severe problems that are very costly to remedy, require inordinate lengths of time to correct, or both. With respect to operation of a landfill, the neglect of proper maintenance and repair can take the form of machinery breakdowns, inadequate compaction, or insufficient application of cover material. Poor compaction and lack of application of cover material can result in adverse impacts to the public health and to environmental pollution.

Consequently, a strong recommendation is made for regular inspection of the equipment used in landfill operations. Some of the equipment may require daily inspection and other equipment may need only weekly inspection. Continuous operation and low frequency of breakdowns (i.e., cumulatively leading to high equipment availability) can be achieved only through the implementation of a preventive maintenance program. The maintenance program should be based on guidelines provided by the equipment manufacturers and supplemented by good preventive maintenance practice.

In connection with the importance to be given to preventive maintenance and proper repair, proper facilities must be provided at or near the landfill for carrying out the various tasks of maintenance and repair. Proper facilities include garages, tools, testing equipment, and a stock of replacement parts. Equipment manufacturers should be required to provide a list of basic replacement parts, and the name and location of a source for spare parts. Ideally, the source should be located within the country.

9.6 Equipment Requirements

The number and types of equipment needed for the landfilling of solid waste are governed by many factors. The factors have been described throughout this section. One of the key factors is the required rate of landfilling of solid waste, i.e., the daily mass flow of wastes received at the facility. As guidance to the reader, some suggested equipment requirements are presented in Table 9-2. When reviewing the table, it should be borne in mind that the availability of proper equipment for landfilling operations can be a substantial problem in some economically developing countries. Thus, in some cases, compromises in equipment requirements and performance may be required in order to conduct a landfilling operation.

Landfill equipment can be owned or leased, depending on local conditions and procurement policies. Regardless of method of procurement, it should be kept in mind that: 1) the useful life of landfill equipment is relatively short, e.g., 5 to 10 years, due to the difficult and strenuous operating conditions; and 2) equipment life is optimized through the implementation of a dedicated preventive maintenance program.

Table 9-2. Suggested Equipment Requirements as a Function of Waste Generated

	Equipment			
Mg/day	Quantity	Type	Weight (kg)	kW
0 to 20	1	TD	<6,800	<60
		TL	<9,000	<50
		RTL	<9,000	<75
		SWC	N/A	N/A
20 to 50	1	TD	6,800 to 9,000	60 to 80
		TL	9,000 to 11,000	50 to 75
		RTL	9,000 to 10,000	75 to 90
		SWC	smallest available	
50 to 130	1	TD	9,000 to 11,000	80 to 100
		TL	11,000 to 15,000	75 to 100
		RTL	10,000 to 12,500	90 to 110
		SWC	as available	110
130 to 250	1	TD	14,000 to 16,000	110 to 130
		TL	15,000 to 20,000	110 to 140
		RTL	12,500 to 16,000	110 to 140
		SWC	14,000 to 19,000	110 to 140
250 to 500	1	TD or SWC	21,500 to 24,000	190 to 220
	and			
	1 or 2 of	TL, RTL, S, DL, or WT		

TD:	Tracked dozer	S:	Scraper
SWC:	Steel wheeled compactor	RG:	Road grader
WT:	Water truck	RTL:	Rubber tired loader
TL:	Tracked loader	DL:	Dragline

Adapted from Reference 1.

Reference

1. Brunner, D.R. and D.J. Keller, *Sanitary Landfill Design and Operation*, U.S. EPA, Report No. SW-65TS (NTIS PB227-565), 1972.

Chapter 10

Operation

10.1 Introduction

Successful operation of a landfill requires careful planning, effective management, proper use of labor and mechanical resources, and frequent monitoring of performance. The monitoring of performance begins with the receipt and landfilling of wastes and continues through those operational activities that bear on the protection of human health and safety and on the protection of the environment. All of the activities and considerations that compose the operation of a landfill are described in this chapter. By the very nature of a landfill operation, the primary operational considerations involve heavy equipment, labor, and control of the impacts of landfilling on the public health and on the environment.

The chapter is organized into three parts: 1) general procedures (i.e., those that are independent of the type of landfill used); 2) specific operational procedures (i.e., those that depend on the type of landfill used); and 3) performance monitoring. In addition, a discussion is presented addressing monitoring for potential negative environmental problems.

10.2 General Procedures

Operational considerations that apply to all types of landfilling operations include the following:

- hours of operation,
- site preparation and maintenance,
- inclement climate,
- waste receipt and vehicle routing,

- environmental control,
- self-haul, and
- salvaging/scavenging.

10.2.1 Hours of Operation

A common practice in the operation of a landfill is that operating hours are set to accommodate the schedule of waste collection. However, proper control and management of disposed wastes, and proper accounting of waste quantities at the landfill, may require modification of collection practices and schedules to accommodate site operations. As an example, disposal sites in the United States typically are open from early morning (e.g., 6:00 a.m.) to late in the afternoon (e.g., approximately 4:00 to 6:00 p.m.). The time period of operation of the landfill should take local traffic conditions into consideration.

Operating hours may be modified based upon seasonal frequency of generation of waste. Certain periods of the year may result in greater waste generation than other times, (e.g., tourist seasons or festivals). If the disposal site is not open 24 hours per day, the gates should be closed such that the operators will be allowed sufficient time to cover the day's waste deliveries and for general cleanup. Large containers can be placed outside the gate to accommodate the disposal of small quantities of wastes delivered after normal operating hours. Posting and announcements of disposal hours is an important aspect of landfill operations.

At the beginning of the day, personnel should arrive at the facility sufficiently early to prepare the equipment and the site for operation prior to the arrival of the first loads of wastes. Among typical preliminary activities are: relocation of fencing for control of litter, maintenance and fueling of equipment, preparation of unloading areas, cleaning of roads, setup for weighing and recordkeeping, and snow removal (where relevant).

10.2.2 Site Preparation and Maintenance

10.2.2.1 Site Preparation

As the working area is filled and additional areas are required for filling, those new areas should be cleared, excavated, and lined. Similarly, as the working areas are filled, a final cover should be applied on them as soon as possible.

The sites must be prepared and constructed according to design specifications. Site preparation and construction include:

- clearing and grubbing,
- installation of surface water drainage systems,
- excavation to meet design requirements,
- installation of liners and leachate collection systems,
- erection of building structures,
- installation of utilities,
- installation of perimeter fencing,
- constructions of roadways, and
- soil stockpiling.

10.2.2.2 Road Maintenance

Maintenance of access roads at landfill sites is a continuous process. Road maintenance often is an expensive operation. Regardless of the type of surface (soil, gravel, or pavement), the roads must be inspected and maintained frequently. Typical repairs include cleaning, adding or grading soil and gravel, filling holes, and cleaning drainage ditches. Since proper road maintenance is a costly operation, it often is neglected. Lack of proper road maintenance subjects vehicles using the disposal site to potential damage and unnecessary delays, and creates unsafe conditions. A few sections of well-marked rough areas, or speed bumps, can be placed on some roads in order to control excessive speed and, therefore, reduce wear and tear on the roads.

10.2.2.3 General Maintenance

All waste treatment and disposal sites require continuous maintenance. At the beginning of the operation, the site manager should prepare a detailed maintenance schedule. Specific dates should be identified for the performance of tasks. The types of tasks that are required include:

- the collection and disposal of litter;
- maintenance of gates, fences, and buildings;
- maintenance of road and drainage systems and final cover; and
- the preparation and upkeep of site maps.

As areas of the landfill are filled and completed, a series of maps indicating their status should be maintained and updated. The maps should identify, by areas, the types of waste that were landfilled, including special wastes, the depth of the fill, as well as other site-specific features. An example map, showing the sequence of operation, is given in Figure 10-1.

10.2.3 Inclement Climate

The proper management of the consequences of adverse meteorological conditions plays an important role in the successful operation of a landfill site. Long periods of excessive rainfall, freezing temperatures, or extreme heat can disrupt routine operation of a landfill. The amount of rainfall during site preparation has a direct impact on the moisture content of the soil, as well as on groundwater levels. Both of these parameters are important in the control of

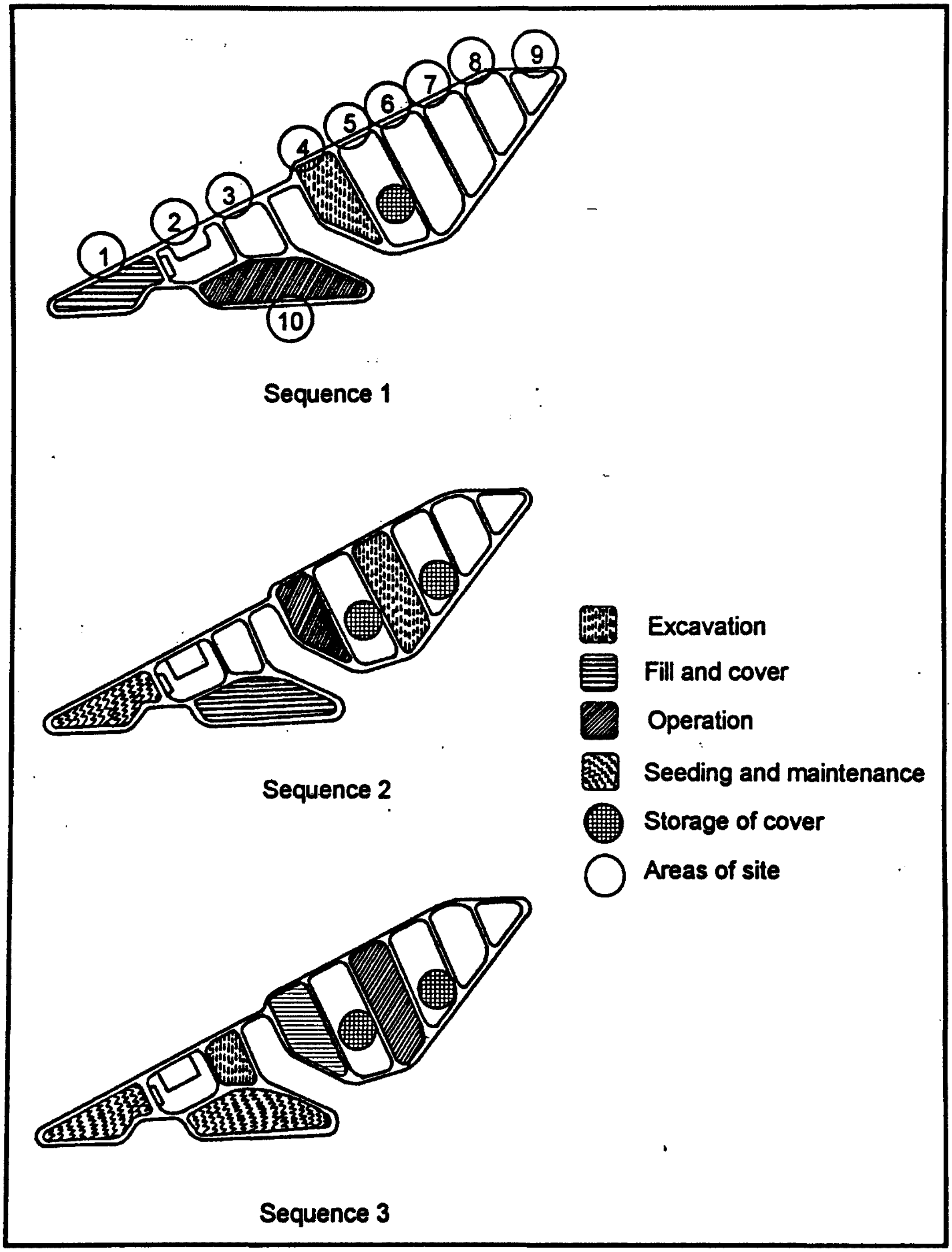

Figure 10-1. Typical Sequence of Operation

soil strength and permeability during construction of a clay liner or other compacted soil components. Extremely low temperatures (e.g., freezing conditions during construction of the landfill site) also impact soil workability and permeability. Ambient temperature can affect the installation of geomembrane liners, in particular the adequacy of seams and their performance.

Meteorology can also have an impact on the performance and operation of the facility. In locations that experience heavy rainfall, conditions can lead to extremely muddy access roads and unloading areas, which leads to long delays to users of the site, unless proper precautions and preventive measures are put in place. Extremely high precipitation also may increase the level of the groundwater and therefore impact groundwater diversion systems designed to protect the fill from groundwater intrusion. Soils wetted and saturated with precipitation can also become unstable if unsupported (e.g., the sidewalls of a trench operation) or if piled or sloped at steep angles. One of the more effective means of managing heavy rainfall and surface water flow is to maintain the slopes of the drainage canals on the periphery of the site so that they continue to divert water away from the wastes. In the event that the site is relatively flat, leachate collection systems help to reduce some of the problems associated with increased precipitation. However, if the leachate collection system does not have the capacity to accommodate the extreme conditions, liquid pressure will build up in the facility. High liquid pressure may result in leachate migration from the site. Decreased soil density, which may cause liner instability, may also result from heavy precipitation.

On the other hand, very dry weather conditions can result in very hard soil that is difficult to excavate or compact. In addition, in the absence or near absence of moisture, organic matter does not readily decompose. In arid areas, evaporation from the ground typically is greater than precipitation. Consequently, very little or no leachate is formed within the fill. Landfills in arid and semi-arid regions may be operated without bottom liners and leachate collection systems, provided that there is adequate protection of the groundwater. In fact, it has been suggested that the best sites for landfills are in arid regions [1]. Dry soil may also lead to the formation of cracks and increase the permeability of the soil. Freezing temperatures may cause stockpiles of soil to freeze and become unusable. Temperatures below freezing may affect the proper operation of site equipment, as well as components of the leachate collection system located above the frost line. Efficient operations require that operational problems such as those described above be anticipated and that contingency plans be developed by management in order to address the problems satisfactorily. In Table 10-1 are listed problems due to inclement weather, and potential solutions.

10.2.4 Waste Receipt and Vehicle Routing

Every landfill operation should maintain a controlled gate. A gate enables the operator to: 1) keep records of weights or volumes of incoming loads, 2) direct incoming vehicles to a specific location, and 3) reject materials that cannot be disposed properly on the site. Signage which clearly indicates site regulations, operating hours, user (tipping) fees, emergency telephone numbers, permit information, and other relevant data should be placed on the gate.

Monitoring the quantities (weights or volumes) of residues received at the landfill allows an operator to assess the efficiency of the operation in terms of land use and compaction. These records also allow the operator to predict, with a certain degree of accuracy, remaining site life. Remaining site life can be calculated in conjunction with topographic surveys or aerial surveys. Aerial surveys may be unnecessary, too costly, or both for certain locations. In addition, user fees can be properly and accurately assessed by monitoring the quantity of waste received. There are various methods to monitor the quantities of waste received. Most large, modern landfills utilize truck scales. Although it is preferable to monitor weights, sites receiving relatively small quantities of waste may opt instead to record volumes of waste. In the absence of a permanent scale on the site, weights of waste may be determined over a short term for the purpose of monitoring and estimating the inflow of waste by using a rented,

Table 10-1. Inclement Weather Practices

Problem	Solution
Muddy Access Roads	**Wet Weather** • Add cinders, crushed stone, or demolition debris • Maintain a special working area that has permanent roads • Inspect for positive drainage and clean and maintain drainage systems as required
Muddy Unloading Area	• Stockpile well-drained soils and apply as necessary • Keep compactive equipment off area by unloading and moving refuse perpendicular to area • Grade unloading area slightly to permit runoff • Inspect for positive drainage and clean and maintain drainage systems as required
Wet/unworkable Soil	• Maintain compacted, sloped stockpiles and/or cover with tarpaulin
Soil Permeability/Density -- varies from design	• Do not compact soils during overly wet weather conditions • Protect soil from the elements (e.g., cover)
Leachate Collection System -- clogging from runoff	• Add barriers for fines • Periodic cleaning of pipe network
Dry Soils -- unable to excavate and increased permeability	**Dry Weather** • Cover soil to prevent drying • Wet soil
Frozen Soil	**Cold Weather** • Insulate stockpiles with leaves, snow, or straw • Salt soil • Continually strip and cut soil • Maintain well-drained soil/sand • Use hydraulic rippers on frozen soil

portable scale. The results of the weight survey can be used to develop user fees and to estimate waste receipts over an annual period. Of course, this method does not take into consideration any changes in the waste stream and, therefore, quantities after the survey is completed.

10.2.5 Environmental Control

In most situations, regulations are established which require the inclusion of environmental controls to protect the environment from the potential negative impacts of landfills. The most commonly used types of environmental controls include impermeable barriers (liners), leachate collection systems, landfill gas control systems, and cover systems. The proper design and construction of these controls are discussed in Chapter 8. Environmental controls are necessary to protect the environment during landfill operation and during closure and post-closure. These practices are described in the following sections and are outlined in Table 10-2.

10.2.5.1 Leachate Control System

The generation and control of leachate is an important aspect of landfill operations because the liquid may migrate beyond the boundaries of the facility and contaminate both ground and surface waters [2]. The rate of leachate production can be substantially reduced by covering the solid waste during facility operation with a material having a low permeability. Leachate production can be controlled after closure of the site by installing and properly maintaining a final cover system that minimizes the amount of liquid that penetrates into the waste. In most cases, leachate will be produced in municipal solid waste disposal facilities. Therefore, in those disposal facilities that have liners, a leachate collection system must be installed, and properly operated and maintained, in order to prevent the accumulation of leachate and, thus, avoid excessive pressure on the liner or soil walls of the landfill. Leachate production, collection, and treatment system operation are discussed in References 3, 4, and 5.

10.2.5.2 Siltation and Erosion

Improper grading generally leads to production of runoff containing high concentrations of silt. During operation of the landfill, grades should be maintained between 2 and 5%, if possible, to promote surface drainage and, at the same time, to minimize flow velocities. Areas lacking vegetative cover should be kept to a minimum during site operation. Ongoing construction and maintenance of sediment control devices (e.g., grass waterways, diversion ditches, rip-rap, sediment basins) are critical for an environmentally sound operation. During final closure of

Table 10-2. Environmental Control Practices in Landfill Operations

Practices	Leachate	Spillage	Siltation & Erosion	Mud	Dust	Vectors	Odors	Noise	Aes-thetics	Safety	Birds	Litter	Fires
Safety program										√			
Maintain washrooms for personnel		√		√	√	√	√		√	√			
Training of new personnel	√	√	√	√	√	√	√	√	√	√	√	√	√
Maintain road markings and trench barriers		√	√	√					√	√			
Maintain fencing						√		√	√	√		√	
Apply insecticides			√	√	√		√	√	√				
Maintain buffer areas and grass		√	√	√	√	√	√	√	√	√			
Proper equipment maintenance	√			√	√			√		√			√
Spray water/liquid asphalt				√	√		√					√	√
Truck wash pad (to clean trucks)			√	√	√				√				
Maintain grass waterways, diversion ditches, rip-rap			√						√				
Final grading of disturbed areas	√		√	√	√				√	√			

(continued)

Table 10-2. Environmental Control Practices in Landfill Operations (cont.)

Practices	Leachate	Spillage	Siltation & Erosion	Mud	Dust	Vectors	Odors	Noise	Aes-thetics	Safety	Birds	Litter	Fires
Chemical masking agent							√						
Workers supplied with health and safety equipment					√		√			√			
Cover solid waste daily	√					√	√		√	√	√	√	√
Water diverted away from site	√		√	√									
Construct low-permeability liners and leachate collection systems	√												
Construct low-permeability final cover system	√					√	√						
Extermination program						√					√		

the landfill, proper final grading, seeding, and maintenance of a final cover system help prevent long-term erosion and siltation problems.

10.2.5.3 Mud

Heavy rains and snowmelt during the spring can result in the production of mud. In order to reduce the adverse impact that muddy conditions can pose on daily operations, access roads should be paved or graveled, and maintained on a regular basis. An alternative to paved or gravel roadbeds is a surface composed of a mixture of materials of relatively large particle size (such as sand or gravel), or clay soils where vehicle traffic is heavy.

Mud can be tracked onto public roadways by landfill equipment or collection vehicles and can result in significantly poor public relations for waste disposal facilities [6]. Ideally, an area for washing should be installed and operated near the gate to the facility in order to remove the mud from transport vehicles. In some cases, landfill sites have specific areas that are used only during poor weather conditions and when conditions in other areas of the facility are muddy and would make operation difficult. Wet weather operation areas should be carefully planned and, if possible, located as close to the main gate as possible in order to reduce on-site travel.

10.2.5.4 Particulate Matter

Airborne particulates (e.g., dust) in a landfill site are generated by collection vehicles and heavy equipment moving over dry dirt roads or dry, dirty paved roadways and by the wind. Particulate emissions can also be generated during the discharge, placement, and compaction of dry waste materials or during the excavation and transport of dry soils. In order to reduce the amount of particulate generation, access roads should be graveled or paved. In addition, water or other environmentally-acceptable dust control chemicals can be applied to dusty or dirty roadways on a continuous basis, or on the basis of need. The relatively common practice of applying waste oils to roads should be discontinued. Excavating or moving soils when they are damp will limit the generation of particulate matter. Similarly, dry waste materials should be slightly moistened prior to disposal. Another means of reducing the total amount of dust generated from a particular facility is to revegetate completed areas as soon as possible.

Especially in the case of the operation of landfills near populated areas, a water truck or trailer should be available, maintained, and used to moisten dirt roads and working areas as a dust control method.

10.2.5.5 Vectors

Flies, mosquitoes, and rodents may be present at landfill sites. These and other vectors can be controlled by frequently placing an adequate quantity of compacted soil over the wastes. It has been demonstrated that a daily cover consisting of 15 cm of compacted soil having some clay content will prevent the emergence, accumulation, and breeding of flies. However, even when daily or frequent covering of waste is practiced, a landfill operation should include a regular inspection and control program for flies. Mosquito control is best accomplished by preventing the accumulation of stagnant water anywhere on the site. The accumulation of stagnant water can be prevented by proper grading, filling low spots, and placing cover soil over waste materials.

Whole tires represent a risk of fire and breeding areas for mosquitoes when water accumulates in them. Consequently, whole tires should not be allowed to be stored on the landfill premises. Moreover, since whole tires tend to migrate to the surface of the fill, they should be cut or placed carefully as far from the surface of the fill as possible.

Rats and mice may be brought into the site with the solid waste from time to time. If habitat is available in areas adjacent to, or in some neglected portion of, the site, extermination by the local health department will be necessary. Employees at the landfill should be trained to recognize burrows and other signs of the presence of rats and mice so that appropriate measures of control can be taken.

10.2.5.6 Odors

There are several potential sources of odor at a landfill. Odors may be generated in the following situations:

- Odors generated by the refuse usually can be mitigated by rapidly covering the wastes and ensuring that the cover is maintained intact.

- Occasionally, loads of particularly malodorous materials may be delivered to the landfill. Deliveries of these materials should be scheduled such that sufficient manpower and equipment are available to immediately cover the waste. If separate handling is not possible, malodorous loads can be mixed or covered with other wastes in order to control the problem of odor emissions. The use of lime or chemical masking agents also can be used to control odors in some cases and with various degrees of effectiveness. Effectiveness is governed by the properties of the offending material.

10.2.5.7 Noise

There are several sources of noise at landfills. These sources include operating equipment and collection vehicles. Typically, the noise is very similar to that generated by any heavy construction activity, and is limited primarily to the site and to the streets used to transport the solid waste to the site. One of the majors generators of substantial noise is vehicle engines, especially engines that do not possess noise control systems (e.g., mufflers). Engine noise is particularly significant while the engine is under substantial load (e.g., while operating the hydraulic unloading equipment of a collection vehicle or while transiting a steep grade). Areas wherein vehicular engines are under significant load should be located remotely from sensitive noise receptors. In order to reduce the total number of individuals exposed to the noise, every effort should be made to route traffic accessing the disposal site through the least populated areas. In addition, the site can be isolated or surrounded by a buffer zone such that the noise does not disturb anyone. The installation of properly designed and constructed barriers, such as earthen berms, walls, and trees, can be effective methods of noise control.

10.2.5.8 Aesthetics

In order to reduce environmental impacts and to make the landfill acceptable to the public, the site should be designed to be as compatible with its surroundings as possible. During site preparation, it is important to leave as many trees as possible in order to form a visual barrier. Berms can also be used to form visual barriers. The use of architectural effects at the entrance, confining disposal to designated areas, and the use of attractive landscaping will assist in the development of an aesthetically pleasing operation. Additionally, every attempt should be made to minimize the size of the working face. Control of dust generation by vehicular traffic and disposal equipment also minimizes the negative visual impact of the facility.

10.2.5.9 Birds

Birds, especially in landfills located in coastal areas, are attracted to landfills because of the potential source of food. Birds can pose a serious hazard to operating aircraft and create a nuisance to operating personnel and neighbors. In the United States, the criteria for the classification of waste disposal facilities and practices stipulate that a solid waste disposal facility should not be sited within 5 miles (or about 8 km) of an active airport. A number of devices have been used to control birds at solid waste disposal sites, some of these devices (noise production, nylon strings, distress calls, or similar measures) can provide some temporary control. However, the most effective control practice is rapid and complete covering of all solid waste.

10.2.5.10 Litter

One of the more frequent complaints from residents living near solid waste disposal sites is blowing litter outside the boundaries of the disposal operation. Blowing litter can be substantially reduced by:

- discharging the waste at the toe (bottom) of the working face,
- frequent and thorough cover of the face and completed portions of the cell,

- application of water or damp waste to loads containing a high concentration of paper and dry dusty solid wastes, and

- installation and maintenance of portable or stationary fencing around the working face.

Generally, despite the operator's best efforts and control measures, the accumulation of some litter is inevitable at a landfill site. The installation of a fence around the site will help to contain litter and to keep it from reaching adjacent properties. Daily cleanups, particularly at the end of the working day, can limit the quantity of litter that can reach adjacent properties and can optimize the collection of litter because, for a given quantity of litter, collection within a confined area is more efficient than collection over a wide area.

10.2.5.11 Fires

Waste disposal sites represent a risk of smoldering waste or fires. The fuel for the reaction can be the solid organics contained in the wastes, the methane generated as a consequence of the landfill processes, or both. Three conditions must exist to support smoldering or burning of wastes:

1. a source of combustible material (i.e., carbon);

2. an oxidizer, usually the oxygen in the air entrapped with the buried wastes; and

3. sufficient heat to support the combustion and pyrolytic processes.

Sources of heat, among others, can be smoldering wastes delivered to the landfill or that caused by chemical reactions occurring in the fill.

Burning of waste at disposal sites in economically developing countries can be intentional (e.g., as a method of volume reduction) or unintentional. Prevention and control of burning wastes within open dumps is difficult because no containment system has been designed into the disposal sites. In this regard, the cell structure and gas control system of a modern landfill, and the practice of compacting the waste, overcome a serious shortcoming of the open dump. High levels of compaction reduce void space wherein oxygen can reside, thereby minimizing the availability of an oxidizing agent.

Control of fires at landfills or open dumps requires similar practices. Essentially, control is achieved by the occurrence of one of the following three circumstances: 1) the source of fuel is removed or consumed, 2) the oxidizer is removed or consumed, or 3) the source of the heat required for the reaction is removed. An in-depth discussion of the mechanics and control of fires in waste disposal facilities can be found in Reference 7.

Uncontrolled ignition of combustible materials (open burning) should not be permitted at landfills. The reasons for this recommendation include protection of worker and public health and safety, the adverse impact of the practice on air quality, and the negative visual impact of the practice on the aesthetics of the operation. Fires and burning wastes also can destroy landfill equipment and facilities, including gas collection piping and synthetic liners, if present. An awareness must be had of potential sources of fires at landfills. The sources include receipt of hot wastes, sparks from vehicles, equipment fire, vandalism, and purposeful incineration for salvaging (e.g., removal of insulation from copper wire). A good security program, combined with alert spotters, can mitigate the occurrence of the majority of fires at the disposal site. Hot and highly flammable wastes should not be mixed and should be directed to specific areas in the landfill and wetted or smothered and diluted with soil or water prior to disposal. All landfill vehicles should be equipped with fire extinguishers to limit damage resulting from equipment fires.

In the event that piped water is not available, a water truck or trailer equipped with a gasoline-powered pump should be on-hand. Several techniques are available for dealing with fires. Burning or smoldering waste near the surface of the fill can be excavated and extinguished with soil and/or water. Deep fires can sometimes be smothered by placing damp soil on the surface of the fill. More commonly, however, deep fires will have to be thoroughly excavated and smothered at the surface. Particularly large fires may have to be dealt with by qualified and experienced fire fighting personnel.

When excavation is used, care must be taken to minimize the potential for the occurrence of rapid combustion or explosion since methane gas may be present and excavating the wastes exposes them to oxygen (air). Control of burning waste is one of the important functions of the cell structure of the sanitary landfill. The cell boundary (i.e., daily and intermediate soil cover) acts as a barrier to burning waste.

In those locations where solid fuels such as coal or wood are used for domestic heating and cooking, hot ash disposed with other domestic wastes represents a risk of fire when the wastes are delivered to the landfill. In those locations, monitoring (or inspection) of loads should be conducted for the purpose of identifying any hot ash or burning or smoldering materials. If such loads are identified, they should be unloaded on a soil surface and extinguished completely with soil or water prior to landfilling.

10.2.6 Self-Haul

Most disposal sites allow the transportation and discharge of wastes by private individuals (self-hauler). Typically, small vehicles comprise a considerable portion of self-haul traffic. These users (either small contractors or private individuals), because of infrequent usage, typically are unfamiliar with practices at the site and, therefore, can damage their vehicles, can cause delays at the working face, and may cause accidents.

Several options exist for managing self-haul vehicles. Self-haul vehicles can be directed to specific areas of the working face away from the area used by large collection vehicles. Alternatively, a small transfer system can be used within the disposal site. Transfer systems commonly used are large self-dumping trailers (which are located remotely from the working face, but which are periodically towed to the working face when full), dump trucks, and roll-off containers. Normally, a platform is constructed to unload small volumes of waste into the large containers.

The transfer point should be located inside the gate and adjacent to a well-maintained main roadway. This area should be located at a point where it can be watched by site personnel. If utilization of the transfer station is frequent, an employee may need to supervise and operate the facility on a continuous or frequent basis. A resource recovery operation can also be added to the transfer station if supervision is available. A transfer station represents potential problems, especially abuse by the users. Litter is a common problem and fires may take place in the container(s). Nevertheless, the value of some type of transfer system is sometimes justifiable in terms of controlling the costs of maintaining roadways, simpler and safer operations at the working face, and good public relations.

10.2.7 Salvage/Scavenging

Scavenging or uncontrolled sorting of raw wastes to recover materials that may be reusable is a common practice in most economically developing countries. This practice is strictly prohibited at the working face of landfills in industrialized countries because of the high risk of injury and health-related hazard to the scavenger. If salvaging is allowed, it should be controlled and should be conducted away from the working face under sanitary conditions and under direct supervision of the operator of the landfill. Salvaging operations and storage must be confined to a specific area or facility so that they will not interfere with the landfill operation. Strict controls must also be established on the types of materials, storage, and removal frequencies so that nuisance conditions do not develop. Individuals working in a salvaging operation should be provided with uniforms, hard hats, masks, boots, and basic sanitation services.

Additional discussion regarding scavenging is presented in Chapter 15.

10.3 Specific Operational Procedures

Three basic operational procedures apply to landfilling and their use depends on the method of landfilling. The three procedures are:

1. site preparation,

2. traffic flow and unloading, and

3. waste compaction and covering.

The sequence and method of operating a landfill are dictated by several factors that are specific to a site. Some of the more important factors include physical site characteristics, types of waste, and the rate of receipt of solid waste. There may be more than one satisfactory method for a given disposal site.

As has been previously indicated, the two basic operational methods are trench and area. The primary difference between the two is that the trench operation employs a prepared excavation and, as such, confines the working face between the two sidewalls. The area method, on the other hand, does not use extensive surface preparation. The width of the working face is, in theory at least, unlimited. A common approach of landfills is to use both methods at different locations or times. For example, initial disposal operations may employ a trench design and, subsequently, the area method may be used on top of the completed trench cells.

10.3.1 Site Preparation

Any excavation of soil during preparation of the site should follow a particular sequence such that the soil that is removed can be used elsewhere on-site without stockpiling. This procedure eliminates double handling of material. A model has been developed to provide assistance in the planning of soil movement [8]. However, it is frequently necessary to stockpile a certain amount of soil in order to take full advantage of the various types of soils. For instance, topsoil should be stockpiled for use on roads, as daily, intermediate, and final cover, or for the construction of leachate collection systems or surface drainage systems. Clay may be selectively excavated and used as liner material, dikes, interim and final cover, or, if necessary, used to supplement subgrades.

Soil that is stockpiled should be placed in appropriate areas, compacted, and appropriately sloped to keep it as dry as possible. Soil should be stockpiled as close as practical to the location where it will be used. Stockpiles should not be placed in areas where they will interfere with traffic or cover soil that might be needed for other functions, or will impede the function of drainage control systems.

10.3.2 Traffic Flow and Unloading

The general procedure for managing the receipt of solid waste at the gate is discussed elsewhere. The procedure is applicable to both the trench and area methods.

The spreading, compacting, and covering of waste can be facilitated by controlling the position of the collection vehicles while unloading. If the collection vehicles are directed over previously filled areas, the areas should be well-compacted. When possible, demolition debris and other dense rubble should be placed to take advantage of the drainage plan. Roads should be designed and built such that they do not interfere with stockpiling or handling of the soil.

The working face should be as narrow as possible without unduly constraining normal operations. To facilitate this, an operator (spotter) should be at the face of the fill during operating hours using a whistle, a bullhorn, or flags to direct incoming vehicles to the appropriate sections of the working face. Barricades and markers can be used to delineate the area that is used on a given day.

It is preferable to keep the unloading area at the toe of the working face. This is because spreading and compaction are easier and generally more effective when performed from the bottom toward the top of the working face (see Figure 10-2). If the unloading of waste occurs at the top of the working face, care must be taken to prevent the waste from simply being pushed over a steep working face without the application of adequate passes by the compactor (a common practice in many economically developing countries). Unloading waste at the toe generally overcomes the risk of this poor operating practice and reduces blowing litter. The unloading area should be kept clean, dry, and level to prevent vehicles from being damaged, tipped, or mired in mud. At small sites, it may be necessary to provide an unloading area that is wider than the working face. At large sites, or at sites that process large quantities of wastes in relatively short timespans, a portion of the unloading area should be set aside for unloading trucks manually. If the face of the fill is not sufficiently wide to allow for this process, manually-operated vehicles may be routed for unloading to the top of the working face.

10.3.3 Waste Compaction and Covering

Spreading and compaction operations should be aimed at maintaining proper cell density, height, slope, and width throughout the day.

The compacted density of the solid waste primarily depends upon four main variables. The degree of compaction is a function of: 1) the thickness of the layers, 2) the weight (or applied pressure) of the equipment used to compact the waste, 3) the slope of the working face, and 4) the number of passes made by equipment. The slope of the working face should not exceed 1:4; 1:5 is a general practice. Usually 4 to 6 passes with heavy (i.e., greater than about 20,000 kg) wheeled or tracked equipment will provide a high degree of compaction. Although passes in excess of 4 to 6 times do result in higher compaction, the return for the effort substantially diminishes beyond 6 passes. A trained and experienced operator knows when additional passes will result in greater compaction. In order to prevent soft spots in the fill area (i.e., areas susceptible to settling when a load is applied), the wastes should be mixed (e.g., a load of plastics or tree limbs should be mixed with mixed domestic wastes), and

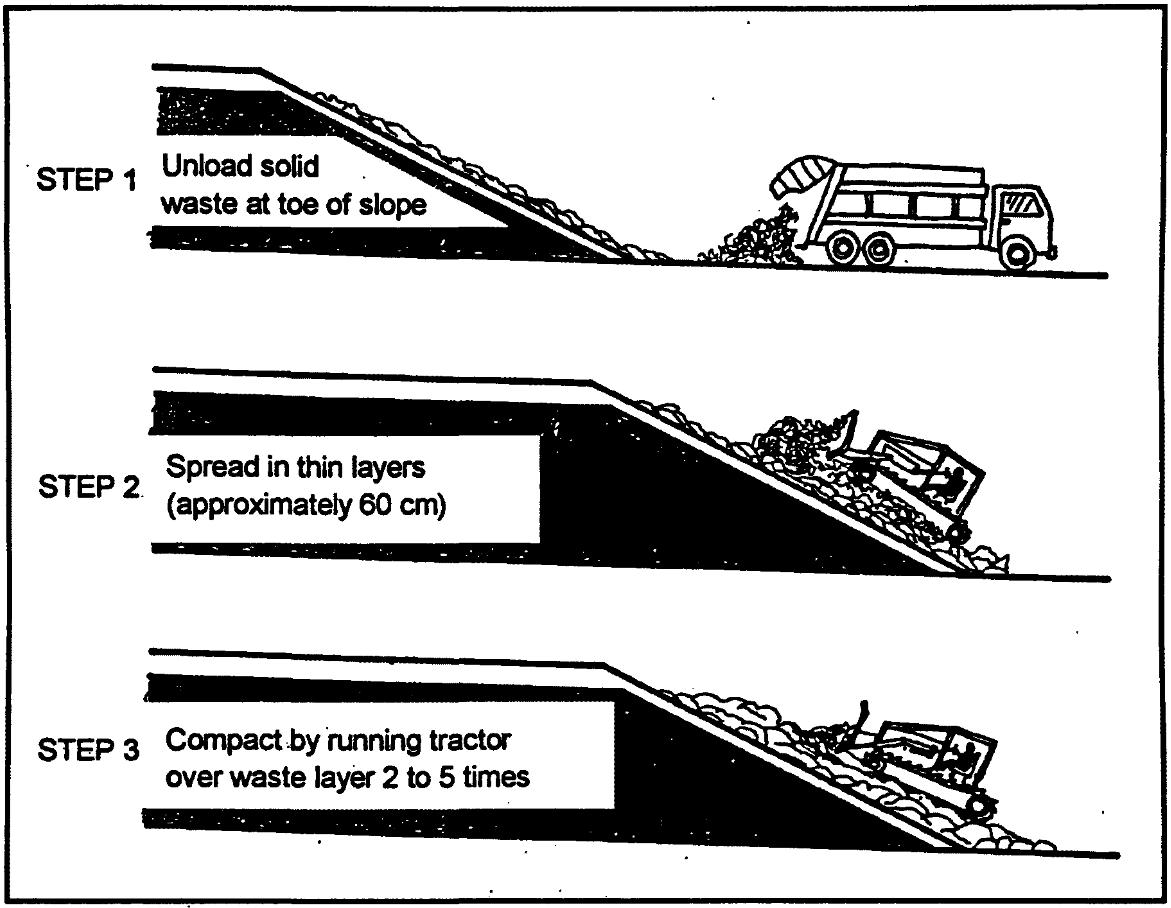

Figure 10-2. Unloading and Compacting Process

excessively wet loads should be separated and mixed with dry materials before and during spreading. The compaction sequence is demonstrated in Figure 10-2.

The final height of lifts usually is determined by the grade plan for the facility, soil usage, and operational limitations. In extremely deep fills with a large number of lifts, the height of the lift may be limited by the equipment. For instance, a lift may be limited to the maximum height at which a scraper can provide complete coverage with soil with one pass. Typical heights for lifts range between 2 to 4 m.

The relation between density and the number of passes, the thickness of the waste layer, and weight of compacting equipment are illustrated in Figures 10-3, 10-4, and 10-5, respectively.

The slope of a cell should not exceed 15°, or about 1:4 (vertical to horizontal). The slope should be established by properly placing and compacting the initial loads, and maintained constantly throughout the day. The more horizontal the working face, the greater the degree of compaction of the waste and of control of the compaction equipment, all other conditions being constant. However, if the working face is too near to horizontal, the potential of problems increases with respect to good drainage and to control of the larger area of exposed wastes. Also, the requirements for cover soil increase as the slope of the working face decreases.

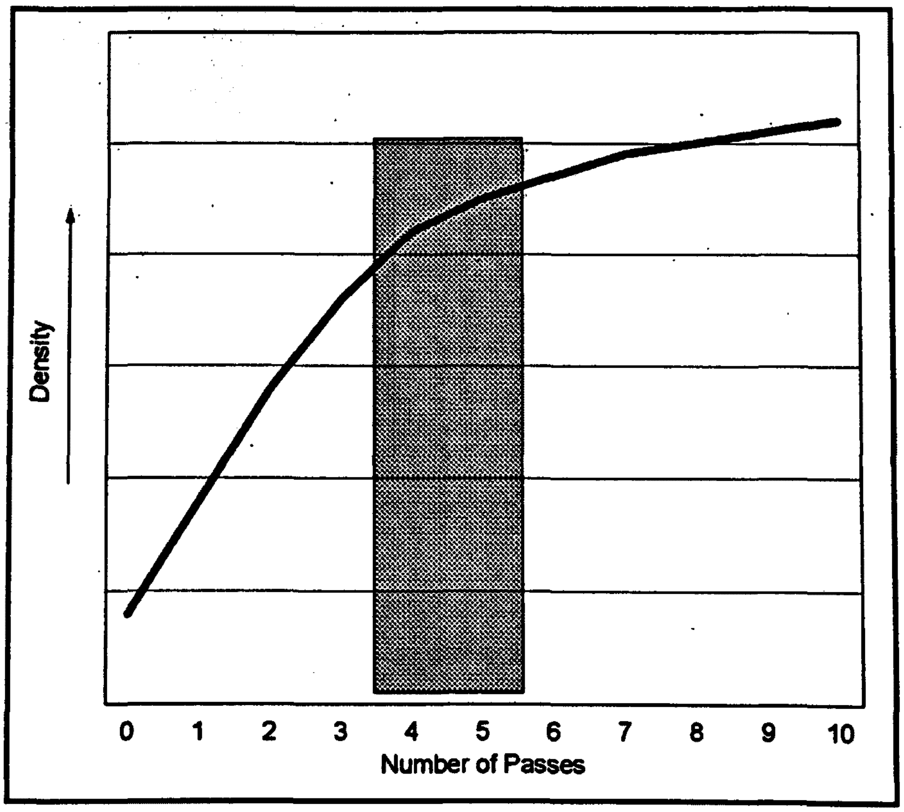

Figure 10-3. Impact of Passes on Relative Landfill Density

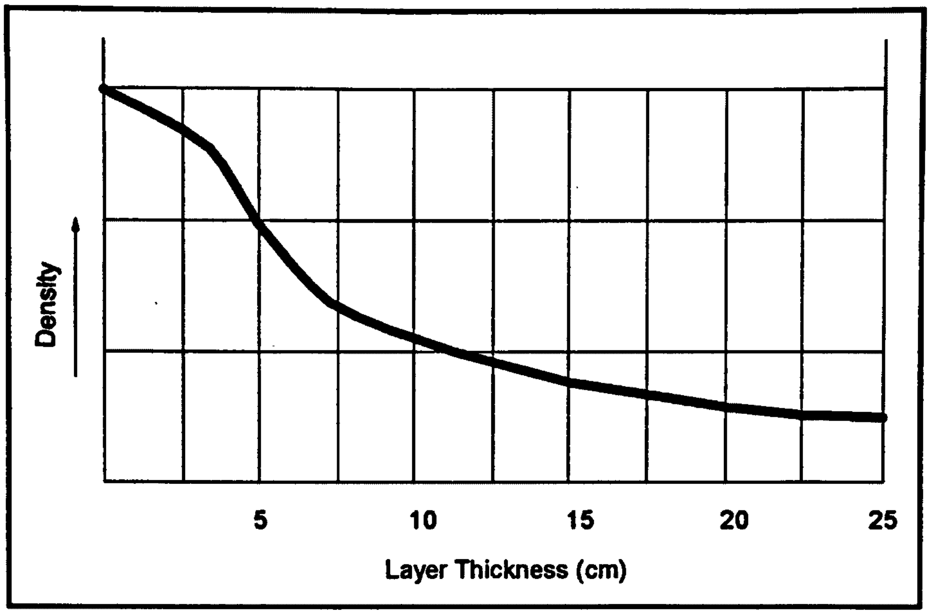

Figure 10-4. Relationship Between Thickness of Layer of Waste and Relative Average Compacted Density

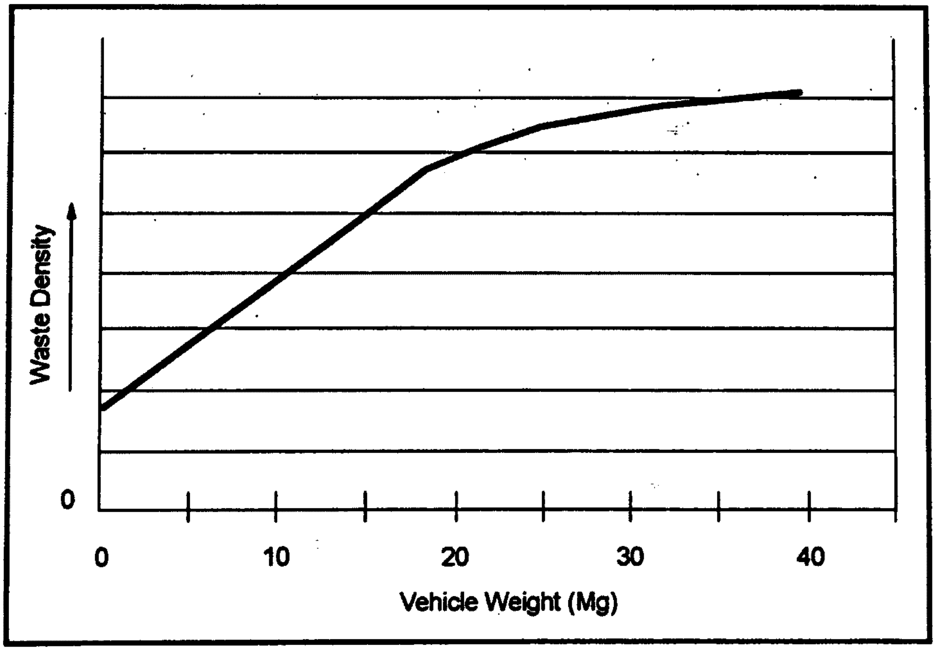

Figure 10-5. Machine Weight vs. Relative In-Place Density

The stockpiling of soil and the method of application of the soil should be carried out such that the cover will not be littered with waste. This situation can be prevented by depositing the soil at the top of the cell or adjacent to the face. At the time that the cover is applied, the soil spreading equipment should travel over only the soil. The spreading equipment should not travel from the waste onto fresh soil because this practice tends to draw waste on top of the cover material. The tires for the various types of equipment should be cleaned before applying or compacting soil.

In industrialized countries, scrapers are the more frequently used types of equipment for the application of cover material. Scrapers reduce the amount of double handling. Unfortunately, they are expensive pieces of equipment, and the tires may be damaged by the waste materials. Draglines can also be used for the application of cover material. The use of draglines, however, requires additional grading and compacting of soil. Regardless of the placement method, the cover should be compacted and smoothed. Bulldozers can also apply cover, although if equipped with only a blade, they may require another piece of equipment to deliver the cover material to near the working face. Typically, two passes using appropriate equipment will provide sufficient compaction for daily cover soil.

The main purposes for applying daily cover are to improve the appearance of the site and to control vectors, litter, odor, water infiltration, and, to some extent, fire. Under ideal circumstances, the solid waste should be spread and compacted on the working face as soon as possible after delivery and covered with daily cover at the conclusion of the day's activities. Compaction of the waste levels the site and facilitates both covering and subsequent operations by providing a smooth surface. Typically, a minimum compacted thickness of 15 cm of daily cover soil is sufficient to accomplish the objectives. The thickness may exceed 15 cm if a greater depth is required to cover all of the waste. Cover should be applied to the top and side slopes as cell construction progresses. The side slope of the active cell (i.e., the exposed surface of waste perpendicular to the working face) should be sloped and covered with cover material as the working face advances. The procedure of compaction and covering of the side slope should be similar to that followed on the working face. These operating procedures serve to control blowing litter. The working face and adjacent side slope should be covered at the end of the working day [9].

Intermediate soil cover has the same general function as daily cover. The intermediate cover, however, remains exposed to the elements for a longer period of time. The intermediate cover may also serve as a temporary surface for traffic movement. The minimum suggested compacted depth for an intermediate cover is 30 cm. This cover should be placed as soon as possible on the lift surface, but kept a sufficient distance away from daily activity to prevent littering from equipment moving over it.

Completed areas should be covered with the final layer of cover as soon as possible, as described in Subsection 8.7. The depth and type of soil to be used and the compaction requirements must be specified in the facility design and operation plan. All but the upper few inches should be compacted in order to reduce the soil permeability. Topsoil can be added to the surface of the final cover. Seeding, mulching, fertilizing, and pH adjustment should immediately follow final covering. A U.S. EPA publication provides some useful information on standard procedures for planting vegetation on final covers [10]. The vegetation should be appropriate for the local soils and climate condition. Soil used as final cover should not be applied when it is too wet or frozen. A certain amount of soil should be saved after site completion to facilitate any grading that may be required to maintain grades to specification. Completion should be phased such that once the final cover is applied, no additional traffic will be permitted to traverse the completed area. A detailed discussion on covers is presented in Subsection 8.7.

10.3.4 Area Method

The area method typically is used in natural depressions, in prepared areas, or on top of filled trench cells. The subgrade may consist of either natural soil, a prepared surface using liners, or compacted soil or soil supplements. The use of either of these materials depends upon local regulations and design preferences. A typical area fill operation is shown in Figure 8-2. An area fill requires imported soil, from on or off the site, for liners and covers.

The primary objective in preparing a site for an area fill is to utilize most of the available soil that meets the design requirements. At the same time, site preparation should keep disturbance of natural soil and vegetation to a minimum. In order to accomplish these objectives, it is necessary to conduct a comprehensive inventory of the amount and type(s) of soil available.

10.3.5 Trench Method

The trench method is most applicable on flat or gently rolling ground with deep soils. The widths and depths of the trenches can vary substantially from site to site. A typical trench operation is illustrated in Figure 8-1. Trench operations usually result in surplus soil and provide lateral confinement at the operating face. Trench fills may require more land and equipment than area fills, other conditions being similar. In addition, trench operations may need extensive soil stockpiling and handling.

Generally, the depth and width of the trench are specified in the design and operating plans. The excavation of the first trench, and even portions of later trenches, may require stockpiling of large quantities of soil. The stockpiling must be conducted such that it will allow the soil to be available for use as liner and/or cover material such that other landfill operations are not impeded.

As previously indicated, the size of unexcavated areas between trenches depends upon the depth of the trench and the characteristics of the soil. In general, the more cohesive the soil the less area that will be required between the trenches. On the other hand, the distance between adjacent trenches increases as the depth of the trench increases.

The amount of soil handling and stockpiling can be optimized by following either of two approaches. The first approach is called the phased fill and covering. This approach uses soil from a trench being excavated to provide cover for an adjacent trench that is in the process of being filled. Soil from the first trench must be stockpiled. The second approach is known as the progressive trench. The progressive trench method uses soil excavated from one end of the trench as cover material for waste deposited at the other end of the same trench.

The working face in trench operations usually is more sharply defined than in area operations. In the trench method, waste is discharged within the trench. Waste should never be discharged from the lip of the trench because of the risk of injury to operating personnel and to users of the site.

In the trench operations, a ramp leading to the base of the trench is built and maintained at a grade appropriate for vehicular traffic. Contingency plans should be designed and implemented during wet weather or when other situations make the ramp hazardous or difficult to use.

The walls of the trench help to control the width of the face and size of the cell. On the other hand, the walls of the trench can interfere with compaction if the side slope is too steep for the wheels or tracks to reach the edge of the waste against the sidewall, and still maintain blade clearance.

Narrow trenches may have a rapid buildup of waste during peak periods of delivery. Under this condition, adequate compaction may not be possible if all of the waste is discharged at the face. In order to prevent this situation, it is best to, at least, loosely compact the waste in the bottom of the trench, and spread and compact it thoroughly as time permits.

When an area fill is placed on top of a completed trench fill, the operation should be phased such that the area fill is commenced as soon as possible after the trench fill. Sufficient soil for use as cover material should be made available so that area lifts on top of trenches will have adequate cover.

10.4 Performance Monitoring

It is important that the landfill manager have the ability to assess whether or not the landfill is meeting its goals. To that end, methods should be established for evaluating the facility's performance. There are many aspects of performance monitoring, ranging from the technical to the non-technical. The major items of landfill performance that can be readily measured or tracked are:

- waste quantities,
- filling rate,
- cover material usage,
- leachate production and control,
- gas collection and control, and
- worker safety.

Closely related to performance monitoring is environmental monitoring. Environmental monitoring is covered in another section of this chapter.

10.4.1 Waste Quantities

All solid waste entering the site should be weighed and the weights recorded, if at all possible. In particular, large landfills should have weigh scales. Different types of waste (e.g., municipal solid waste and industrial waste) should be weighed and recorded separately. Depending on the management structure for the landfill authority and its service area, it may also be necessary to weigh and record refuse loads according to origin. The latter type of information may be especially useful to solid waste management planners and might also be necessary for cost accounting and billing purposes. Weight data should be meticulously recorded and kept as part of the landfill operating record. To ensure validity of the data, weigh scales should be calibrated at the initial opening of the landfill and at least once every six months thereafter.

In some locations, the landfills may either be too small to warrant the installation of scales, or the municipality may not have the resources to install one. In such cases, the volume of refuse of each truckload (by type of waste) should be recorded as accurately as possible. This can be done by measuring the length, width, and height of the load and then computing the volume as follows:

$$\text{Volume } (m^3) = \text{Length } (m) \times \text{Width } (m) \times \text{Height } (m).$$

In some cases, standard load sizes of incoming vehicles will be known. Since some of the waste may be compacted in the truck, it will be important to account for such differences in recording the load sizes. The most effective way to account for waste density variations is to convert all measured volumes to weights. Once the density of the waste is known or estimated, the mathematical conversion is simple:

$$\text{Weight } (Mg) = \text{Volume } (m^3) \times \text{Density } (Mg/m^3).$$

Density estimates can be developed from past experience, from limited test weighings of representative loads of waste delivered to the facility, and from information obtained from the manufacturers of compaction vehicles. Test weighings can be conducted with the use of portable scales brought to the site.

As discussed in Chapter 4, the densities of solid waste vary greatly with respect to level of economic development of the country and as a function of waste type, source, and moisture content. Since density values are of utmost importance in properly managing landfill operations and differ considerably from location to location, it is important that waste density information be determined for local conditions.

10.4.2 Filling Rate

The rate at which a landfill is filled has a direct bearing on the lifespan of the facility. For example, if the filling rate can be reduced or moderated through good management, the landfill will have a longer service life for a given fixed capacity (volume). The filling rate is a function of the rate of waste disposed and of cover material used. The most reliable way to determine filling rate is to conduct periodic land or aerial surveys of the filled area and, using that information, calculate the volume, or "air space," consumed between the two survey dates. At large landfills, it may be practical to obtain yearly surveys of the landfill surface by digital aerial photogrammetry. In this way, annual volumes can be determined by computerized calculations using the digitized elevation data from successive mappings. Depending on the use of the survey data and the length of time between surveys, settlement of the fill may need to be considered when interpreting the results and when applying them to future estimations.

A less reliable, but still useful, means of estimating filling rate is to convert waste quantity data to volumetric estimates of the in-place compacted waste. The volume of daily cover material used in the landfilling operation must be added to the estimated volume of in-place waste. Using waste quantity data requires that reasonably accurate values of the compacted waste density be known and that compaction procedures be maintained as constantly as practical.

Once the volumetric filling rate is established, the rate can be correlated with weigh scale data so that landfill capacity can be expressed in terms of either weight (Mg) or volume (m^3) of solid waste.

Regardless of the method selected for estimating the filling rate, a knowledge of the rate is essential to predicting the remaining life of an active landfill. Knowledge of the facility's remaining capacity will be of value not only to the landfill manager, but also to others responsible for solid waste management planning.

10.4.3 Cover Material Usage

A knowledge of the rate of usage of daily and intermediate cover material is important because the material occupies capacity (volume) in the landfill that otherwise would be available for waste disposal. Thus, soil cover has two costs: the direct cost of the cover material and the indirect cost of lost capacity to dispose of the waste. One important goal of filling operations should be to utilize the minimum ratio of cover material-to-waste that is consistent with good landfilling practices. Since the minimum recommended depth of daily soil cover is about 15 cm, normally the only way to decrease the cover material-to-waste ratio is to increase the depth of compacted waste before it is covered. This manner of operation may or may not be practical, depending on the particular situation.

By monitoring usage of cover material in relation to incoming quantities of waste or compacted fill quantities, the landfill manager can look for trends in cover requirements and for possible opportunities to reduce the cover to soil usage. To determine usage of cover material, the operator can use a count of vehicle loads of cover material and their volume or measure quantities of cover material removed from dedicated borrow areas. Counting loads of known volume may be the most practical method of estimation for smaller operations. Measuring volumes removed from borrow areas can be done either by load counts or by land surveys before and after excavation.

10.4.4 Leachate

In any landfill that has leachate collection facilities, the quantity of leachate should be routinely measured and recorded. Leachate quantities can be measured in either of two ways: taking readings of liquid levels in leachate storage tanks or impoundments, or taking readings from leachate pumps or discharge lines equipped with totalizing flow meters.

Leachate quantities should be recorded and analyzed for trends or significant variations over time. Attempts should be made to correlate changes in leachate quantity with changes in precipitation. Variations not related to precipitation effects may be traceable to operational changes at the landfill. A comparison of actual rate of leachate generation with the original design estimates is also instructive. If actual rates exceed the estimates by a substantial margin, an operational problem may be indicated as the reason for excessive leachate generation, or excedences could indicate that the facilities for collecting, transporting, or treating the leachate are undersized.

10.4.5 Landfill Gas

Where partial or complete final covers have been installed, the landfill surface should be checked periodically for adverse signs attributable to landfill gas. These signs may include indication of stress to cover vegetation, strong odors, or visible breaches in the cover system where vapors are being emitted or where smoke or burning flames of gas are observed. In the case of landfill covers constructed with geomembrane liners, excessive buildup of gas pressure below the liner may actually lift the cover system and create large bubbles in the liner.

Any of the signs described in the preceding paragraph would indicate that additional measures are needed to contain, collect, or vent the gas. In passive systems, the addition of vents at identified trouble spots may correct the problem. In active systems, unwanted emissions or buildup of gas may be controlled by increasing the vacuum on existing extraction wells or vents, or by installing additional wells or vents in problem areas.

10.4.6 Worker Safety

The human element of landfill operations is the single most important consideration in landfill performance. Worker safety should be emphasized in all aspects of landfill operations through training of the workforce and by monitoring of the worksite for unsafe practices. Health and safety training and monitoring of health and safety programs is a specialized area of practice that should be conducted by qualified and experienced professionals.

At landfill sites where safety is given a high priority, likely benefits are high workforce morale and a high level of operational efficiency. A landfill that compiles a good safety record usually is a well-run operation. Conversely, a landfill with a poor safety record probably suffers from other operational problems as well. For these reasons, it is important that worker safety be tracked for the duration of operations. Perhaps the most useful measures of safety performance are the numbers of lost-time injuries and lost-time hours. Also, in the United States, it is a common practice to post prominent signs at worksites reading, "We have worked XX,XXX hours without a lost-time injury," as a safety reminder and as an incentive to employees to maintain safe working habits.

10.5 Environmental Monitoring

Environmental monitoring refers to periodic inspections and testing performed to assess the impacts of the landfill on its surrounding environment. Environmental monitoring for landfills is conveniently divided into the following four categories:

1. erosion and sedimentation,
2. groundwater quality,
3. surface water quality, and
4. air quality and gas migration.

Some monitoring activities encompass more than one of the above categories. For example, examination of the landfill cover for seeps of leachate applies to both Items 2 and 3 above.

10.5.1 Erosion and Sedimentation

At any time during the life of the landfill, large areas of disturbed land likely will be exposed to the elements. Thus, the potential exists for substantial problems associated with erosion and sediment deposition if proper control measures are not applied. Even after closure, erosion and sedimentation control will be a long-term maintenance requirement.

Environmental monitoring should include periodic inspection of the landfill surface and drainage systems for indications of excessive erosion or sediment deposition. Sediment that has become deposited in channels should be removed promptly. Downstream sediment basins or traps will need to be cleaned out from time to time to maintain their designed level of performance. Natural waterways that receive runoff from the landfill site should be monitored frequently and after each major storm event for any signs of sediment deposition from the landfill. Measures to restore affected water bodies or wetlands to their natural conditions should be undertaken as appropriate to the situation.

10.5.2 Groundwater Quality

Groundwater quality monitoring serves two purposes: 1) to demonstrate that the landfill is not causing significant degradation of groundwater; or 2) if groundwater quality has been degraded, to evaluate the character, magnitude, and extent of contamination of the groundwater resource [11,12]. Groundwater quality monitoring is particularly necessary when the location of the landfill is within 1,500 to 3,000 m horizontally of any groundwater source downgradient that is a potable water source for human consumption or is within 10 to 20 m vertically of such a source.

Normally, groundwater monitoring wells are installed at a landfill site at the time of hydrogeologic evaluations. Additional wells may be drilled at the time of landfill construction or during the active life of the facility. Wells should be installed upgradient (background water quality) and downgradient from the landfill. The wells may be constructed within the overburden or extend down into bedrock (Figure 10-6). They may also be screened at different depths, depending on the stratigraphy. The type, number, placement, and depth of monitoring wells will depend on the particular geology and the size of the site, and should be established as part of an overall groundwater monitoring plan developed by a qualified professional [13].

Groundwater quality sampling and testing should be performed at intervals throughout the year. Sampling times should be adjusted so as to account for possible variations in water quality related to seasonal fluctuations in the water table. The following water quality parameters are common indicators of possible contamination by landfill leachate. It is recommended that groundwater samples be collected and analyzed for these constituents at least twice per year.

- pH*
- specific conductance*
- alkalinity
- biological oxygen demand
- chemical oxygen demand
- chloride
- manganese
- nitrate/nitrite nitrogen
- total Kjeldahl nitrogen
- iron
- sodium
- sulfate

* measurements by portable field instruments

Analyses for the following parameters are more costly to perform but should be considered for inclusion in the groundwater testing program at less frequent intervals as circumstances allow:

- arsenic
- barium
- cadmium
- chromium
- mercury
- lead
- selenium
- total phenols
- volatile organic compounds

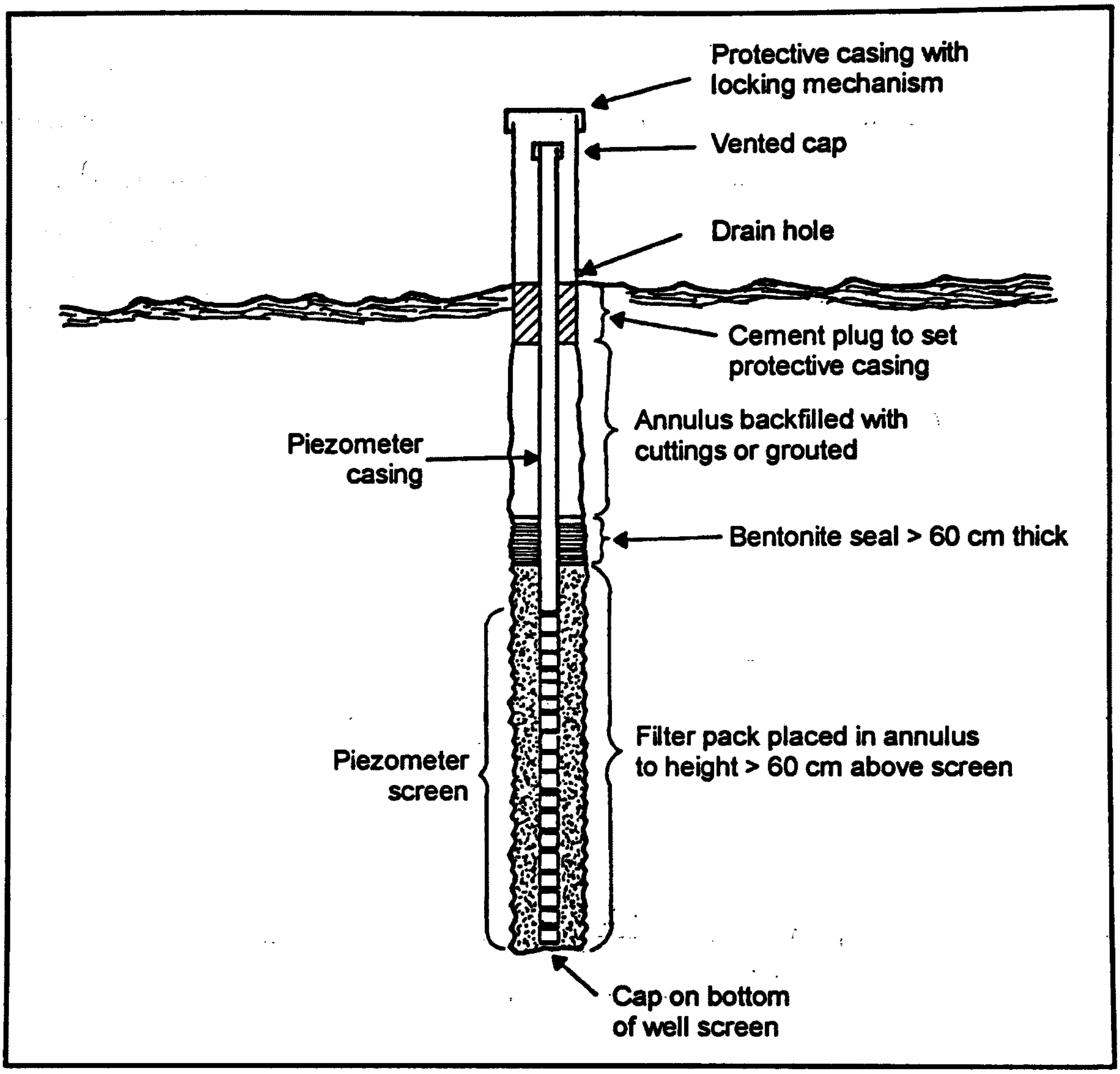

Figure 10-6. Example of a Groundwater Monitoring Well

A more comprehensive testing program would be indicated for landfills receiving highly toxic wastes in low quantities or receiving substantial quantities of hazardous wastes. Analytical parameters should be selected on the basis of the chemical characteristics of the accepted wastes.

10.5.3 Surface Water Quality

Downgradient surface waters should routinely be inspected for visible signs of environmental degradation. In addition to sediment deposition, as previously discussed, evidence of degradation may include such obvious signs as dead or unhealthy flora and fauna, visible leachate pools or streams, unnatural water clarity or color, and unusual odors. Besides making frequent visual inspections, the surface waters should be checked whenever groundwater monitoring wells are sampled. During those sampling rounds, field measurements at representative surface water locations should be taken for the following parameters:

- pH
- specific conductance
- biological oxygen demand
- total Kjeldahl nitrogen

Surface water samples should be collected from any location that shows obvious degradation for which the landfill is believed to be the probable cause. Samples should be collected both upstream and downstream of suspected sources of contamination. If a tributary stream is a suspected source, it too should be sampled.

To a large degree, the sampling points and analytical parameters appropriate to a specific situation will be based on past experience, professional judgement, and common sense. For example, contaminants known to be present in groundwater may be contributing to surface water degradation near the site. In the absence of any specific data, the first tier of water quality parameters listed in Section 10.5.2. may serve as a reasonable starting point for analyzing surface water samples. Based on those findings and on the results of concurrent groundwater quality testing, the list of analytical parameters might be expanded to include those in the second tier. Over time, it may be possible to effectively monitor water quality by selecting a smaller number of "indicator" parameters for most samplings as a way to minimize analytical costs.

10.5.4 Air Quality and Gas Migration

Since most economically developing countries lack specific air quality regulations and allowable emissions levels for land disposal facilities, the measurement of air quality at landfills would not be a normal practice. However, two aspects of air quality and emissions, namely, odors and gas (methane) migration, are issues relevant to all landfill sites regardless of the state of regulatory development, and require monitoring as part of modem landfill practice. For the most part, odors should be monitored through the awareness of landfill workers and by attending to the complaints of neighboring property owners and other populations. If odors should become a continuous problem for the affected parties, then the problem should be resolved by implementation of appropriate adjustments to landfill operating methods. (In the extreme case, odors may be controllable only by means of an active gas collection and treatment system.)

Landfill gas migration, on the other hand, requires that specific procedures be established for its assessment. The need for gas migration monitoring derives from its flammability and explosive potential (see Chapter 14 for further discussion of landfill gas). The purpose of monitoring gas migration is to ensure that landfill gas does not migrate to and accumulate in on-site structures or to off-site locations in concentrations that are a hazard to humans or property. In the United States, federal rules have been established that require landfill gas concentrations to be no greater than the following limits:

- 100% of the lower explosive limit (LEL) at the property boundary of the landfill facility, and
- 25% of the LEL in any structure within the landfill facility.

These limits also serve as functional guidelines for an economically developing country. The LEL is equivalent to a concentration of 5% methane in air, and the 5% figure is used in the two gas migration requirements listed above. LEL is measured by means of a field-portable combustible gas indicator.

To monitor and assess off-site gas migration, monitoring probes (Figure 10-7) usually are installed along the site boundary at various intervals. Spacing between probes will depend on the particular circumstances of the site. Where migration is of substantial concern to abutting properties, a maximum distance of 100 m between probes would be a reasonable guideline in most cases. Along site boundaries where there is little potential or negligible risk of gas migration, probes may be omitted. Gas migration probes typically are constructed to a depth that is equal to the highest water table elevation or to the bottom elevation of the landfill, whichever is higher, or to the most permeable soils above the water table.

Structures on or near the landfill are vulnerable to the accumulation of landfill gas. Routine monitoring for landfill gas is necessary to ascertain that gas is not seeping into these locations. The operator should bear in mind that landfill gas tends to follow the path of least resistance underground. Experience and measurements have shown that landfill gas can travel considerable distances from the source. In addition to the obvious landfill structures that may be affected, the following can serve as either conduits or collection points for landfill gas:

- gravel-filled or stone-filled underground trenches (e.g., subdrains);
- underground pipelines or utility lines;
- underground manholes, vaults, or basement structures; and
- highly permeable soil strata.

Before entering any underground or confined space in the vicinity of the landfill, the space should be tested for gas concentration with a combustible gas indicator. Human entry should be forbidden at any level above 10% of the LEL.

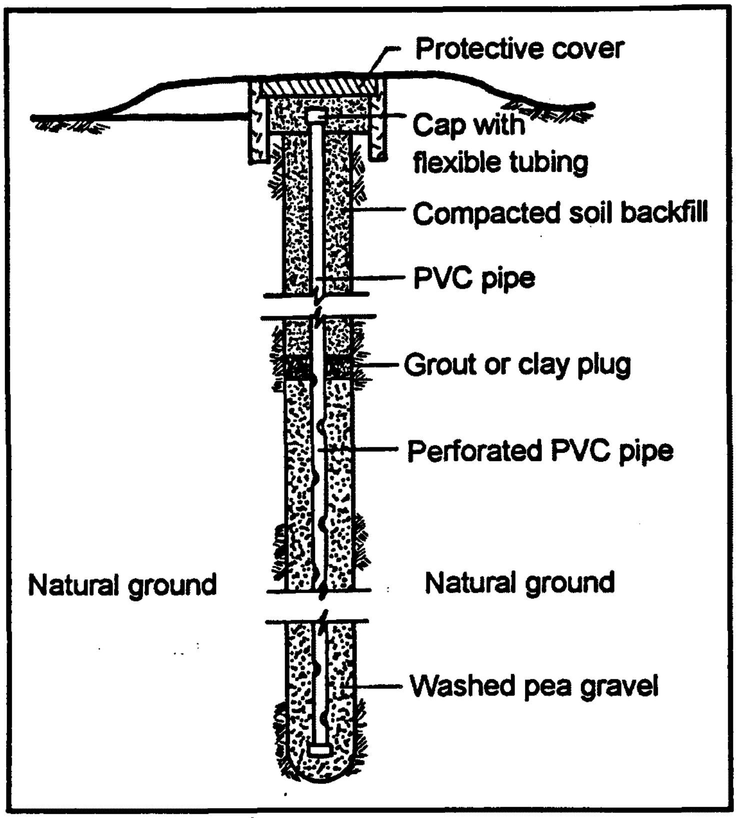

Figure 10-7. Typical Single-Screen Gas Monitoring Probe (not to scale)

With regard to both landfill structures and monitoring probes, monitoring for gas should be performed on a regular schedule -- for example, once every three months. Gas readings (% LEL) are taken by inserting the instrument sensor into the monitor probe casing. At structures, readings should be taken in below-grade and above-grade interior spaces, around the outside of foundations at ground level, and in any cracks or holes in the foundations or floors. Measurements at off-site structures close to the landfill are also recommended, especially if they are inhabited or have basements, where the gas accumulates preferentially. Off-site measurements of gas concentrations may also be prudent if stress or damage to vegetation off-site is visually apparent. Thus, off-site visual reconnaissance should be used as a monitoring tool. Any readings of gas concentrations that exceed the above-referenced guidelines indicate the need for increased vigilance and monitoring and possible corrective actions, or even evacuation of the building(s).

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Chapter 11

Landfill Processes

11.1 Introduction

In this chapter are discussed the key processes that take place within the volume of the landfill that contains solid wastes. The processes that take place within the landfill environment can be characterized by considering three general aspects: 1) the quantity, composition, and characteristics of the disposed wastes; 2) fill design and operation; and 3) the phenomena associated with physical, chemical, and biological processes that occur within the buried wastes. The performance (i.e., consequences) of operating and maintaining the fill are the manifestations of the aforementioned processes.

The three aspects are closely interrelated with respect to their impacts on the completed fill. For example, the quantity and composition of the wastes determine the quantities and characteristics of products associated with physical, chemical, and biological processes, which in turn are influenced by fill design and conduct of the fill operation. Moreover, they also determine the extent and the course of the physical and biochemical processes. Because of this interrelationship, all three are discussed under the single heading, "Key Processes."

One manifestation of the result of these processes in the landfill is the decomposition of the wastes. Decomposition is the breakdown of a material into simpler, or less complex, chemical units. Physical breakdown of material also occurs in the landfill.

The division of the key processes into physical, biological, and chemical categories is somewhat arbitrary, particularly since the processes themselves do not lend themselves to exact definitions and because synergies among the processes occur in the landfill. However, the division allows some degree of organization of this complex topic that could not otherwise be achieved if the processes were simply listed in an arbitrary order and described.

11.2 Key Processes

After waste is placed in a landfill, a number of processes occur. The processes, to one degree or another, are influenced by certain external conditions along the boundary of the fill. The external conditions include, but are not limited to, such factors as amount and rate of rainfall and the permeability of the cover/waste interface to water penetration. For practical purposes, three processes dominate within a landfill. These processes can be described generically as physical, chemical, and biological. The processes do not act independently of one another, and during the life of a landfill the relative domination of each process may vary as a function of time and as a function of position in the fill. Of the three generic types of processes occurring in a landfill, the biological processes are the most significant. However, the biological processes are strongly influenced by the physical and chemical processes. At the same time, the physical and chemical processes also are influential on the biological processes.

11.2.1 Physical

Generally, the most significant physical processes occurring in the fill are: compression (compaction), dissolution, sorption, and particle size reduction. In the occurrence of a strictly physical process, no change in chemical composition occurs.

Compression and settlement of the fill are closely related processes; thus, they are described jointly. In like manner, dissolution and transport are closely associated mechanisms, but not to the same degree as compression and settlement. All areas within the fill experience the four processes.

Compression of waste at the disposal site is an ongoing process that begins with compaction (and size reduction) of the waste by machinery used to crush (i.e., compact) the wastes during the daily fill activities and continues after the wastes are in place. The continuing compression is a consequence of the degradation of the wastes and is a result of the force exerted by the weight of the overlying burden of wastes and the soil cover. Loss of mechanical strength of some of the waste materials in the fill, as a consequence of chemical and biological reactions, results in some size reduction of the wastes due to the internal compressive forces. Settlement of soil particles and other fines among the larger particles of waste due to the gravitational force is also responsible for some consolidation. Settling (defined as the decrease in volume containing a given mass of material) of the completed fill is an end result of compression. This settling is in addition to the settlement brought about by other reactions (e.g., the loss of mass due to chemical and biological decomposition).

Absorption is also a physical phenomenon that takes place in a landfill. The primary consequences of absorption are: 1) the bulk retention and immobilization of dissolved pollutants by preventing water from transporting them and suspended pollutant particulates outside the boundary of the fill, and 2) softening and subsequent loss of strength of the biodegradable organic materials. Absorption is the process whereby substances are taken in by capillary attraction. The absorption potential of a fill is closely related to its fiber content. In industrialized countries, most of the absorption potential of landfilled municipal waste is derived from its paper content. Only minor absorption takes place on other types of fibers (e.g., cotton and wool). The reason is that their concentrations in waste disposed in industrial countries are relatively small.

In economically developing countries, the circumstances may be significantly different. For example, the concentrations of paper and other types of fiber usually are small and, therefore, absorption due to fibers typically is minor in extent. In addition to low concentrations of fiber, much of the fiber may already be saturated or nearly saturated since the solid wastes in many developing areas contain high concentrations of wet, putrescible matter. However, exceptions to these circumstances exist. For example, certain crop residues (especially dry residues) may provide some absorption potential, and some island communities can have high percentages of paper packaging in their waste streams as a result of their dependence on imported commodities.

Finally, it should be recognized that in many cases, eventually all absorbent materials in a fill become saturated. Consequently, absorption may only function as a delaying action with regard to the release of pollutants.

The absorption of gas in water also is an absorption phenomenon that occurs within the environment of the landfill. For example, CO_2 (a major component of landfill gas) dissolves in water within the landfill environment.

Reduction of particle size occurs as a consequence of some landfill processes. For instance, compaction equipment reduces the particle size of waste components such as glass containers and paper packaging when they are first placed in the fill. Once the wastes are within the fill, microbial attack breaks down the compressive and tensile strength of many of the organic components -- thus, resulting in their breakup. At the same time, the shifting of the particle size distributions of the materials to finer sizes promotes the chemical and biological reactions that occur in the fill. The rates of the reactions are promoted because they usually are strong functions of the available surface area of the substrate (in this case, waste materials in the fill) and, therefore, of particle size.

11.2.2 Chemical

Two major types of chemical reactions occur in a landfill: oxidation/reduction reactions and pH dependent reactions. The pH dependent reactions are a consequence of the presence of organic acids and carbon dioxide (CO_2) produced or synthesized by the biological processes and dissolved in water (H_2O). The pH dependent reactions include those that affect the microscopic surface characteristics of materials, such as adsorption, and those that affect the solubility of chemical compounds. The extent of the oxidation/reduction reactions in a fill is controlled by the level of oxygen in the fill; initially, the oxygen is incorporated into the fill when it is constructed. Ferrous metals are particularly susceptible to the oxidation/reduction reaction.

Reactions involving organic acids and dissolved CO_2 are typical acid-metal reactions. Products of these reactions primarily are the metallic ions and salts in the leachate within the fill. The presence of the organic acids leads to the dissolution and mobilization of substantial quantities of waste materials in the fill and, consequently, to potential sources of pollution. The dissolution of CO_2 in water lowers the pH, rendering many metals soluble, but especially calcium and magnesium. Carbonates and metal ionic matter are characteristically found in leachate.

The amount of water that enters a fill has a very important bearing on the reactions occurring in the fill. Water acts as a medium for the solution of soluble substances and for the transport of unreacted materials. These unreacted materials consist of living and non-living particulates. Particulate sizes range from colloidal to several millimeters. The solubility of many chemical compounds is a strong function of pH.

In a typical fill, the broad variety of components and particle sizes of the wastes provide conditions that lead to an extensive amount of adsorption. Of all the physical phenomena that take place in a fill, adsorption is one of the more important ones because it brings about the immobilization of many living and non-living substances that could pose a problem if allowed to reach the environment external to the landfill. Adsorption is the adhesion of molecules to a surface. Adsorption can play an important role in the containment of viruses and pathogens and of some chemical compounds. However, adsorption has its limitations. One significant limitation is its lack of longevity. A number of factors can alter the longevity of adsorption sites. For example, the properties of the sites can be altered by the effects of biological and chemical decomposition.

Chemical reactions, as well as chemical characteristics of some of the materials in the landfill, can have a negative effect on the environment. This is particularly the case in disposal sites in economically developing countries which do not have adequate controls of inputs and allow the final disposition of different pollutants such as insecticides, herbicides, caustic materials, and others. The by-products of reactions usually can be found in monitoring wells.

Some important compounds that can be used as indicators of potential migration of pollutants from the landfill are nitrates (NO_3), volatile fatty acids (VFAs), and ammonium ions (NH^{3+}). Of the three indicators, the latter two are better and preferred in comparison to monitoring of nitrates. The ammonium ion is found at relatively high levels in the breakdown of products of organic materials. Ammonium ions are particularly troublesome because generally they are very mobile in a moist subsurface system. The application of NH^{3+} as an indicator of possible pollution would be valid provided that other possible sources of ammonium ions, such as fertilizers, are not located in the vicinity [1].

Other indicators of off-site migration of chemical species and pollutants are elevated levels of Ca, Mg, Cl, specific conductance, total organic carbon, and BOD and COD in monitoring wells or surface waters. Local circumstances and conditions generally govern and dictate which indicators are the more appropriate for monitoring purposes.

11.2.3 Biological

The biological reactions in a fill are important for two reasons. One reason is that the biodegradable organic materials contained in the wastes are rendered biologically stable and, therefore, no longer constitute a potential source of pollution. The major types of biodegradable organic solid wastes include food waste, vegetative wastes, paper and paper products, and "natural fibers" (fibrous material of plant or animal origin).

The second reason of importance is the conversion of a sizeable portion of the carbonaceous and proteinaceous solids into gas; thereby substantially reducing the mass and, therefore, the volume of the biodegradable organic solid wastes.

Only a small fraction of the nutrient elements in the waste is converted into microbial protoplasm. Eventually, as portions of the microbial population die, this protoplasm will be subject to decomposition and, hence, will make up a reservoir of material for breakdown in the future.

In general, biological decomposition can take place under aerobic or anaerobic conditions. Since wastes are placed and rest in the fill over a substantial period of time, the environment within the landfill system is a dynamic one. For a particular location within the fill (i.e., with reference to the initial volume containing a particular mass of wastes), the aerobic reactions precede the anaerobic reactions. Although both phases are important, anaerobic decomposition exerts the greater and longer-lasting influence in terms of associated characteristics of the fill. A typical time-history of the aerobic and anaerobic processes in a landfill is illustrated in Figure 11-1.

The primary form of decomposition immediately after the wastes are buried is aerobic. This period of time is called the "aerobic phase." The decomposition continues to be aerobic until all of the oxygen (O_2) in the air entrapped in the fill is depleted and all dissolved oxygen in intruding precipitation has been utilized. The by-products of the aerobic reaction are heat and CO_2, H_2O, and inorganic material if sufficient oxygen is available for the reaction to proceed to completion. In practice, the duration of the aerobic phase is relatively brief and depends upon the design and operating conditions of the fill, including the degree of compaction of the wastes and the moisture content (moisture displaces air from the interstitial spaces among particles of waste). Microbes active during this phase include obligate, as well as some

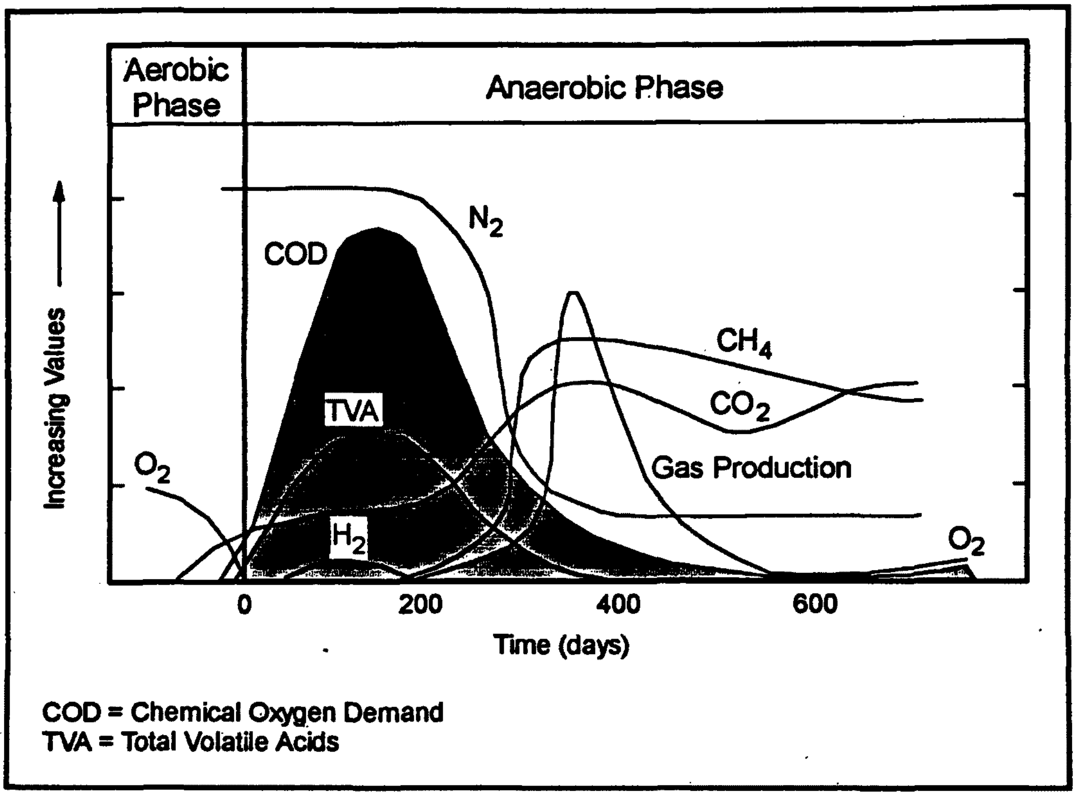

Figure 11-1. Characteristics of Chemical and Biological Processes Occurring in a Landfill

facultative, aerobes. During the aerobic phase, temperatures in the interior of the fill can be as high as 45 to 55°C.

Adverse environmental impacts during the aerobic phase are minimal because the ultimate end-products of biological aerobic decomposition are inert inorganic solids, CO_2, and H_2O. Although intermediate breakdown products may be released during the aerobic phase, typically their amounts and relative contribution to pollution are small.

As previously indicated, the amount of oxygen buried with the wastes is depleted relatively rapidly. Consequently, most of the biodegradable organic matter in a landfill eventually is exposed to anaerobic biological processes. Microorganisms responsible for anaerobic decomposition include both facultative and obligate anaerobes. Among other features, a noticeable distinction between the aerobic phase and the anaerobic phase is the absence of any significant generation of heat in the latter phase. Consequently, the temperature or the rise in temperature in the landfilled wastes gradually drops from the high temperatures or heat generation rates, respectively, that are characteristic of the aerobic phase to those that approach that of the ambient during the course of the anaerobic phase.

The by-products of anaerobic decomposition can exert a considerably adverse effect on the environment unless they are properly controlled. Two groups of by-products can be defined: 1) volatile organic acids, and 2) gases. Most of the organic acids are short-chain fatty-acids and characteristically are malodorous. They form a portion of the intermediate products (others are H_2 and CO_2) produced during the first phase (commonly termed the acid forming stage) of the anaerobic process. Examples of organic acids are formic, acetic, propionic, and isovaleric acids. Because of the presence of the acids, the pH of the local environment is low (acidic) and the liquid (leachate) is chemically aggressive. The result is high strength leachate, both in terms of concentrations of ions and organics. In addition to serving in chemical reactions with other components, the acids serve as substrates for methane-producing microorganisms. The second phase (methanogenic) of the anaerobic process is characterized by conversion of the fatty acids and H_2, produced in the acid forming stage, to CO_2 and CH_4. The environment of this phase is characterized by a neutral pH and a leachate that is less aggressive than that of the acid-forming phase.

The two principal gases formed during the anaerobic process are methane (CH_4) and carbon dioxide (CO_2). Hydrogen sulfide (H_2S), hydrogen (H_2), and nitrogen (N_2) usually are present in trace or minor concentrations.

The environmental factors that affect all biological activities substantially influence the processes, rate, and extent of biological decomposition in a fill. The processes of biological decomposition determine the nature of the decomposition products. The rate of decomposition governs a number of activities, including the length of time during which the completed fill must be monitored for possible emissions of pollutants and the time period that must pass before the completed fill can be used. This situation exists regardless of the eventual end use, whether for recreation, agriculture, or other purposes.

One important effect of decomposition on the use of the completed fill is its influence on the rate and amount of settlement (i.e., reduction in elevation of the landfill surface). Settlement usually is a major constraint on the use of the completed fill. Settling continues until the process of biological decomposition is completed. Obviously, any enhancement of the rate of decomposition will render the site fit for use sooner than can be achieved if the processes are left to their normal (i.e., uncontrolled) rate of reaction. Equally obvious is the fact that the use of landfill property prior to biological stabilization can be a risky and potentially dangerous undertaking.

The principal factors that affect biological decomposition in a modern landfill are moisture, temperature, the microbial nutrient content, and degree of resistance of the waste to microbial attack. Of the above factors and considering the majority of landfill environments and operating practices, moisture is the most important variable with respect to rate and degree of decomposition that will occur in a fill. Under anaerobic conditions, the higher the moisture content of the waste, the more active are the biological processes. When the moisture content of biologically degradable wastes is less than approximately 20%, anaerobic activity is substantially reduced. Therefore, anaerobic decomposition can be expected to proceed very slowly in the case of modern landfills (where water intrusion is substantially controlled and curtailed) and the wastes are relatively dry or in the case of disposal sites situated in arid regions that accept wastes having low concentrations of wet wastes (e.g., biosolids, food preparation wastes, and green vegetative wastes).

Microbial activity increases with a rise in temperature until a level of about 40°C is reached if other conditions are not limiting. For some types of microbes, the upper temperature impeding activity is on the order of 55 to 65°C. The former type of microorganisms are termed "mesophiles," and the latter type are termed "thermophiles." Some mesophiles are high temperature tolerant (facultative thermophiles), and some thermophiles are tolerant of temperatures in the mesophilic range (facultative mesophiles). Because temperatures in tropical regions are more favorable (as are the conditions of moisture in the humid tropics), decomposition proceeds very rapidly and to a greater extent than in other regions of the world.

Nutrients play an important role in the processes of decomposition. Wastes that possess a high percentage of readily putrescible organic matter approach the ideal in terms of supplying the levels of nutrients required to optimize the process of decomposition of the substrate. Among the wastes that fall into such a category are green crop debris, food preparation waste, market wastes, and animal and human manures. A noteworthy point is that such a combination of ideal decomposition factors oftentimes exists in economically developing countries which are in humid tropical regions of the world.

11.3 In-Place Density

Some of the more important factors that determine or influence in-place density (i.e., density after the wastes have been deposited in the fill) include:

- initial composition and characteristics of the wastes, including moisture content;
- fill design and operating conditions, especially those conditions that determine the initial in-place density of the wastes (type of compacting equipment, number of passes) and the extent of moisture in the fill;
- the processes of decomposition and their end-products;

- weight of cover material; and
- settlement of the entire mass.

Settlement of the mass occurs over the course of time as a consequence of a progressive increase in density brought about by several phenomena acting in parallel. The phenomena include the consolidation of landfill components, the pressure exerted by the overlying weight of the wastes and cover material, and the decomposition of the wastes.

The in-place density of municipal solid wastes in a properly constructed and operated, and relatively deep, landfill in industrialized countries can be on the order of 900 kg/m^3. On the other hand, the in-place density of waste in a poorly compacted fill might be only about 300 kg/m^3. In the United States, the usual range of density directly after compaction is on the order of about 475 to 710 kg/m^3 [2]. On the other hand, the in-place density of wastes landfilled in countries in the Latin American region has been found to be on the order of 860 kg/m^3 (wet basis), due primarily to the relatively high moisture content of the waste and its effect on the realized levels of compaction and settlement [3].

11.4 Settlement

The settlement of the wastes in a landfill is manifested by a decrease over time in the height of the affected mass and subsequent reduction in elevation of the surface of the fill. The rate and magnitude of settling is not uniform as a function of time nor of location within the fill. The lack of uniformity may be a serious constraint on the use of the completed fill. Generally, the larger the concentration of organic wastes placed in the fill and the deeper the fill, the greater will be the magnitude of the settling. If the degree of compaction and type of waste are similar, the rate of settling depends primarily on the rate of decomposition of the wastes and, hence, upon the factors that influence decomposition.

Natural variations in the above factors and wide differences between operational procedures encountered in landfill practice similarly yield wide variations among reported rates and the magnitude of settlement. The total settlement of a completed volume of fill in an industrialized country over its lifespan usually is within a range of 1 to 20%, with the value falling within 10 to 15% in the majority of cases. Of the total settling, usually about 90% takes place during the first year [2]. Some sites have reported that the rate of settlement was greatest during the first month after completion, and was small and relatively uniform after the third month.

Regarding the influence of climatic conditions, one study of a 6 m deep fill in a region of moderate rainfall (>11 cm/yr) and moderate temperature, reported settling of about 20% after the first year of completion. In comparison, a 23 m deep landfill and a 14 m deep fill in an arid region (<6 cm/yr of rain) and somewhat warmer temperature, experienced settling of only about 3% by the third year after completion [2].

In "Settlement of Landfill," A.C. Cheney [4] states that no physical settlement will occur if the initial density exceeds 1,060 kg/m^3; nevertheless, a theoretical settlement of 40% is possible due to waste decomposition processes. According to the same reference, overall annual rates of settling of 0.5 to 4.7% have been measured in practice in the case of fills having original in-place densities of 650 to 1,200 kg/m^3.

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Chapter 12

Leachate Formation and the Water Balance

The quantity of leachate that could be generated in a landfill can be predicted by performing a water balance. A water balance involves an accounting of liquid flows into and out of the landfill system, and of liquid stored within the system. The major component of the liquid phase in landfills is, of course, water. In most landfills, the significant inflows are precipitation and water contained in the delivered waste, and the significant outflow is leachate. Under some special circumstances, water produced during the decomposition of waste and water lost as water vapor may be of significance to the water balance. Such circumstances can include the case of a landfill located in a desert location. Initially, for a new volume of landfilled waste, some of the water inflow (from percolation into the fill) will be absorbed by the waste. However, in the long run, the rate of leachate produced by a landfill becomes essentially equal to the rate of infiltration of precipitation.

As discussed in Section 6.3, the water balance around a landfill system is also relevant to the classification and selection of potential sites for landfill development.

12.1 Water Balance

All of the various components of a water balance for a landfill are presented in Figure 12-1. As shown in the figure, the sources of water are: water entering the fill through the cover, moisture in the cover material, and inherent moisture in the solid waste. As a consequence of the processes of decomposition that occur in a landfill, a certain amount of moisture is converted to the gaseous constituents of the landfill gas (i.e., CH_4 and CO_2). In addition, water also leaves the landfill in the form of saturated water vapor in the landfill gas. The remainder of the water becomes leachate. Each one of these primary sources of water is discussed in the following sections.

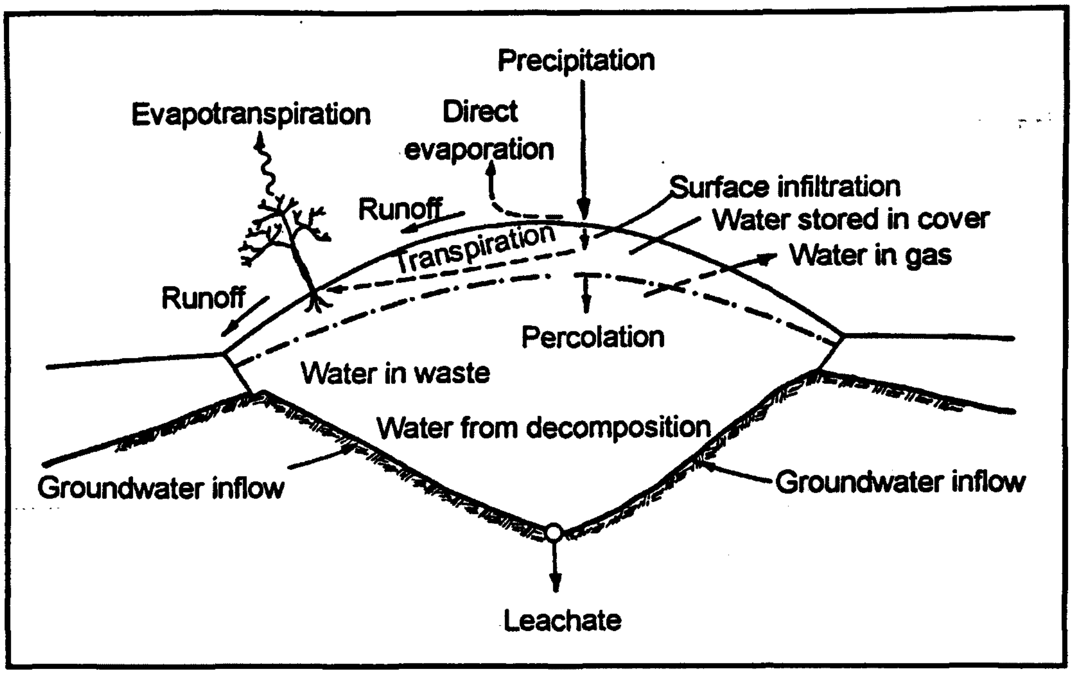

Figure 12-1. Various Components of a Water Balance for a Landfill

12.1.1 Water Entering Through the Cover

This component of the water balance consists primarily of rainfall that percolates through the cover (strictly speaking, there may be other sources of surface water such as storm water runoff and artesian springs). One of the most important steps in the performance of a water balance in a landfill is the prediction of the quantity of rainfall that actually penetrates the landfill cover. In developing countries, where the refuse rarely is covered, the major portion of the precipitation would enter the fill. Flow in a vertical percolation layer either is downward (due to gravity drainage) or removed (via evapotranspiration). Some computer models have been developed to predict the amount of water that percolates through the landfill cover. A computer model widely used in the United States is called the Hydrologic Evaluation of Landfill Performance (HELP) [1]. Following is another approach that can be used to obtain an approximation of the quantity of percolation that can be expected in a landfill by means of a conventional hydrological water balance.

$$\delta MC = P-RO-ET-PER$$

where:

δMC = change in the amount of moisture stored in a unit volume of landfill cover (cm),

P = quantity of net precipitation (incident precipitation less runoff) per unit area (cm),

RO = quantity of runoff per unit area (cm),

ET = quantity of moisture lost through evapotranspiration per unit area (cm), and

PER = quantity of water which percolates through the cover per unit area of soil cover (cm).

The total amount of moisture that can be stored in a unit volume of soil is a function of two variables -- the field capacity (FC) and the permanent wilting percentage (PWP). The FC is defined as the maximum quantity of liquid which remains in the pore space under gravitational force. The PWP is defined as the quantity of water that remains in a soil after plants are no longer capable of extracting anymore water. Basically, the difference between the field capacity and the permanent wilting percentage is equivalent to the quantity of moisture that can be stored in a particular type of soil. Runoff coefficients, given as a function of rainfall for different types of soils with and without a vegetative cover, are presented in Table 12-1.

Other information required, such as rainfall and evapotranspiration, are site-specific and generally can be obtained through local or national weather institutions.

12.1.2 Water Present in the Solid Waste

Moisture that enters the landfill with the residues is that water inherent in the waste, as well as that moisture which has been absorbed from other sources (e.g., rainfall). Depending upon climatic conditions, as well as the type and quality of the containers used to store waste for collection, the inherent moisture and the moisture from other sources have a range of values.

Table 12-1. Runoff Coefficients for Different Soil Cover Materials and Different Vegetation Types

		Soil Texture		
Soil Cover	**Slope (%)**	**Sandy Loam**	**Loamy Clay**	**Clay**
Grassed Soil	0 to 5	0.10	0.30	0.40
	5 to 10	0.16	0.36	0.55
	10 to 30	0.22	0.42	0.60
Bare Soil		0.30	0.50	0.60
		0.40	0.60	0.70
		0.52	0.72	0.82

Source: Reference 2.

The moisture content of municipal solid waste commonly ranges from 30 to 60% (wet-weight basis), depending upon the location and season.

12.1.3 Water in the Cover Material

The quantity of water that enters with the cover material depends upon the type and source of the cover material, as well as the time of the year and climatic conditions of the particular location. The maximum amount of water that can be contained in the cover material is determined by the field capacity of the material.

12.1.4 Water Utilized in the Formation of Landfill Gas

The decomposition of the organic fraction of the waste utilizes a certain amount of water. The quantity of water used in the process can be estimated using theoretical approximations of the decomposition process.

12.1.5 Water Lost as Water Vapor in Landfill Gas

Landfill gas typically is saturated with water vapor. The quantity of moisture that leaves the landfill in this form may be estimated by using the perfect gas law.

12.1.6 *Water Exiting the Fill*

Water that leaves the landfill is called leachate (the term "leachate" also applies to water within the landfill that is in contact with the waste).

12.1.7 *Field Capacity of a Landfill*

Water which enters the fill, is not used in the biochemical reactions, and does not exit as water vapor with the landfill gas may have either of two fates: 1) the water may be held within the landfill, or 2) the water may become leachate. The materials that compose the cover and the waste in the fill each have their own field capacities which can store moisture and, therefore, keep it from flowing until saturation occurs. The potential quantity of leachate that can be generated in a particular landfill is the amount of moisture in the landfill in excess of the field capacity. The field capacity of a landfill varies as a function of the weight of the overburden. The FC (i.e., the fraction of the water in the waste based on the dry weight of the waste) can be estimated using the following equation [3]:

$$FC = 0.6 - 0.55 \, [W/(10{,}000 + W)]$$

where:

FC = field capacity, and

W = weight of overburden calculated at the middle of the lift (kg).

Given all of the elements in the previous indented sections, the components of the water balance for a landfill can be expressed as follows:

$$\delta MC = W_{sw} + W_c + W_p - W_{lfg} - W_v - W_{evap} + W_{leach}$$

where:

δMC = change in the quantity of moisture stored in the landfill (kg/m^3),

W_{sw} = moisture in the incoming solid waste (kg/m^3),

W_c = water in the cover material placed on the waste (kg/m^3),

W_p = water from precipitation and other outside sources (less runoff) (kg/m^3),

W_{lfg} = water utilized in the formation of landfill gas (kg/m^3),

W_v = water lost as saturated vapor with the landfill gas (kg/m^3),

W_{evap} = moisture lost due to evapotranspiration (kg/m^3), and

W_{leach} = water leaving the (control volume) landfill as leachate (kg/m^3).

The water balance for a landfill during a particular time increment is prepared by adding the mass of water that enters a unit area of a particular layer of the fill to the mass of water of the same layer which remained from the previous time increment and subtracting the mass of water lost from the layer during the present time increment. The result of this analysis is known as the "available moisture" for that particular layer of the landfill at a particular time. In order to ascertain if any leachate will be formed, the available moisture is compared to the field capacity of the fill. Leachate will be formed if the amount of water present (available moisture) exceeds the field capacity of the fill.

12.2 Leachate Migration

In "typical" landfills, leachate migrates to the bottom of the fill. In situations where the landfill is not lined, the leachate will have the tendency to migrate in a generally downward direction through the underlying soils. However, depending upon the type of material surrounding the fill, it is possible that a certain amount of lateral migration of the leachate will take place along the soil-waste interface. One of the major concerns associated with the uncontrolled vertical migration of the leachate is the potential contamination of the groundwater. The rate of migration of the leachate can be estimated by using Darcy's law, as discussed in Chapter 6.

$$Q = KS\Delta H/L$$

where:

Q = flow rate of leachate (liters/yr),

K = hydraulic conductivity (liters/m^2-yr),

S = cross-sectional area of the fill through which the leachate flows (m^2),

$\Delta H/L$ = hydraulic gradient (m/m), and

ΔH = head loss (m).

Typical values for the hydraulic conductivity for various soils are presented in Table 12-2.

Table 12-2. Hydraulic Conductivity (K) for Various Soils[a]

Material	m/day	liters/m^2-yr
Uniform Coarse Sand	4.1×10^2	1.5×10^8
Uniform Medium Sand	1×10^2	3.7×10^7
Clean, Well-graded Sand and Gravel	1×10^2	3.7×10^7
Uniform Fine Sand	4.1×10^0	1.5×10^6
Well-graded Silty Sand and Gravel	4×10^{-1}	1.5×10^5
Silty Sand	9×10^{-2}	3.3×10^4
Uniform Silt	5×10^{-2}	1.8×10^4
Sandy Clay	5×10^{-3}	1.8×10^3
Silty Clay	9×10^{-4}	3.3×10^2
Clay (30 to 50% clay sizes)	9×10^{-5}	3.3×10^1
Colloidal Clay	9×10^{-7}	3×10^{-1}

[a] Adapted from References 2 and 4, and based on laminar flow.

12.3 Characteristics of Leachate

The wastes in the landfill undergo processes of decomposition. During the processes, both organic products and inorganic soluble compounds leach into solution. As is evident from earlier chapters, some leachate characteristics are governed by the environmental conditions in the fill, primarily by the presence or absence of oxygen (air), while other characteristics are relatively independent of the conditions. A summary of the characteristics of leachate from municipal solid wastes is presented in Tables 12-3 and 12-4. The data in the table demonstrate the variability of composition and properties of the leachate. Thus, it is advisable not to depend on "average" values, but to collect actual data on the characteristics of the leachate before a treatment system is designed. The chemical characteristics of leachate depend not only on the composition of the waste, but also on the age of the landfill and the events that took place prior to the collection of the sample. For instance, the biological oxygen demand of the leachate decreases with time. This, of course, is due to the fact that the biodegradable materials in the fill are reaching a state of stability.

Table 12-3. Example of Leachate Characteristics from Municipal Solid Wastes (acid and methanogenic phases)

		Acid Phase		Methanogenic Phase	
Parameter	Units	Average	Range	Average	Range
pH	--	6.1	4.5 to 7.5	8	7.5 to 9
BOD_5	mg/l	13,000	4,000 to 40,000	180	20 to 550
COD	mg/l	22,000	6,000 to 60,000	3,000	500 to 4,500
BOD_5/COD	--	0.58	--	0.06	--
SO_4	mg/l	500	70 to 1,750	80	20 to 600
Ca	mg/l	1,200	10 to 2,500	60	20 to 600
Mg	mg/l	470	50 to 1,150	180	40 to 350
Fe	mg/l	780	20 to 2,100	15	3 to 280
Mn	mg/l	25	0.3 to 65	0.7	0.03 to 45
Zn	mg/l	5	0.1 to 120	0.6	0.03 to 4

Source: Reference 5.

Table 12-4. Example of Leachate Characteristics that are Relatively Independent of Landfill Phase

Parameter	Units	Average	Range
Cl	mg/l	2,100	100 to 5,000
Na	mg/l	1,350	50 to 4,000
K	mg/l	1,100	10 to 2,500
Alkalinity	mg$CaCO_3$/l	6,700	300 to 11,500
NH_4	mgN/l	750	30 to 3,000
org. N	mgN/l	600	10 to 4,250
Total N	mgN/l	1,250	50 to 5,000
NO_3	mgN/l	3	0.1 to 50
NO_2	mgN/l	0.5	0 to 25
Total P	mgP/l	6	0.1 to 30
As	µg/l	160	5 to 1,600
Cd	µg/l	6	0.5 to 140
Co	µg/l	55	4 to 950
Ni	µg/l	200	20 to 2,050
Pb	µg/l	90	8 to 1,020
Cr	µg/l	300	30 to 1,600
Cu	µg/l	80	4 to 1,400
Hg	µg/l	10	0.2 to 50

Source: Reference 5.

References

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Chapter 13

Leachate Collection and Management Systems

13.1 Introduction

The decision to either include or exclude a leachate collection and treatment system in the design of a landfill facility in an economically developing country is a critical one. It is an important decision because if the system is included, it will require a commitment of additional funds not only for the design and construction, but also for the operation and maintenance of the system. On the other hand, if a leachate collection and treatment system is not included, the conditions could be such that the leachate could contaminate the land as well as potential sources of water supply.

Under some conditions, methods of leachate treatment can be relatively simple and inexpensive in comparison to those that use complex liner systems, piping systems, and systems for processing the collected leachate. The conditions include those where the threat to land and water resources and the public safety are low. Under these special sets of conditions, natural soils or even liners of compost may serve as "treatment systems."

The decision regarding the need for control and treatment of leachate and regarding the design of the system required to achieve the necessary degree of control must be based on factual information (including that related to the degree of risk) and in close coordination with knowledgeable professionals.

In general, the implementation of a leachate collection and treatment system involves the following four major steps: 1) identification and selection of the type of liner to be used; 2) preparation of a grading plan for the site, including location of channels and pipelines for the collection and removal of the leachate; 3) design of the facilities for the removal, collection, and storage of the leachate; and 4) selection and design of the leachate management (e.g., treatment) system.

The rate of leachate production can be estimated by conducting a water balance. It is important to design for the maximum estimated inflow rate because this rate has a direct effect on the depth of leachate on the collection system. Typically, maximum inflow rates take place in areas without any final or intermediate covers, such as the active working face and any areas awaiting waste deposition.

13.2 Identification and Selection of Liner

As has been previously indicated, the type of bottom liner to be used for a landfill is a function of a number of factors. Some of these factors include geological conditions of the site, requirements for environmental protection, and availability and cost of the liner material. The location and quality of the groundwater, as well as the requirements for the control of leachate and gas migration, will also have an influence on the final selection.

13.3 Leachate Collection Systems

The primary purpose of the leachate collection facility is to collect, as quickly as possible, leachate from the landfill. The amount of leachate within the landfill must be kept to a minimum because the water pressure can drive leachate through a permeable liner or through imperfections in the liner, and can adversely affect the integrity and properties of the liner. The relative size of the leachate collection facility is a function of climatic conditions, topography of the site, operating procedures, and the quantity of leachate to be expected. Installation of the facility should be made in a manner which is compatible with the contour of the bottom of the landfill and with the liner system. The design must be made such that the leachate collection system functions as an effective drainage unit, and clogging of its components must be prevented at all times.

The drainage system plays an important role in the performance of the leachate collection system. The drainage layer performs two key functions: 1) it provides a path for the leachate to easily and preferentially migrate toward the collection pipes, and 2) it offers protection to the bottom liner from both the solid waste deposited in the first lift and from the heavy equipment. The most appropriate material for use as drainage layer is gravel (preferably rounded and free of roots, vegetation, and construction debris). Coarse sand or a mixture of sand and gravel can also be used, but the trend has been to use more permeable materials. The material should be carefully graded to prevent clogging of the gravels surrounding the collection pipes. Leachate drainage systems may include more than one layer of filters. Clogging between the filter layers can be prevented by installing filter fabrics between them. The efficiency of the leachate collection system is highly dependent upon the hydraulic conductivity of the drainage layer. As the hydraulic conductivity decreases, the rate of removal of the leachate decreases, and thus the liquid accumulates at the bottom of the fill.

There are several types of designs that can be used for the collection and removal of leachate from a landfill. The most common design in the United States and Europe consists of a liner with shallow, sloped (about 3 to 5%), V-shaped troughs, each with a collection pipe located at the inverted apex of the troughs. The troughs and pipes are spaced on centers of 30 to 40 m and sloped about 1% to the sumps on one end. The leachate is collected downgradient and pumped through a sidewall riser. Two other leachate collection system designs are described in the following subsections.

13.3.1 Piped Bottom

As the name implies, the design of the piped bottom leachate collection system involves the placement of clay barriers (or other suitable liner material) and perforated leachate collection pipes at the bottom of the site. As shown in Figure 13-1, the barriers take the shape of a rectangle having a width similar to that of a landfill cell. In industrialized countries, a layer of

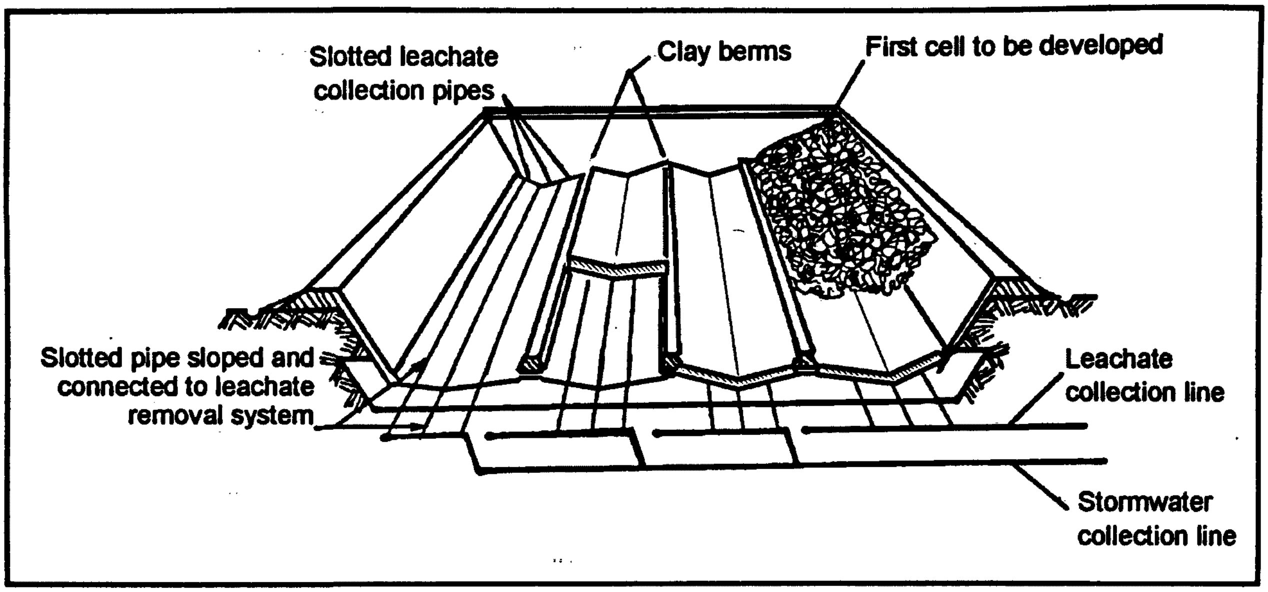

Figure 13-1. Diagram of Piped Bottom Design

geomembrane is placed on the clay, as shown in Figure 13-2. Once the barriers (clay and geomembrane) are in place, a series of slotted leachate collection pipes are placed directly on top of the geomembrane. Typically, the leachate collection pipes are perforated and have a diameter of about 10 cm. In the United States, the slots are cut very precisely (by means of lasers), such that they are about the size of the smallest grain of sand (about 0.00025 cm). The leachate collection pipes are spaced about 10 to 20 m apart and are carefully covered with a layer of sand or gravel (drainage layer). The spacing between the pipes dictates the depth of leachate that will be allowed to accumulate at the bottom of the fill. Generally, the drainage layer is about 60 cm thick and is placed on the pipes well before any waste is deposited on the site. A filter fabric can be used above the drainage layer to prevent clogging. The first layer of waste (about 1 m thick) placed on the drainage layer generally is not compacted. The bottom of the fill is sloped between 1 and 2% to promote flow of the

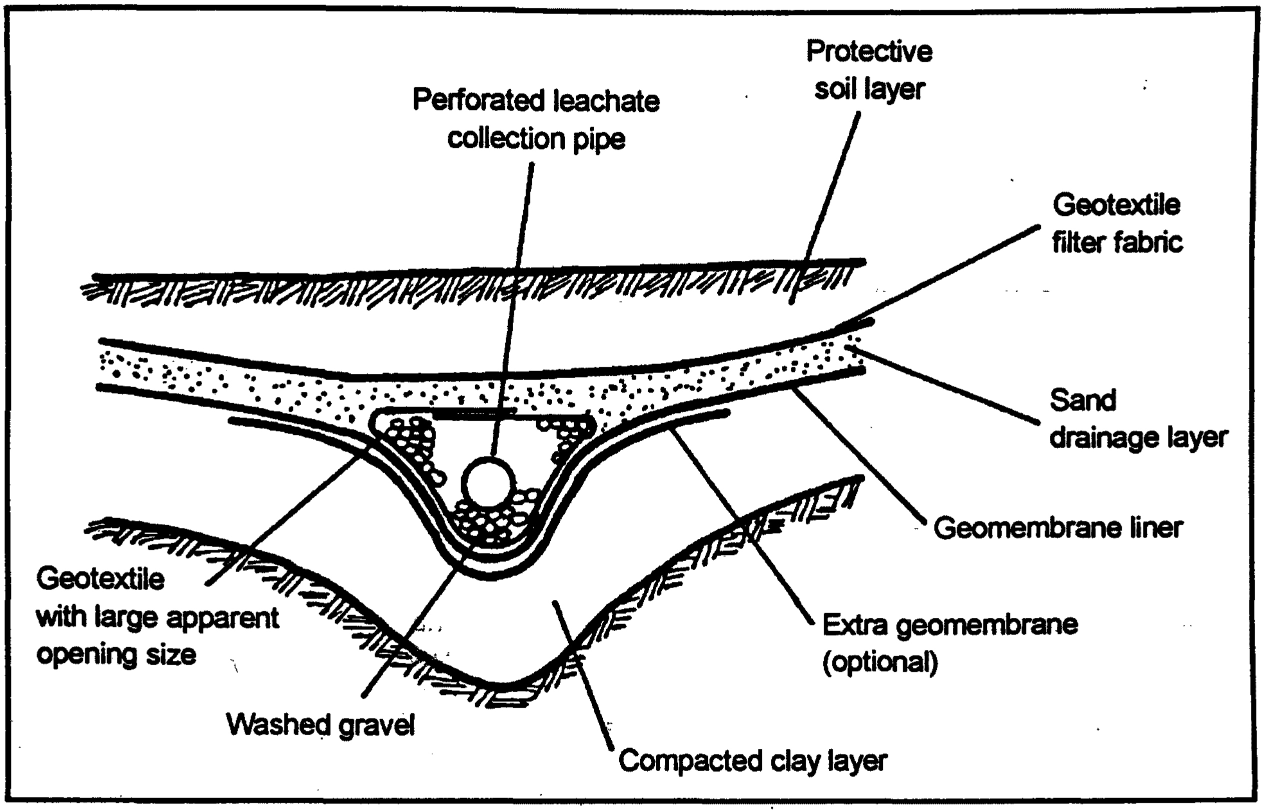

Figure 13-2. Detail of Leachate Collection System

leachate toward the collection points. Leachate collection pipes are installed such that they are drained by gravity.

The piped bottom design also allows for the use of the leachate collection pipes to remove stormwater in the portion of the landfill not receiving waste. In this arrangement, the leachate pipes are connected directly into the stormwater collection pipes. Once the portion of the landfill is put into operation, the pipes simply are disconnected from the stormwater system and joined to the leachate collection system.

13.3.2 Sloped Terraces

In the sloped terrace system, the bottom of the fill is sloped into a series of terraces. The terraces are sloped (between 1 and 5%) such that leachate flows toward collection channels. Each collection channel consists of perforated leachate collection pipes surrounded by washed gravel (about 4 to 5 cm). In order to prevent clogging, the gravel may be enclosed by a protective layer of geotextile filter fabric. The pipes are used to transport the leachate to a collection point for removal or treatment. The drainage channels are sloped between 0.5 and 1.0%. The length of the drainage channel is a function of capacity of the drainage facilities. A diagram of the sloped terrace design is presented in Figure 13-3.

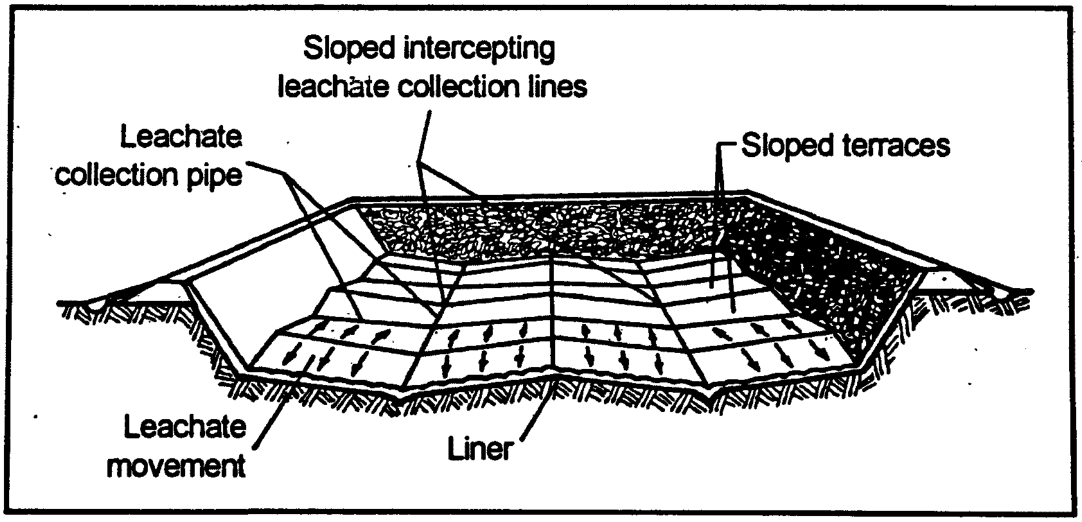

Figure 13-3. Diagram of Sloped Terrace Design

13.4 Leachate Removal and Storage

There are two options for the removal of leachate from a landfill. In the first option, the collection pipe passes through the side of the fill; whereas, in the second option, an inclined collection pipe located inside the fill is used to collect the fluid. In the first option, the piping must be carefully constructed and installed in order to ensure the integrity of the landfill liner system.

Adequate access should be provided to most parts of the leachate collection system in order to allow the inspection of the system and the performance of maintenance. Adequate access includes the installation of cleanouts in order to be able to reach any section of the pipe. Due to landfilling operations, it may not be possible to extend cleanouts vertically within the landfill area. In this situation, cleanouts can be extended laterally on the bottom, toward the perimeter of the landfill, and then along the side slope toward the surface.

Leachate that is collected from a landfill either is stored in a vault, tank, or pond, or drained or pumped directly to a treatment facility. Storage requirements depend upon the size of the fill, quantity of leachate generated, and the ultimate treatment or disposal option planned for the leachate.

Holding tanks are designed to store between 1 and 3 days of leachate during peak production. Both metallic and plastic tanks have been used for this purpose, although plastic tanks are more corrosion resistant than untreated metallic tanks.

13.5 Management Alternatives

The method of managing the leachate formed in a landfill will dictate the risk associated with polluting underground aquifers. There are several alternatives for the management of the leachate. Some of the alternatives that are used include: 1) discharge to an off-site wastewater treatment system, 2) evaporation (natural or induced), 3) recirculation or recycling, and 4) on-site treatment.

13.5.1 Discharge to an Off-Site Wastewater Treatment System

In the event that the landfill is located relatively close to a conventional wastewater treatment facility, it may be possible to discharge the leachate into the piping system for treatment at the plant. Before this is attempted, however, it is important to ascertain that the treatment plant would be capable of accommodating and treating the quantity and quality of the leachate, e.g., additional organic loading. In some cases, it may be necessary to institute some type of pre-treatment of leachate prior to discharge into the sewer. If a local sewer is not available within a convenient distance from the point of discharge at the landfill, utilization of a tanker truck is an alternative to transport the leachate to the wastewater treatment facility.

13.5.2 Evaporation

This is one of the simplest alternatives for the management of leachate. In this alternative, the leachate is stored in an evaporation pond. (Under ideal circumstances, the pond would be properly lined with an impermeable material or membrane.) The rate of evaporation, of course, is a function of climatic conditions. In the event that there is a season of heavy rainfall, the pond must be designed to retain the associated volume of liquid or, if practicality permits, it may be covered with an impermeable membrane. The rate of evaporation may be increased by spraying the leachate on the surfaces of both the operating and completed fills. Although spraying increases the evaporation rate, the process brings about the potential for the generation of odors, as well as the generation of aerosols which may contain bacteria.

Evaporation can also be enhanced by heating the leachate by means of a heat exchanger. In the event that there is a system for the collection of landfill gas, the biogas can be used as a source of energy for the evaporation process. Otherwise, another source of energy must be sought. This option can be costly in a developing country without reserves of fossil fuels. In addition, care must be taken in the control of potential emissions of volatile compounds, as well as in the management of corrosion and fouling of the heat transfer surfaces.

13.5.3 Recirculation or Recycling

Leachate can be effectively managed by collecting it and recirculating it through the landfill environment [1]. At the beginning of landfill operations, the leachate typically will contain relatively high concentrations of BOD, COD, total dissolved solids, heavy metals, and nutrients. The recirculation and recycling of the leachate results in a certain amount of attenuation of these constituents due to the biological activity and to the physical and chemical reactions that take place within the landfill. For example, since the pH in the landfill becomes neutral to slightly basic as methane is produced, some of the metals will be precipitated and retained within the landfill.

The design and operation of a leachate recirculation system should take into consideration the fact that recirculation results in a steadily increasing reservoir of leachate if percolation of water into the fill is greater than evaporation of collected leachate. Thus, in locations that have low or insufficient rates of evaporation, buildup of leachate as a consequence of recirculation will be the norm and require the eventual removal and treatment of excess leachate.

In the event that rapid stabilization of the organic matter, as well as the collection and beneficial use the landfill gas, are primary objectives of the operation, leachate recirculation can result in an increase of landfill gas production due to the increase of the moisture availability within the fill. An increase in the rate of stabilization would lead to an increased rate of settlement in the landfill. A sizeable reduction of the COD and BOD can be obtained through recirculation, particularly over the short term. Leachate recirculation is more effective in landfills whose operations involve the application of refuse in relatively thin layers.

Care must be exercised when adopting recirculation as a strategy to manage the leachate. First of all, purposeful introduction of moisture into the landfill may lead to pollution of the surroundings by leachate migration through either the bottom or the sides. Second, continuous recirculation will lead to the buildup of salts, metals, and other undesirable compounds in the leachate. Furthermore, in the event that intermediate covers have been applied, the introduction of leachate may lead to the formation of perched or ponded (accumulated) water within the landfill, which may eventually leak through the sides of the landfill.

Leachate recirculation, including treatment of the leachate, is being actively pursued in Brazil [2].

13.5.4 On-Site Treatment

If none of the alternatives presented in the preceding paragraphs are viable, then some type of treatment will be necessary in order to properly manage the leachate. Just as the composition of the waste deposited in the landfill can vary substantially from municipality to municipality, the leachate produced in landfills can also have widely varying characteristics. Unlike wastewater, the quality and quantity of the leachate may undergo substantial variations as the climate changes. In addition, as the degradation of the contents of the landfill takes place over time, the quality of the leachate will also change.

Several types of designs have been used to treat leachate. Some of the processes include biological, physical, and chemical steps. A typical design would involve three stages of treatment: 1) pre-treatment, 2) biological treatment, and 3) physical and chemical treatment. Generally, pre-treatment involves screening, sedimentation, and pH adjustment. The biological treatment is designed to remove primarily the BOD, COD, and some of the nutrients. The more common methods of biological treatment include oxidation ponds, aerated lagoons, and activated sludge. The last and final stage may involve a series of processes principally designed to remove color, suspended solids, heavy metals, and any remaining COD. Processes that may be used for this stage include settling, ozone oxidation, sand filtration, flocculation, and others. Specific information on the design and operation of these systems is available in standard texts on wastewater treatment, e.g., References 3 and 4.

A complex leachate treatment system, which uses pH adjustment, followed by flocculation, settling, biological treatment of the waste supernatant by means of an aerated pond, and chlorination, is in operation in one of the final disposal sites serving Buenos Aires, Argentina.

Simple (and therefore affordable) leachate treatment systems may be the only feasible choice for some locations. With respect to simple systems, storage and evaporation is the likely choice. Where evaporative systems are not feasible, simple biological treatment systems may be a reasonable choice for leachate treatment, especially if the wastes are predominantly of domestic origin, putrescible, and cellulosic. In such situations, anaerobic or aerobic systems would be the applicable form of treatment. Simple aerated systems (e.g., aerated lagoons, oxidation ponds) with hydraulic residence times of 30 to 60 days may work well, depending primarily on the BOD of the leachate. The design and performance of various types of aerobic, as well as anaerobic, systems for treatment of landfill leachate are discussed in Reference 5.

13.6 Existing Unlined Landfills

A large percentage of land disposal sites in economically developing countries do not have bottom liners. Furthermore, these facilities also lack leachate collection and removal systems, such as those described in the preceding paragraphs. Obviously, the installation of such a system in an existing land disposal site, in many cases, would require the rather unrealistic task of excavating and removing the solid waste. It is possible that in some instances the particular conditions may be such that the installation of a liner as well as a leachate collection system may be feasible. For example, in some cases, and especially for large land disposal sites that are significantly polluting the environment and/or threatening the public health, it may be necessary to implement some type of corrective action or to improve an open dump site. In this particular situation, a series of steps should be followed in order to conduct the work. Although each particular case will be different, some of the steps that would be common to most situations are: identification and determination of magnitude of problem, control and diversion of runoff, application of a cover, and installation of some type of leachate collection system.

If a leachate collection system is required for an existing disposal site, it may be feasible to install a perimeter collection system. In this case, as its name implies, a trench is excavated around the perimeter of the disposal site, most importantly on the groundwater downgradient side. Ideally, the trench should be sufficiently deep to reach low permeability bottom soils below the level of the bottom of the fill. The trench is filled with gravel and equipped with piezometers. In addition, the trench should be connected to a leachate collection sump by means of a drain. The entire perimeter of the disposal site should also be encircled, if feasible, by means of a low-permeability cut-off wall located beyond the trenches and installed down to a natural low permeability layer. The cut-off wall serves as a barrier to lateral migration of leachate. In cases where the required depth of the perimeter trench is too deep for economical construction, a suitable substitute may be a series of wells spaced sufficiently close together to simulate a continuous trench.

If the land area of the disposal site is too extensive, or for another reason the perimeter collection system is not practical or cost-effective, then it may be possible to devise another alternative such as installation of extraction wells within the landfill. These and other options must be carefully evaluated in terms of practicality, cost-effectiveness, operation and maintenance requirements, and other characteristics before a system is selected for installation.

13.7 Summary

The design of a leachate treatment facility must take into consideration management and ease of maintenance. Even the simplest design will require a certain degree of attentive management. Furthermore, leachate treatment systems involving sophisticated, maintenance-intensive equipment require concerted and continuous attention in order to support optimal operation.

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Chapter 14

Landfill Gas Extraction and Utilization

14.1 Gas Production and Quality Relative to Time

Landfill gas (biogas) constitutes one of the more important groups of products generated as a consequence of the biological degradation of the organic fraction of the wastes disposed in the landfill. Over the lifetime of a specific volume of waste in the fill (i.e., a control volume in the engineering sense), the environment proceeds from one of aerobic processes of decomposition to one of anaerobic processes. The transition from aerobic to anaerobic decomposition and the latter's attendant methane production proceeds as a series of phases. The first phase is the aerobic phase. Its duration is the time required to use up the entrapped O_2. This may be a few weeks or several months. The predominant gases synthesized during this initial stage are carbon dioxide (CO_2) and water vapor. The second phase begins as conditions shift from aerobic to anaerobic; obligate aerobes die off and facultative aerobes shift to their anaerobic mode; and CO_2 and, to a lesser extent, hydrogen (H_2) are the principal gases produced. The third phase is marked by the gradual appearance of methane (CH_4). Methane concentration becomes constant (in the range of 40 to 60%) in the fourth phase. Also produced during anaerobiosis is an assortment of reduced sulfur and carbon compounds in trace concentrations (e.g., sulfides and volatile organic acids, respectively). Hydrogen sulfide (H_2S) is the predominant reduced sulfide compound in raw landfill gas.

The concentrations of CH_4 and CO_2 under methanogenic decomposition (and other constituents of the gas) are influenced by several factors, including the composition of the waste being decomposed and access to moisture to dissolve CO_2. Typically in the case of landfills and landfill gas in industrialized countries, the ratio of CH_4 to CO_2 is on the order of 40:60 to 60:40. An example of the components of landfill gas and their concentrations is presented in Table 14-1. The gas may also contain volatile organic compounds that may have

Table 14-1. Typical Composition of Landfill Gas [1]

Component	Component % (dry volume basis)
Methane	47.5
Carbon Dioxide	47.0
Nitrogen[a]	3.7
Oxygen[a]	0.8
Paraffin Hydrocarbons	0.1
Aromatic and Cyclic Hydrocarbons	0.2
Hydrogen	0.1
Hydrogen Sulfide	0.01
Carbon Monoxide	0.1
Trace Compounds[b]	0.5

[a] The presence of nitrogen and oxygen in the gas could be due to leaks in the gas monitoring system or to intrusion of air into the fill.

[b] Trace compounds include sulfur dioxide, benzene, toluene, methylene chloride, perchloroethylene, and carbonyl sulfide, in concentrations up to 50 ppm.

been disposed with the refuse. A sample of the type of organic compounds found in a landfill in California, United States, is given in Table 14-2.

Rate and volume of gas production are governed by the characteristics of the disposed wastes and by the particular conditions prevailing within the landfill. The conditions include temperature, pH, moisture content, and particle size of the wastes. The conditions within the landfill can vary as a function of time, depending on the design and operation of the landfill and on the age of the disposed wastes. In keeping with the fact that the characteristics of wastes and landfill conditions vary markedly from one region to another, the reported rates of emission of landfill gases encompass a wide range of values [1,2,3]. For example, reported

Table 14-2. Trace Organic Compounds in Raw Landfill Gas, Mountain View Landfill, 1980 [4]

Compound	Concentration (mg/m^3)
1,2-Dichloroethylene	5.2
Trichloroethylene	10.4
Methyl Isobutyl Ketone	5.1
Chlorobenzene	0.4
Toluene	4.0
Tetrachloroethylene	4.5
Ethylbenzene	4.0
Xylene	2.3

(estimated or measured) total yields of gas generation from landfills in industrialized countries range from 0.064 to 0.44 m^3/kg of refuse disposed. Annual rates of total gas (CH_4 and CO_2) generation have been reported within the range of 1.19 to 6.8 m^3 gas/Mg/yr of waste disposed. Most of the production occurs during the 20 years following landfill closure, although production is most robust during the first 5 years or so. Gas production, in gradually dwindling amounts, may continue indefinitely.

Several models have been developed to predict the production rates of gas from landfills. Most of the models, however, require actual measurements of gas production in order to determine the values of constants for the models.

A relatively rigorous stoichiometric approach (i.e., relative to other approaches) for estimating landfill gas production is described in *Recovery, Processing, and Utilization of Gas from Sanitary Landfills* [5]. This approach takes into consideration the two major classes of material that decompose to produce landfill gas. The first class consists of the easily biodegradable fraction (e.g., food waste or garbage, garden debris). The second class includes the less easily biodegradable fraction (e.g., paper, textiles).

The variables mentioned in the preceding paragraph, as well as others, have an effect on the accuracy of models developed for predicting rates of landfill gas generation; rates of methane collection by a gas collection system present additional variables. Among the variables for rates of methane collection are the volume of gas that escapes the collection system, the percentage of carbon that is converted to methane, and the percentage of carbon that becomes a part of microbial protoplasm or is rinsed out in leachate. Consequently, such models should be regarded only as being approximate indicators of expected gas collection trends.

Although most municipal wastes in economically developing countries have a high concentration of biodegradable organic matter, the wastes usually are not placed in an impermeable (or nearly impermeable) repository, nor are they adequately covered; thus, the gases readily escape from the disposal area. Also, the gas yield (on a wet-weight basis) from landfills in economically developing countries may not necessarily correspond to those from fills in industrialized countries due to generally higher moisture content of the waste. Consequently, the importance of estimating gas yields (and rates of production) based on local conditions cannot be overemphasized.

14.2 Safety Aspects

The gases generated within the fill, if uncontrolled, will disperse and migrate beyond the boundary of the fill. Accumulated gases and uncontrolled dispersal and migration can represent a potentially hazardous situation due to several characteristics of the landfill gases. The characteristics include flammability, asphyxiating properties, and trace organic concentrations.

The slightly positive gas pressure usually existing within a landfill permits gases to flow uncontrolled from the fill to areas of lower gas pressure by convective gas transport. Furthermore, gases with higher concentrations of CO_2 and CH_4 can diffuse into regions containing gases with lower concentrations of these two gases. Finally, if landfill gas accumulates in the fill, the growth of plants rooted in the cover can be inhibited unless appropriate precautions are taken.

In the absence of adequate methods of gas control, landfill gases migrate to the atmosphere through the landfill cover; or, they can migrate laterally through the soil around the fill. If they reach areas from which they cannot escape (such as a building), an accumulation occurs. As long as the concentrations are relatively low, the gases pose only a potential nuisance. However, when the concentration (i.e., accumulation) reaches a critical value, methane gas is flammable and the potential of an explosion exists if the gas is confined and ignited (the flammable concentration of methane in air is between 5 and 15% by volume). At higher concentrations, methane is flammable only when diluted (usually by air) to within the above range and when in the presence of oxygen. Under these conditions, the accumulation of methane represents a hazard of fire and explosion. Because of the possibility of gas accumulation, buildings on or near landfills should not have underground structures, unless such structures are thoroughly and continuously ventilated.

Accumulation of gases in the landfill can be avoided through the use of a porous final cover. Migration of gases from the fill and the attendant hazards can be averted by providing pathways of high permeability in the landfill that result in controlled movement of the gases and, ultimately, to their venting to the atmosphere. Venting of the landfill gases at the surface of the landfill results in their dilution in the atmosphere to harmless levels (Figure 14-1).

A number of methods can be employed to provide designed pathways of high permeability to landfill gas. The methods include boreholes, gas wells and trenches within the fill, and

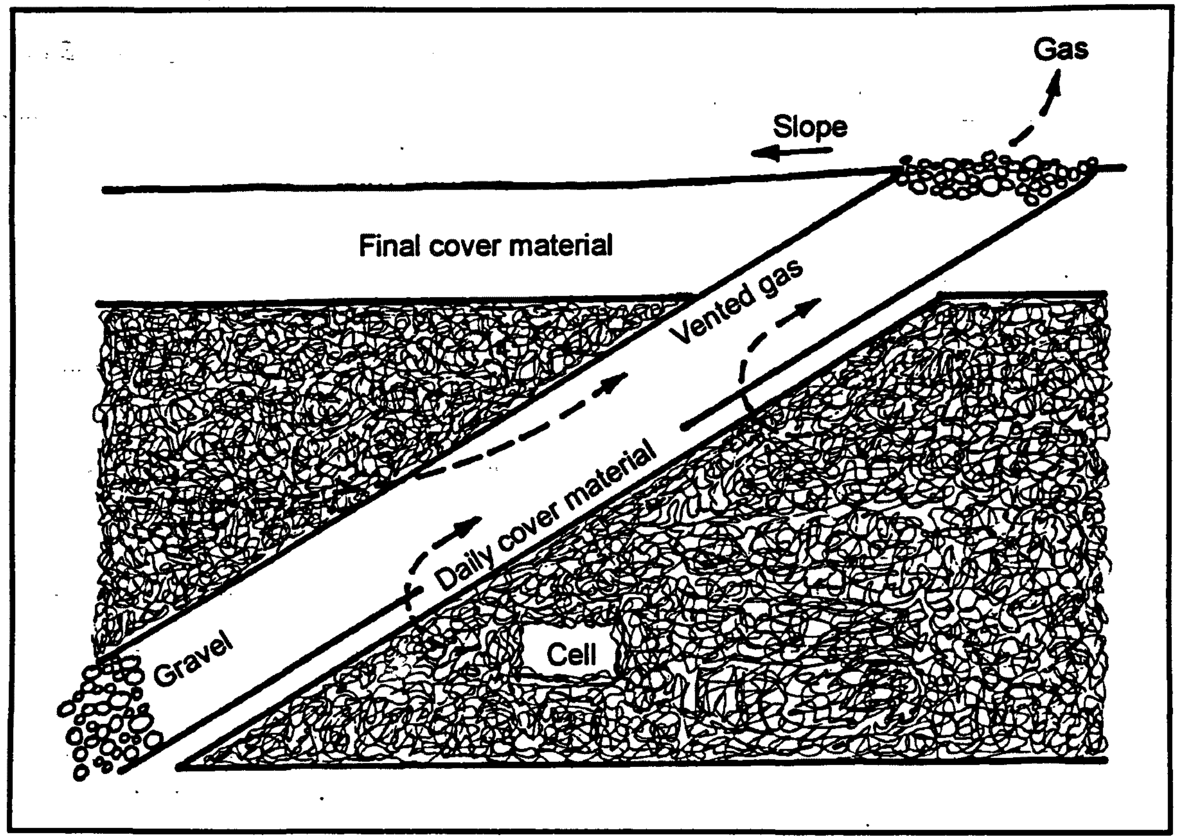

Figure 14-1. Dissipation of Landfill Gas Using a Porous Pathway Within the Fill

interceptor trenches or wells installed around the borders of the fill. An illustration of an interceptor trench is given in Figure 14-2. Additional discussion concerning venting is presented in Chapter 8.

Although venting the landfill gas into the atmosphere averts potential local problems and adverse impacts, this approach contributes to the greenhouse effect on the global scale. Consequently, every effort should be made to collect and use the gas or to burn the gas using a flare system.

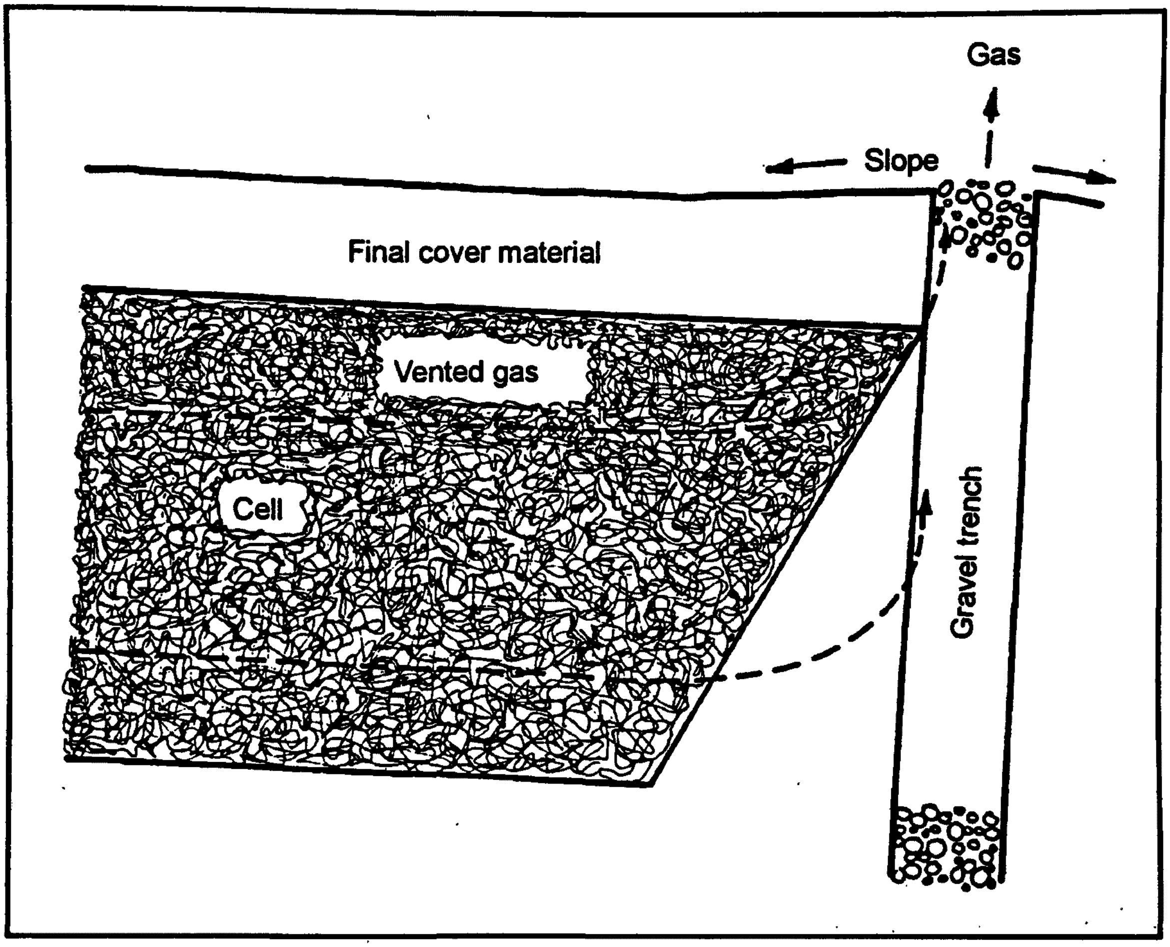

Figure 14-2. Dissipation of Landfill Gas Using an Interceptor Trench

14.3 Basic Design of Gas Extraction Systems

Gas recovery is instituted at landfills for two reasons. One is recovery of gas for the purpose of gas control, i.e., for environmental control. Methods of environmental control include flaring (burning) and simple dilution and dispersion. Environmental control is essential for the operation of modern, large landfills. The second reason for gas recovery is to take advantage of the energy content of the gas through energy recovery and utilization. Energy recovery is desirable, but not mandatory, for the operation of a landfill. The determination of the feasibility of energy recovery from landfill gas usually is based solely on a financial analysis.

Where the purpose for collection and recovery of landfill gas is environmental control, the burning of the collected gas (e.g., using flares) and natural dispersion (wherein no combustion is performed) are methods of control that merit consideration. The decision with regard to whether or not the collected gas is burned for solely environmental reasons is a function of a number of considerations, including but not limited to the availability of resources for procuring and operating a flaring system, the capacity of the disposal site, the existence of structures that can confine the gas, the emphasis placed on control of gases that contribute to global warming, etc. The design of some simple methods of gas control is discussed in Chapter 8.

If methane recovery and utilization is planned for a new landfill facility, certain features should be incorporated into its design. Some of the requisite features are characteristic of modem landfill design regardless of whether or not the methane is to be recovered.

For methane recovery, the fill must be effectively sealed off from the surrounding land and water environment. The steps involved in providing such sealing are the same as those described throughout the guidance document for leachate collection and control, or to minimize water infiltration at the surface of the landfill. Old or existing fills should be sealed to the extent economically and practically feasible.

Gas extraction and recovery involves designing the fill such that the gases that are generated by the decomposition of the wastes can be controlled and collected. The collected gases either can be used directly as a medium-calorific fuel, or can be processed (purified) to form a high-calorific fuel. The collection of the landfill gas (i.e., mixture of gases) is provided by a network (i.e., grid) of strategically spaced wells or trenches within the fill and by constructing each well or trench with high permeability materials through which the gas can pass easily and enter the piping system. The gas is extracted from the wellheads by way of a piping or header system and a suction pump is used to pull the gas from the fill through the headers [1,5,6], as shown in Figure 14-3.

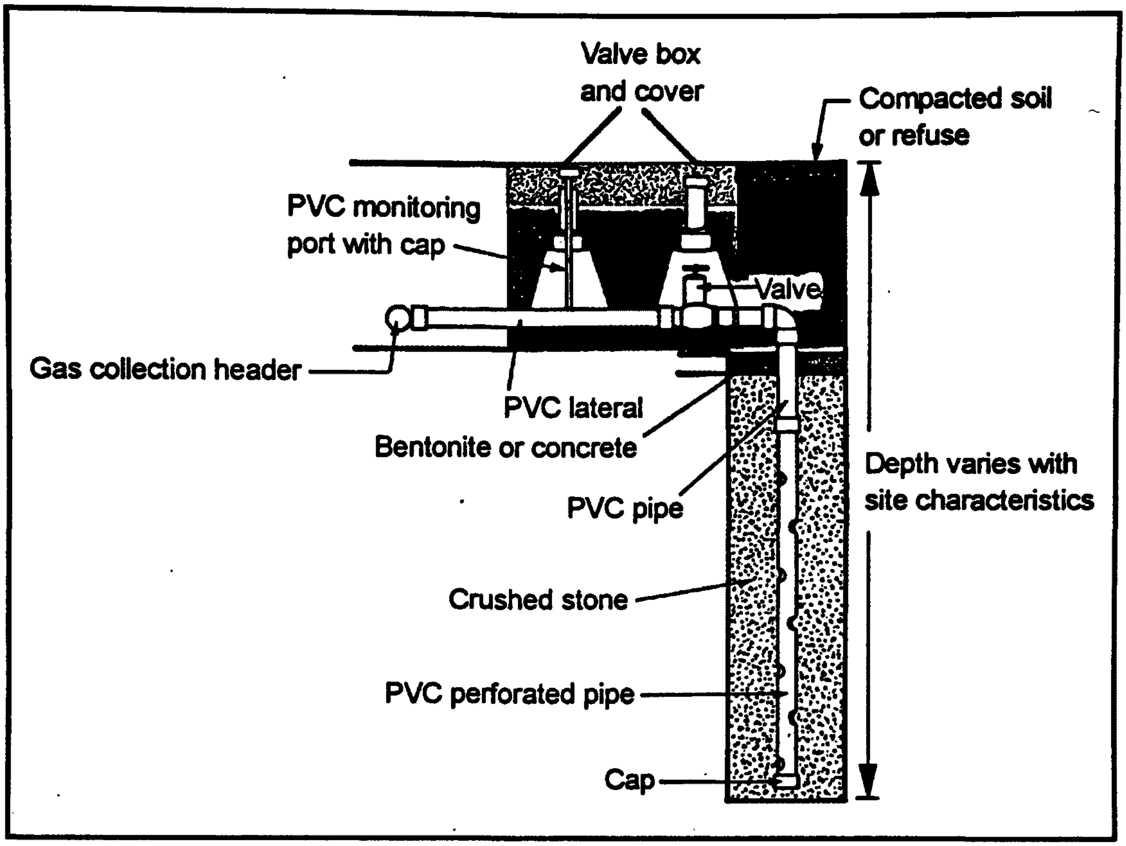

Figure 14-3. Gas Collection Well

Proper functioning of the gas collection system is ensured through the use of blowers. The blowers are operated such that a partial vacuum is created in the headers and collection system and, consequently, the gas is pulled from the landfill. Although some gas will flow unassisted into the collection wells because of the slightly elevated internal pressure of the landfill, the flow rate is too low to ensure proper collection performance. A system without blowers (pumps) is called a passive system. Blowers both increase the flow of gas from the landfill and broaden the effective landfill area serviced by each gas extraction well. The blowers can be adjusted either: 1) to pull gas from the fill and discharge it for dispersion, flaring, or combustion; or 2) to compress the gas to higher pressures for distribution or for further processing.

The potential exists to recover gas from two general types of existing disposal sites: 1) a landfill not originally intended for gas recovery if the landfill used daily and final cover and has a surrounding soil layer (i.e., at the side and bottom interfaces with the wastes) of low permeability, or 2) an open dump if the wastes from which gas is to be extracted are effectively sealed from the surrounding land environment and from the atmosphere. The reasons these situations promote the feasibility of recovery of gas are: 1) covering and sealing the wastes inhibits the rapid loss of landfill gas to the atmosphere or the suction of air into the landfill if gas is actively withdrawn, and 2) migration of landfill gas into surrounding soils is minimized if they are of low permeability.

The gas extraction wells generally extend to 60 to 90% of the waste depth and are slotted over the bottom 50 to 66% if they are used for gas collection and use. If the wells are used solely for venting of the gas, the entire length of the casing is slotted. To accommodate the settlement in the fill, various strategies are practiced with regard to the wells. In the United States, the most common practice is to plan on the settlement and to cut out sections of the well pipe periodically. A less common approach is to use telescopic connections between pipe segments.

The wells are built by progressively backfilling gravel around the gas collection pipe. The backfilled gravel (or a coarse substitute) serves as a highly permeable collection zone through which the gas flows into the collection pipe for removal from the well. The gravel area is covered with a gas-tight seal topped by backfilled soil to form a barrier against intrusion of external air into the well. Air intruding into a well (or into any part of the fill) would dilute the collected gas and, thereby, lower its heating value and complicate purification. Moreover, intruding air can lead to the development of serious problems. With respect to dilution, the concentration of nitrogen in the collected gas would be increased and the quality of the gas would be lowered correspondingly. Potentially more serious problems could result from the presence of oxygen in the air introduced into the fill. The oxygen would inhibit the activity of the methane-forming microorganisms. More importantly, from a safety standpoint, oxygen introduced into the fill might result in an explosive or combustible environment, with methane as the fuel and oxygen as the oxidizer.

The arrangement of the gas collection wells is determined by their respective capacities, by the characteristics of the soil cover and provisions for directing gas movement in the fill, and by the gas production rate of the decomposing wastes. The dimensions of the fill area affected by a well is a function of the rate of pumping. For example, a 12-m deep fill located in California with a gas well 6 m deep was being pumped at 2.8 m^3/min. The pressure in the waste ranged from -5.1 cm of water at the well to less than -0.8 cm at a distance of 30.5 m from the well. Increasing the pumping rate to 8.5 m^3/min brought the respective negative pressures to -17.8 and -2.54 cm [7]. As a general rule, a well or trench can be expected to collect gas a distance of 30 m to 40 m horizontally (and 5 m to 10 m vertically in the case of horizontal trenches), depending on the degree of compaction of the waste, the moisture content in the fill, etc.

14.4 Use of Landfill Gas

Uses of raw (i.e., unprocessed) landfill gas are somewhat limited. They may include domestic heating and cooking, brick and cement manufacture, and industrial process heat. For a number of uses, landfill gas must be upgraded in order to be of feasible utility. Upgrading is especially essential if the gas is to be used as a fuel for an internal combustion engine, or is to be injected into natural gas transmission lines.

In comparison to natural gas, the quality and calorific content of raw landfill gas are substantially less. Moreover, its composition and other characteristics are more variable than those of natural gas. For example, daily measurements can be ±50% of long-term averages of daily measurements for heating value, moisture content, and oxygen concentration of landfill gas. Variations can also occur on a seasonal basis. The heating value of landfill gas typically is in the range of 7,450 to 22,350 kJ/m^3; whereas, the lowest heating value of natural gas is about 37,300 kJ/m^3. In terms of moisture content, raw landfill gas can be saturated (i.e., 100% relative humidity), or the water content can be as low as 5%. Oxygen content varies from trace levels to levels that render the gas mixture potentially explosive. In practice, explosive levels are seldom reached. The high concentrations of CO_2 and N_2 in raw landfill gas dilute the heating value of the CH_4 in the gas mixture. The quality of landfill gas can be increased by subjecting it to various levels and stages of processing.

The uses for processed landfill gas include on-site generation of electricity and injection into a public utility transmission line. Two predominant alternatives exist for on-site generation of electricity from landfill gas – internal combustion engines or gas turbines. If the gas is to be used in an internal combustion engine, typically it is compressed to about 33 kPa. To fuel a gas turbine, the gas is compressed to a much higher pressure, e.g., 100 kPa.

Processing systems are available for removing water, CO_2, and N_2 from raw landfill gas, thus raising its heating value substantially. Dehydration of raw landfill gas can result in about a 10% increase in heating value. Dehydration, in combination with removal of CO_2 and hydrogen sulfide (H_2S), can result in a heating value of 22,360 to 26,000 kJ/m^3. Among methods of dehydration are in-line gravity outflow; filtering; use of special solvents (e.g., glycol, polyethylene); passage through molecular sieves or permaselective membranes; and subjection to heating, air cooling, and refrigerant cooling. Of these alternatives, the use of a molecular sieve offers a good combination of relatively low cost and high efficiency.

The most popular process for dehydration of gas is the triethylene glycol (TEG) system. This system has several beneficial characteristics which, when taken in total, account for its extensive use. The characteristics are chiefly those of the working fluid (i.e., glycols), namely, high degree of hygroscopicity, excellent thermal and chemical stability, low vapor pressures, and moderate cost.

In a TEG system, gas is compressed initially as it enters the system and bulk contaminants are removed also in this first stage. Subsequently, the gas is cooled to capture and remove the majority of the moisture. Next, the gas is passed through a triethylene glycol absorber/separator tower where free liquids in the gas are removed as the gas flows from the bottom (separator section) to the top (absorber section) of the tower. In the upper part of the tower, the gas is contacted with triethylene glycol on bubble trays to further remove moisture from the gas stream. A diagram of a TEG dehydration process is shown in Figure 14-4.

Water, as well as two other major impurities in raw landfill gas, CO_2, and H_2S, can be removed by coupling the TEG system with a hot potassium carbonate scrubbing system.

Certain uses of landfill gas (e.g., space heating and household cooking) require only that H_2S be removed from the gas. Hydrogen sulfide can be removed by passing the raw landfill gas through a dry-gas scrubber that contains a mixture of ferric oxide and wood shavings (commonly termed an "iron sponge"). The removal capacity of the mixture is about 105 kg of sulfur/m^3 mixture. The mixture can be regenerated by exposing it to air. The exposure of the mixture to air converts the ferric sulfide formed in the scrubbing reaction to ferric oxide and elemental sulfur. A schematic diagram of an iron oxide processing system is given in Figure 14-5.

Several factors play a decisive role in determining the financial feasibility of recovering and using landfill gas. The more important factors are: size and location of the fill, permeability of cover material and surrounding soil layer, climatic conditions, and proposed use of the gas. With regard to permeability of the surrounding soil layer, the provision of an impermeable barrier between the landfill contents and the surrounding soil while the fill is in the design stage is much preferred to the installation of one after the fill has been completed. If the landfill design criteria offered in the guidance document are followed, low permeability of cover and surrounding soil layer should promote the technical feasibility of recovery and utilization of

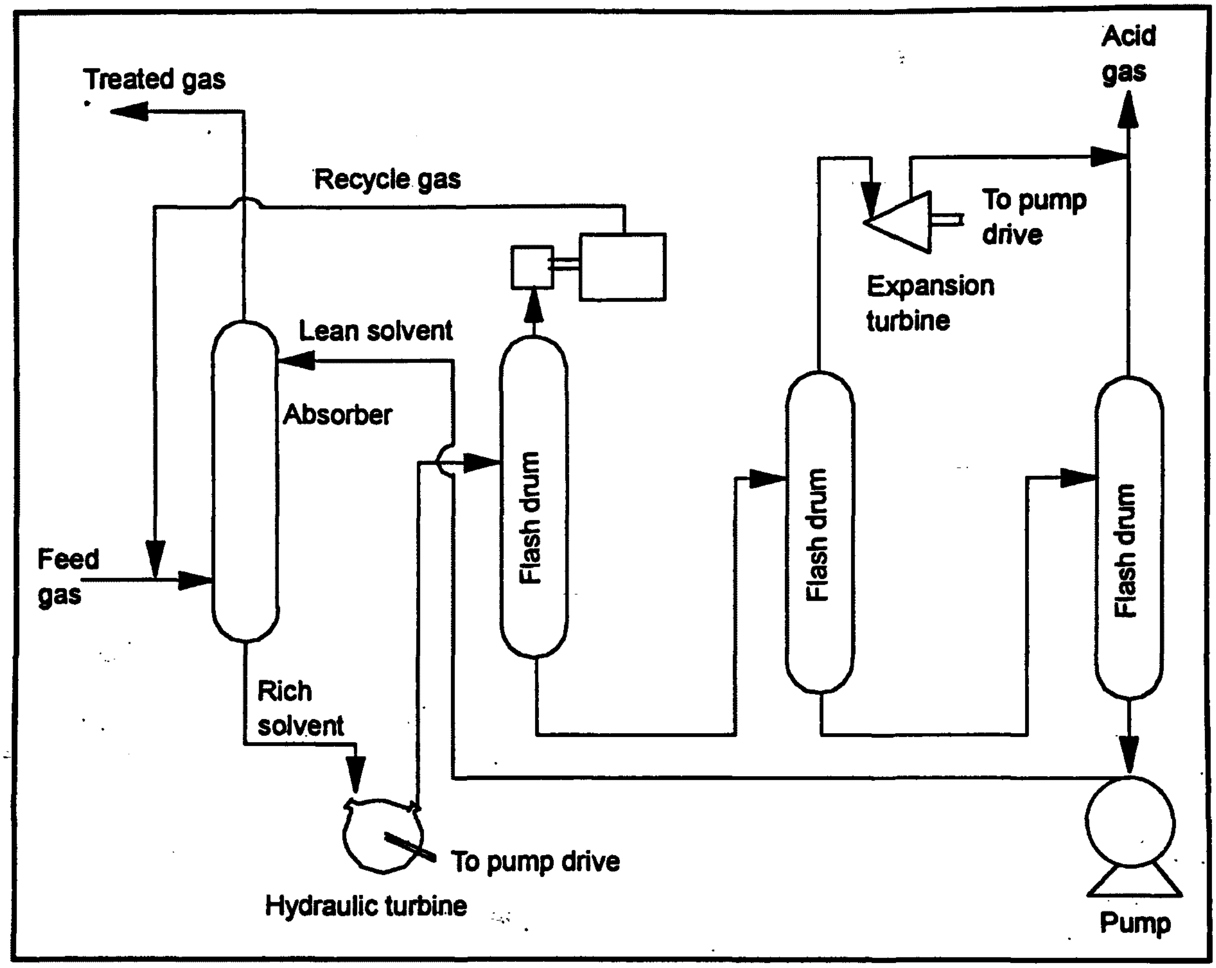

Figure 14-4. Schematic of a Landfill Gas Dehydration System Using Triethylene Glycol (TEG)

landfill gas. The size and location of a completed fill, or of one presently in use, governs the quantity and rate of collection of landfill gas and the potential markets. Climatic conditions also govern the type of markets and uses that might exist. For example, in tropical countries, the use of landfill gas for cooling is more probable than for heating (an exception would be the local need for industrial process heat). In economically developing countries, the need for a high-quality gas in order to have a market or use for it may render gas recovery and utilization

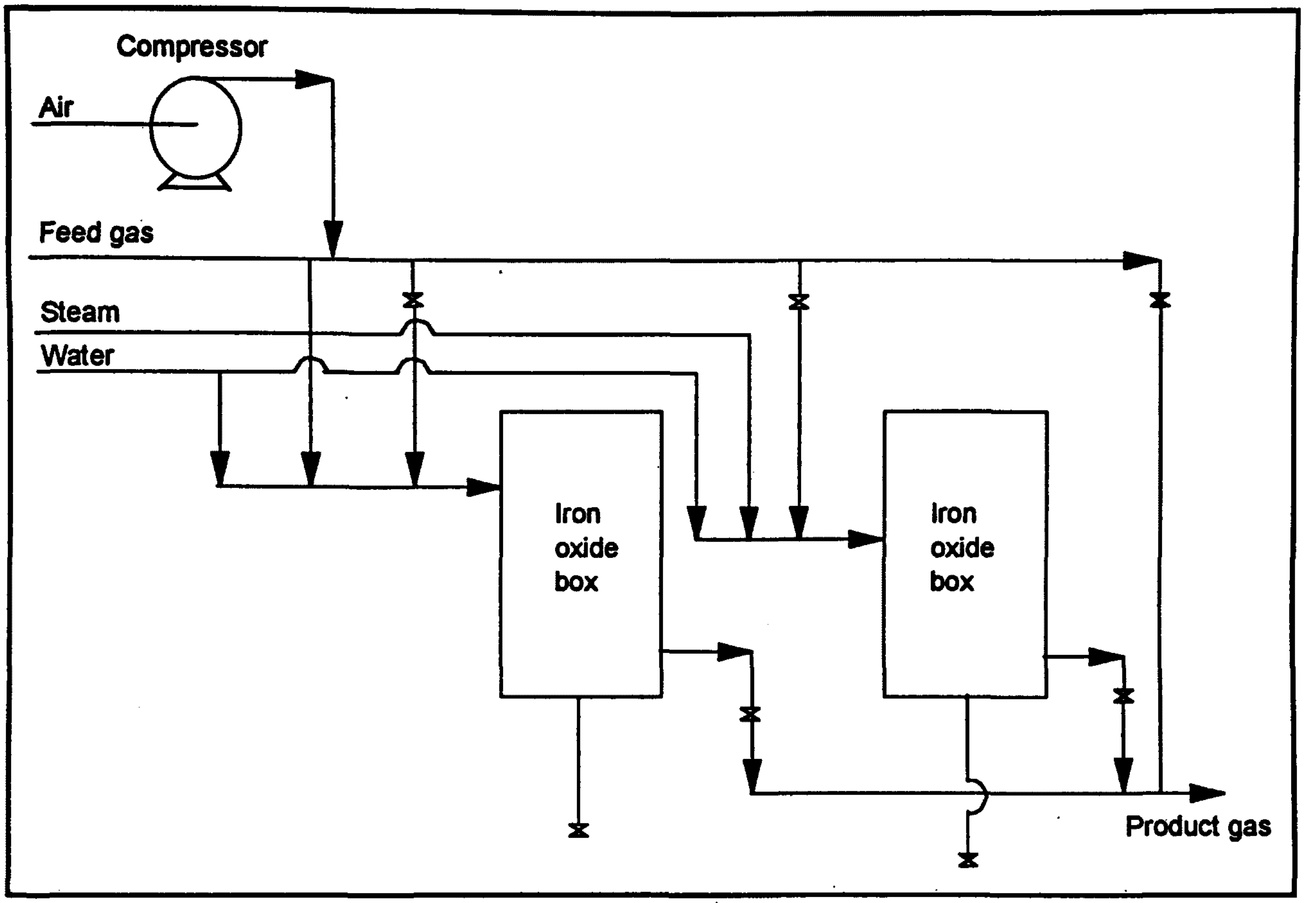

Figure 14-5. Schematic of an Iron Oxide Process to Remove Hydrogen Sulfide from Landfill Gas

unfeasible due to the cost of processing being prohibitively high or to the lack of sufficient technological infrastructure. This circumstance exists as well in economically developing countries.

The mass of waste in the fill should be sufficient to ensure an eventual total gas output that would have a monetary and energy value in excess of that expended on necessary departures from conventional fill practice. The size of the fill must be great enough to ensure gas production over a period sufficiently long to warrant the installation of equipment needed for collecting, upgrading, and using the gas.

Based on the experience had in industrialized countries, landfill gas recovery and utilization is not advisable for a fill that is less than 13 m deep. Additionally, at least two million Mg of municipal solid waste should be in place in the disposal site [6]. It has been estimated that at the peak rate of generation, raw gas production from a 2 million Mg fill would be in the range of 28 to 34 m^3/min, or about 760 MkJ/day [6].

The recovery and use of landfill gas must be carefully evaluated prior to design and installation of a recovery system. Gas processing systems can be expensive to procure and to operate, especially if a high-quality gas is required by the market or use. In an economically developing country, a technically and financially feasible use for landfill gas might be as a fuel for steam generation or for an internal combustion engine (with or without an electric generator) after a limited degree of cleaning. The high probability of high moisture contents and of corrosive elements in raw landfill gas and the costliness of gas transmission over long distances usually dictate on-site usage being more feasible than use of the gas off-site.

14.5 Information on Number and Types of Projects Worldwide

A number of projects have been implemented around the world to take advantage of the energy potential of landfill gas (LFG). In countries within the European Economic Community, approximately 180 LFG utilization projects were reported in 1990, with a reported gas utilization rate of 750 million m^3/yr (not all facilities reported gas production) [8]. Within Latin America, 11 LFG projects were reported in 1990 among the countries of Brazil, Colombia, and Chile [8]. In the United States, approximately 130 landfills collect and utilize LFG to produce energy in some form [9]. Approximately 75% of the landfills with gas recovery systems use LFG to generate electricity; about 25% of the landfills sell LFG for off-site use. The production capacity of the LFG electrical generating systems ranges from 70 kW to 50 MW. Other countries of the world reporting LFG utilization projects (1990) were South Africa (2), Australia (4), Hong Kong (1), and India (3) [8].

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Chapter 15

Resource Recovery and Utilization

15.1 Introduction

For the purpose of this chapter, resource recovery is defined as the physical recovery of materials from wastes for marketing as secondary materials, as sources of energy (i.e., as fuels), or both. Since landfill gas recovery does not involve the physical recovery of materials, gas recovery is excluded from this discussion and is described separately in Chapter 14. Resource recovery utilizes mechanical and/or manual methods of processing.

In terms of landfill design and operation, resource recovery is a potential consideration in the case of a new landfill, as well as in the case of an existing disposal site that is under evaluation for conversion to modern landfill standards. In the latter case, scavenging, i.e., manual resource recovery, already may be practiced to one degree or another. Where scavenging is practiced, the prevalent form of resource recovery in economically developing countries is salvaging of materials for sale to secondary materials markets as opposed to fuel markets. The list of materials that may have economic value includes aluminum cans, tin cans, and various grades of paper and of plastic.

The processing of wastes at a landfill can occur immediately after delivery (or shortly thereafter), or after the wastes have been buried for some time. In the latter case (i.e., processing after burial), the method of processing commonly is termed "landfill mining" or "landfill mining and reclamation."

The processing of wastes upon their delivery to the landfill can take several forms. The forms include processing of mixed solid waste (a heterogeneous mixture of materials) and of nearly homogeneous waste. A nearly homogeneous waste is a mixture of types of materials (e.g., wood, paper) that is relatively homogeneous and that can be processed efficiently in terms of yield of recyclable materials. A homogeneous mixture of waste is one that is composed of a high concentration of materials that have a number of similar characteristics. Construction and demolition debris is an example of a special waste; it can have large concentrations of wood, concrete, and metal. Mixed waste, on the other hand, is a heterogeneous mixture, i.e., mixed wastes are composed of many types of materials, with no type(s) of material dominating the composition of the mixture. Consequently, the recovery of materials from mixed waste usually is less efficient than recovery of the same materials from special waste.

If resource recovery is designed or practiced as a component of a landfill operation, the recovery operation should be designed and operated such that it does not create environmental or health and safety problems. This admonition applies regardless of whether the operation is mechanical, manual, or both.

15.2 Mechanical Recovery

As the name implies, mechanical methods of resource recovery depend predominantly on the use of mechanical equipment to process the wastes. When mechanical recovery systems are employed at disposal sites, they usually are simple in terms of number of pieces of equipment and in terms of technology. The reasons include:

- A landfill operation is dynamic, i.e., the location for discharging the waste moves about the site over time as portions of the fill are completed. Equipment that is simple can be moved with relative ease.

- A complex processing operation usually would require an enclosure for protection of the equipment from the elements and for environmental control. Normally, a dedicated processing facility is used in this case, such as a transfer station or a resource recovery facility. A discussion of these types of facilities is outside the scope of this document.

At some landfills in industrialized countries, simple mechanical processing systems typically employ several of the following: conveyors, screening equipment, magnetic separators, and size reduction equipment (e.g., crushers, grinders, and shredders). Existing, as well as historical, applications of mechanical systems to resource recovery include the following:

- The processing of green waste and wood waste using size reduction for the production of a mulch or a boiler fuel and for further processing by composting to produce a compost product. In some locations in the United States, size-reduced green and wood wastes, partially biologically stabilized, are used for daily cover.
- The processing of construction and demolition debris using the operations of size reduction, magnetic separation, screening, and flotation to recover soil, aggregate, wood, and metals. Potential uses for the recovered aggregate and soil include cover material and road construction.
- The recovery of steel containers from mixed wastes using size reduction and magnetic separation.

Mechanical equipment can also be employed to excavate wastes from a completed fill and to process the excavated wastes for recovery of materials. This application is termed landfill mining and reclamation (LFMR), as mentioned in the Introduction of this chapter. Although a number of reasons exist for considering or implementing LFMR, in the case of economically developing countries, the immediate practical use would be to remediate open dumpsites. Materials recovery and recovery of disposal volume might be secondary reasons, or reasons that become more feasible in the future. From a technical standpoint, the recovery of a soil fraction from disposal sites wherein the solid wastes are biologically stabilized is feasible through the application of simple screening systems. Thus, disposal sites that have received or are receiving wastes composed predominantly of uncontaminated putrescible wastes (e.g., those of domestic origin) can be candidates for LFMR, depending on a number of considerations. In the United States, LFMR projects have reported yields of soil fractions in the range of about 30 to 60%. (Of course, a portion of the soil fraction is composed of the cover soil used during the construction of the fill; a component that may or may not exist in land disposal sites in developing countries.) Uses of the recovered soil include land development (reclamation) and landfill cover; the latter material is sometimes unaffordable or unavailable in some locations. Since the most likely application of LFMR in the case of economically developing countries is remediation, the technology is reserved for discussion in Chapter 17.

15.3 Manual Recovery

Methods of manual resource recovery (scavenging) use primarily human labor to process and recover materials from wastes as they are dumped at the disposal location. Generally, simple hand tools (e.g., hooked implements) are used by scavengers to facilitate recovery of the recyclable materials from the wastes. The scavenging process typically consists of four activities: 1) picking (i.e., recovery) of recyclable materials from discharged loads of waste, 2) carrying of the captured materials (in cloth sacks or in fiber or metal containers) from the dumping location to an area reserved for accumulation and storage, 3) organization of the recovered materials into organized lots for the marketplace, and 4) transport of the materials to market. Typical materials recovered and recycled in this way include some or combinations of the following: unbroken bottles; and many types of metal, plastics, paper products, and textiles.

15.4 Impacts of Scavenging

Scavenging can present risks and problems to a landfill operation. The risks exist as a consequence of the exposure of the scavengers to safety, health, and environmental hazards that, in turn, are a consequence of the proximity of the scavengers to the wastes and landfill equipment; the conditions may also affect the health and safety of the landfill employees. The problems presented by scavengers to a landfill operation include interference caused by the scavenging activity. Scavenging activities can prevent the efficient and timely conduct of the landfilling of the wastes. Scavenging oftentimes delays the timely compaction of waste and application of the soil cover.

The hazards caused by the coexistence of scavenging and the equipment-oriented landfilling activity increase as the number and size of the heavy equipment increase. Consequently, in the case of a large landfill serving a municipality, especially a large urban city, scavenging can present significant risks, problems, and disruptions to landfill operations.

The accommodation and approval of scavenging at a landfill must be considered in terms of the drawbacks presented in the preceding paragraphs. If scavenging is allowed, then the scavenging activities must be properly coordinated with and integrated into the overall operation of the landfill such that the primary function of the landfill, i.e., the protection of the public health and of the environment, is not compromised or jeopardized.

15.4.1 Control and Management of Scavenging

Many of the negative consequences of scavenging on landfill operations can be lessened or even eliminated by treating the scavenging activity as a distinct first step in the series of steps that compose the overall landfill operation. The approach of treating the operations of scavenging and of landfilling of wastes as sequential is a departure from their usual performance as essentially parallel activities.

To achieve the distinct separation of scavenging from the disposal operation, the optimum arrangement is a spatial separation of the two activities. Of course, such a separation adds to the complexity of a landfill operation. For this approach, the scavenging step encompasses two components, the second of which is essentially an activity that would be additional to those of the typical parallel practice of scavenging and burial: 1) discharge of the incoming wastes at the scavenging portion of the disposal site, and 2) transfer of the residue remaining after scavenging to the burial site.

In keeping with the goal of separating the scavenging and waste burial activities, two general types of systems can be defined:

1. Local/Moveable -- The scavenging area is located nearby, but distinctly separate from, the working face. Therefore, the scavenging area is moved often in order to minimize the burden on the burial operation as a consequence of the need to transfer the residues from the scavenging operation to the working face.

2. Remote/Fixed -- The scavenging area is located on the landfill site but distant from the burial location. Consequently, the scavenging area is a permanent site.

In the case of the Local/Moveable system configuration, the scavenging area is relatively close to the working face, and the transfer of wastes from the scavenging area to the face can be accomplished quickly by means of equipment that possesses a blade or bucket, e.g., a bulldozer. Precautions must be taken to ensure that the two areas are not located so closely as to defeat the goal of separating the two activities, i.e., elimination of interference between the scavengers and the function of waste disposal. This arrangement requires that the scavenging area be moveable.

In the case of the Remote/Fixed system configuration, the scavenging area is remotely located from the working face, e.g., 1 to 2 km, and a loading system and hauling vehicles are required in order to efficiently transfer the post-scavenged wastes to the working face. The rate of transfer and, therefore, transfer system requirements are a function of the daily volume of wastes received. Suitable transfer vehicles would include dump trucks, and farm tractors and trailers.

A fixed scavenging site for the lifespan of the fill would be indicated if transfer by bulldozer is not feasible. A fixed scavenging site would be neither feasible nor advisable for a disposal site having a relatively short lifespan. Dedication of a fixed portion of the disposal site to scavenging takes on many of the characteristics and advantages of a transfer station. For instance, scavenging limited to a fixed area can be sheltered from the elements (wind, rain, etc.), and an undesired impact upon the environment can be avoided or minimized. The operation itself can be kept orderly and closely controlled, and abuses can be discouraged. Furthermore, efficiency can be improved by including a limited amount of mechanization, e.g., conveyor belts or rolling equipment for loading post-scavenging wastes onto transfer vehicles. An important benefit of this arrangement is avoidance of encounters between scavengers and landfill equipment. Additionally, this system allows for the provision of much needed sanitary facilities and a good working environment for the scavengers. Collectively, these arrangements and benefits serve to stimulate an efficient and well-operated landfill.

Perhaps the strongest objection to designating a fixed site is the fact that the added step of loading and transferring mentioned earlier becomes a necessity. This objection does not come into play until the distance between the scavenging and burial sites becomes so large that transfer of wastes by bulldozing is no longer feasible. Of course, the capital expenditure associated with the erection of a building and introduction of added equipment would be another disadvantage.

The capacity of a disposal site is the decisive factor regarding advisability and necessity for dedicating a portion solely to scavenging. In general, a capacity of 10 years or more would justify the incorporation of a fixed scavenging area into a landfill operation.

Important factors when managing scavenging activities are the relative priorities of the scavenging and the burial activities. Burial should have precedence over scavenging since the reason for the fill is the disposal of wastes. Therefore, scavenging must be managed in a manner that does not unduly interfere with the main activity of the landfill site, i.e., proper disposal of waste. A secondary, but nonetheless important, consideration is the impact of a potential loss of income to the scavengers, as well as potential losses of secondary materials to the local industry should the scavenging operation be operated inefficiently, ineffectively, or both.

Unless carefully managed, traffic due to scavenging activities can be one of the more disruptive interferences between scavenging and waste burial operations (disposal). Among the more obvious causes of disruption are the differences in physical size, number, and speed of vehicles associated with scavenging in comparison to other vehicles operating on or using the landfill property. The types of vehicles serving the scavenging activities may range from those as small as a non-motorized pushcart, to large vehicles used to transport the large loads of salvaged material. On the other hand, waste collection and haul vehicles typically surpass the scavenger vehicles in terms of size, weight, and speed. In some instances, long delays in discharge and burial of waste are caused by the discharge and transfer to the scavengers of recyclable materials stored by the collection crews on the waste collection vehicles. Where scavenging is not subject to control and management, waste hauling traffic will move at a much faster pace than will scavenger traffic, and the unloading and burial of waste will be considerably slowed both by intermingling of scavenger and other vehicular traffic and by the overall traffic density. Probably the best way to manage the two types of traffic is to separate them, i.e., use separate roadways. A disadvantage of this arrangement is the cost of the extra roadway. Hence, the decision as to separation of traffic flow usually rests upon economic feasibility.

The extent of access by scavengers to the burial location depends upon the degree of separation between the scavenging traffic and disposal traffic. If separation is complete, the access could range from unlimited to moderately limited. On the other hand, if the two traffic patterns are not separated, unlimited access by the scavengers is ruled out because of the likelihood of excessive interference with the disposal traffic. If access is to be restricted, the question becomes one of which individuals are to be excluded or have limited access. In arriving at a decision, political and social considerations oftentimes enter into the analysis and deliberations.

The activities of the scavengers should be under the direction of a supervisor. The supervisor's principal responsibilities are to manage and control the scavenging operation to promote and maintain efficiency and fairness and to minimize interference with the disposal operation. Fulfilling the latter responsibility requires that the scavenging supervisor work closely with the manager of the disposal operation. The latter manager should be the ultimate authority at the landfill site concerning any operational priority and conflicts affecting the disposal operation (landfilling). The supervisor of the scavenging activity may be assisted by subordinates, if efficiency of operation requires such a provision. Efficiency and safety demand that good housekeeping practice be employed and rigorously enforced at the scavenging operation. Enforcement of the practice is another of the responsibilities of the supervisor.

15.4.2 Guidelines

To manage and control scavenging at a disposal site, a set of policies and rules should be established, those that generally apply to all participants and those specific to the individual parties involved in the scavenging activity. Among the policies and rules suggested for consideration are the following:

- assignment of spaces, loads of waste, etc. to individual scavengers or groups of them;
- implementation of procedures for the removal of salvaged materials from the site, e.g., frequency and methods;
- rules for the sale of the salvaged materials; and

- the scavengers should be provided with safety equipment, sanitary facilities, showers, eating facilities, and first aid supplies (additionally, the provision or requirement of uniforms for the scavengers fosters orderliness, cleanliness, and worker self-esteem).

Chapter 16

Management and Recordkeeping

16.1 Management Responsibilities

The operation of a modern sanitary landfill requires attentive management, monitoring, analysis of overall performance, and corrective action when necessary. The responsibilities and obligations of management can be organized into three areas: operational, social, and financial.

The operational areas that require managerial oversight include:

- quality assurance (i.e., conformity of the operations with the operational plan and with regulatory requirements),
- routine and daily operations,
- security of the site,
- preventive maintenance and repair, and
- status of equipment and provision of replacement when necessary.

The social areas that require managerial oversight include:

- public and civic relations,
- ensurance of the health and safety of the operational staff and of the users of the site, and
- hiring and training of personnel.

The fiscal areas that require managerial oversight include:

- equipment and personnel recordkeeping,
- operational recordkeeping,
- development and monitoring of budgets, and
- financing.

Generally, the size of the landfill operation (i.e., the magnitude of the daily flow rate of disposed wastes) governs the advisability of investing the management responsibilities in a single individual or of entrusting them to a management team headed by a single manager or authority. Regardless of the management structure, the manager of the site must be qualified and experienced.

The management of a large-scale landfilling operation in an economically developing country must consider and address with equal intensity the tasks of managing personnel and equipment. In economically developing regions, labor usually is relatively abundant and wages are relatively low compared to the availability and cost of equipment. This situation is in stark contrast to that of industrialized countries in which labor is relatively expensive in comparison to the cost of equipment.

16.1.1 Personnel

The number and classifications of personnel that are required for a landfill operation are predominantly determined by the type and complexity of the landfill system. Complexity is measured in terms of number and size of the equipment employed in the active filling operations, as well as in terms of number and types of supporting equipment and systems, e.g., leachate and gas control and monitoring activities and instrumentation. In general, the number of personnel required can be considered to be approximately proportional to daily capacity of the fill, whereas the job classifications of the required personnel are functions of the complexity of the landfill system, as well as the capacity of operation. Thus, the need for trained operators and for job classifications for those operators (mechanics, equipment operators, etc.) increases as the daily capacity of the operation and the complexity of the landfill increases.

Few published data are available on the number of staff for operating a landfill in developing countries. One reference [1] suggests that one employee is needed for every 65 Mg of solid wastes disposed per day. With respect to type of landfill, trench operations generally are more labor intensive than are area fills.

For a facility handling less than 50 to 70 Mg/day, one full-time position, that of an equipment operator, can usually monitor receipt of waste, landfill of the wastes, and performance of minor administrative and maintenance functions. A landfill receiving hundreds of Mg/day would require one or more site supervisors, equipment operators, mechanics, laborers, and monitoring attendants. Some work functions can be combined among personnel in order to optimize productivity if the personnel are trained to perform more than one function and are well managed.

The following is a discussion of the major job classifications for a landfill operation.

16.1.1.1 Supervisor

The responsibilities of a supervisor encompass all functions and activities of landfill operation. A supervisor with training in equipment operation and maintenance lends flexibility to the operation of the landfill in that the supervisor can use any non-supervisory time to operate and maintain equipment. In particular, for landfills of small daily capacity, this type of dual capability for the supervisor is almost a necessity in order to save costs.

The supervisor should have experience in landfill operations and should be fully knowledgeable of the objectives and practice of landfilling, including protection of human health and safety and of the environment. The supervisor should be familiar with the use, servicing, and maintenance of all heavy equipment that may be used on the site. In those locations that lack locally available technical expertise (e.g., outside of large metropolitan areas), a site supervisor with some technical background in the basic engineering principles of landfill design and construction, and of environmental protection, is a good asset to ensure a well-operated landfill.

16.1.1.2 Equipment Operator

An equipment operator should be qualified and experienced in the operation and performance of the types of equipment used in landfill operations. Equipment operators should be trained to operate a variety of equipment and to perform preventive maintenance and minor repairs. Familiarity with methods and procedures used in landfill operations is also a useful and worthwhile qualification. In remote locations, the operators should also be qualified and experienced in major equipment repairs if at all possible, since the availability of repair services would be limited or non-existent.

The availability of qualified and experienced equipment operators will be greatest in large urban areas. In other areas, training is particularly advisable in order to ensure proper landfill practice and operation of the equipment.

16.1.1.3 Monitoring Attendant

The duties and responsibilities of a monitoring attendant are one or more of the following: observing and recording of incoming loads of waste (by number, volume, weight, etc.); direction of traffic within the site; facilitation of unloading of difficult loads or of freeing vehicles stuck in mud, etc.; and enforcement of site policies and regulations concerning ingress and egress of individuals, vehicles, and materials. While sites of small daily capacity often do not require monitors, they usually are required at large capacity landfills in order to adequately control the traffic and the unloading of waste near the working face, and to aid in the maintenance of safe conditions for the operators and the users.

In the case of landfills of large daily capacity, a separate monitoring attendant may be necessary in order to monitor incoming loads of waste for unacceptable materials and to record data and information concerning the number and frequency of incoming loads, and their volumes and weights. If a scale is used to measure the weight of wastes delivered to the landfill, a monitoring attendant would take on the role of a weighscale operator, i.e., weighmaster, and the attendant should be qualified and trained to measure and record the data.

16.1.1.4 Skilled and Unskilled Laborer

Laborers engage in the physical and manual work about the landfill. Among the many work activities of laborers are: collection of litter, installation of drainage lines, performance of landscaping tasks, routine maintenance on buildings and other facilities, and assistance to the monitoring attendant when a busy period of traffic occurs at the working face.

16.1.1.5 Mechanics

In an economically developing country, the uninterrupted operation of a landfill oftentimes depends upon the proper functioning of a piece of equipment for which no replacement is readily available nor affordable. This situation is particularly acute at landfill operations that are remote from large, urban areas. Mechanics must be qualified and experienced in the maintenance and operation of heavy equipment.

16.1.2 Equipment

The importance of proper and uninterrupted operation of heavy equipment at a landfill in an economically developing country requires that a concerted effort be placed on the management of the equipment. A precaution against equipment failure which normally is available to management in industrialized nations is redundancy of equipment. Unfortunately, standby or redundant equipment is an unaffordable luxury in most economically developing countries. Even though manual labor usually is plentiful in economically developing countries, unfortunately it cannot entirely compensate for a lack of basic equipment, especially heavy equipment. Thus, management must make every effort to ensure that the equipment is maintained in operable condition.

When considering options for maintaining the productivity of the equipment, management should realize that the potential financial advantages of purchasing obsolete or used equipment usually are outweighed by the problems inherent in the scarcity of replacement parts and by the inordinately high costs of maintenance in comparison to new equipment. The scarcity of parts and the attendant substantial maintenance and downtime also measurably diminish the benefits of used equipment.

The full potential of a piece of equipment cannot be realized without a competent and well-qualified operator. Inasmuch as landfill operation is heavily dependent upon equipment, an efficiently functioning and environmentally sound operation depends on the realization of that potential. Ultimately, the competency and qualifications of the equipment operator are major factors in a well-managed landfill. Ideally, the operator should have extensive experience in equipment operation. New operators should undergo an adequate training program by qualified and experienced site personnel or equipment representatives, or should attend a certified training program. In addition, all operators should have access to operation manuals for the equipment.

The cost of equipment maintenance is an expensive item that can be substantially lowered by the institution of a program of daily preventive maintenance. Equipment maintenance is a critical aspect of landfill operations. Unfortunately, maintenance is a task that often is overlooked, and in some cases virtually ignored. The lifespan of equipment can be optimized by performing periodic and thorough preventive maintenance. Daily, routine maintenance includes activities such as checking water and oil levels, lubricating moving parts, and keeping radiators clean. Management should ensure that maintenance activities are conducted frequently and properly.

A comprehensive, daily report should be completed for each piece of equipment and be readily accessible to management. Daily recordkeeping is one form of assurance that maintenance is being performed regularly.

When supplying equipment to the buyer, reputable manufacturers provide an operating and maintenance manual that includes a list of maintenance procedures and their frequency, as well as a suggested list of replacement parts. Very small jurisdictions can rely on private enterprises (contractors) for the maintenance and repair of the equipment. On the other hand, medium to large landfills (i.e., larger than 300 to 500 Mg/day) should consider the retention of a full-time mechanic on staff for performing routine maintenance and repairs. Furthermore, in the interest of fostering the importance of equipment maintenance to landfill operations, management should insist on the provision of an adequate structure to maintain and repair equipment, including, at the very least, some form of protection from the elements and a supply of basic tools, supplies, and spare parts.

16.2 Performance Monitoring

The operational aspects of monitoring landfill performance are described in Chapter 10. Good recordkeeping is essential to the monitoring and analysis of landfill operations. Without the maintenance of good records, it will not be possible to assess whether or not the landfill is meeting its performance goals or whether changes in operations are having the desired effects on performance. Records should be maintained on the following: waste quantities, filling rate, equipment and supplies, leachate, landfill gas, worker safety, and expenses and revenues.

16.2.1 Waste Quantities

A continuous log of incoming waste quantities, either by weight (Mg) or by volume (m^3), should be maintained for all waste types accepted at the facility. For purposes of administration, cost recovery, or both, it may also be necessary to record incoming loads by source or carrier. If materials recovery is practiced at the facility, the quantities recycled should be recorded. The actual waste quantities landfilled can then be calculated as the difference between incoming and recycled quantities. All quantities should be totaled daily. Monthly and annual summaries should be compiled from the daily records and be reported to management.

16.2.2 Filling Rate

At least once a year, the filling rate should be computed by the methods described in Chapter 10. Depending on available resources and on the method selected, it may be practical to perform this computation on a more frequent basis. The relevant parameters are as follows:

- solid waste, by weight (Mg) or volume (m^3);
- soil cover, by weight (Mg) or volume (m^3);
- waste plus soil, by volume (m^3); and
- soil:waste ratio, by volume.

Measurements of waste plus soil volume may be determined from topographic surveys or from the summation of daily waste and soil volume data. Volumes are the in-place (compacted) values for waste and soil. If volumes are estimated from weights, the conversions must be based on reliable values of in-place waste and soil density (Mg/m^3). Once the volumetric filling rate (m^3/yr) is known, the estimated remaining life of the landfill can be calculated using the following relation:

$$\text{Remaining Life (years)} = \frac{\text{Remaining Air Space } (m^3)}{\text{Annual Filling Rate } (m^3/yr)}$$

The estimate can be improved by estimating the degree of settlement of the wastes that will occur over time and modifying the results accordingly.

Remaining air space is calculated as the volumetric difference between the existing landfill surface and the proposed final landfill contours.

16.2.3 Leachate

For lined facilities, the landfill operating record should include measurements of leachate quantities and biochemical characteristics. The quantities of leachate generated and collected in the system should be recorded daily and summarized monthly and annually. (This guideline also applies to any leachate captured from the leak detection zone of a double-liner system.) Analyses of leachate quality should be performed periodically, depending on the needs of the treatment facility. The maintenance of a daily record of precipitation also is good management practice. Correlations between precipitation and leachate quantity or quality may be evident when the data is plotted graphically. For example, leachate quantities, when plotted against daily or monthly precipitation, may show trends that are indicative of changes in landfilling operations.

16.2.4 Landfill Gas

Any of the possible problems listed in Chapter 10 should be documented, and corrective actions described for the landfill operating record. In the case of an active landfill gas collection system, the record should include data important to operation of the system, such as gas temperature; gas pressure (vacuum) at wellheads and control points; gas concentrations of CH_4, CO_2, and O_2; ambient air temperature; and condensate volumes (see Chapter 14).

16.2.5 Worker Safety

Any lost-time accident or significant safety infringement should be fully reported and any corrective measures documented. Accident records should be maintained as part of the permanent landfill record and should be integrated with individual personnel files. The number of lost-time accidents and lost-time hours should be summarized monthly and annually. These data should be plotted in graphical form as a simple way to track safety performance.

16.2.6 Accounting of Revenue

In the final disposal sites that charge a fee, all sources and potential sources of revenue should be recorded. Records should be kept by waste type and by generator. It is preferable that frequent or regular users such as municipalities and institutions not be required to make cash transactions. Instead, a system of invoicing should be developed wherein the users receive a bill at a certain frequency (typically, monthly). The bill should include, at least, the following information: dates of delivery, quantity and type of waste (per delivery and total for the reporting period), and fee (per delivery and total for the reporting period). The total of the revenues is then used to balance the costs of disposal. The development of the disposal costs is described in Chapter 18.

16.3 Environmental Monitoring

This subsection assumes that environmental monitoring is a component of the operation of the landfill. The landfill operating log should include a record of all environmental monitoring activities, including inspections, analytical data, and corrective measures. Guidelines for environmental monitoring are presented in Chapter 10.

16.3.1 Erosion and Sedimentation

The time, date, weather and surface conditions, and findings of all inspections of the landfill surface, drainage, and erosion control systems, should be recorded. The record should also document any maintenance and corrective measures such as removal of sediment deposits, restoration of eroded slopes, and reseeding.

16.3.2 Groundwater Quality

A written record should be kept of all water quality samplings and analytical test results. An annual report of the analytical data should be prepared for management in tabular form, including all data from previous years for each sample point (monitor well). The annual summary should be reviewed for the purpose of identifying any groundwater quality problems or trends. The findings should be included in the annual report, along with a summary of the analytical data.

16.3.3 Surface Water Quality

A written record should be maintained of surface water quality in the same manner as for groundwater quality. It is recommended that the reports on surface water quality and groundwater quality be integrated and that possible interrelationships between surface water quality and groundwater quality be evaluated. In addition to the analytical data, visual inspections of surface waters should be reported. If any restorative measures to affected surface waters or wetlands are indicated or implemented, the findings and actions should be included in the record.

16.3.4 Air Quality and Gas Migration

All complaints of obnoxious or offensive odors should be recorded, as well as any corrective measures taken. Routine and periodic monitoring for landfill gas migration should be performed, as described in Chapter 10, and all field measurements recorded. Any corrective actions taken to reduce or eliminate gas migration at structures or at the landfill boundary should be noted in the record. A corrective action plan should be developed where landfill gas concentrations exceed the following limits:

- 100% of the lower explosive limit (LEL) at the property boundary of the landfill facility, and

- 25% of the LEL in any structure within the landfill facility or any off-site structures included in the monitoring program.

At landfills that have active gas collection systems and monitoring probes at the landfill perimeter, the measurements of CH_4, CO_2, and O_2 concentrations should be made and recorded. These data are important in assessing the performance of the gas extraction and control system.

Reference

1. Flintoff, F., *Management of Solid Wastes in Developing Countries*, WHO Regional Publications, South-East Asia Series No. 1, New Delhi, India, 1976.

Chapter 17

Closure, Post-Closure, and Corrective Action

17.1 Introduction

Landfill closure implies the completion or cessation of filling operations; solid waste is no longer accepted at the facility for disposal and, therefore, it must be directed to another disposal facility. However, it is possible that an operation related to solid waste management, such as materials recovery or a transfer station operation, might be implemented or continued at the site as long as disposal of the waste residues from the operations occurred off-site.

In the simplest terms, landfill closure refers to the period of time when the filling operation has ceased and the fill is "capped" with a final cover system. The period of time during which the fill subsequently is maintained and monitored for an indefinite length of time is referred to as the post-closure period. However, in practice, landfill closure and post-closure include the conduct of a number of activities. The activities are listed below and are broadly categorized into closure and post-closure phases:

<u>Closure</u>

- cessation of waste delivery for disposal by burial at the landfill;
- preparation of the site (preparatory grading) to receive the final cover system or cap;
- installation of the final cover system;
- provisions for gas collection and control;
- improvements or repairs to drainage systems, erosion control features, access roads, etc.;
- restoration of disturbed peripheral areas;

Post-closure

- operation and maintenance of systems for the following, including:
    - cover system,
    - leachate management (including liner integrity),
    - gas management,
    - erosion and sedimentation control,
    - surface water management, and
    - site access and security;
- environmental monitoring; and
- special provisions for use of the site.

Closure and post-closure care are important activities in the lifecycle of a landfill because they complete the requirements for environmental management of the facility. Generally, post-closure care should continue until such time as the solid waste has stabilized to a level at which it no longer is a hazard to public health and safety or to environmental quality. The ultimate duration of post-closure care is not known beforehand, and it will be specific to each site. In the United States, a post-closure maintenance and monitoring period of at least 30 years is the norm. The costs of closure and post-closure can be very large and should be adequately accounted for in the planning and fiscal management of a landfill.

17.2 Closure Plan

The closure of any landfill should be performed in accordance with a prepared plan. The purpose of the closure plan is to give clear guidance and procedures in order that:

- the landfill is closed according to applicable regulations;

- appropriate controls are in place for the management of leachate, landfill gas, and surface drainage; and
- the approved final land use is achieved.

Landfill closure requires substantial planning and preparation. A number of studies are likely to be needed before implementing closure, the timing and content of which will depend on the particular circumstances of the site.

17.2.1 Planning Considerations

The closure of a landfill impacts the overall solid waste management plan for the service area. Expansion of an existing landfill sometimes is feasible to accommodate future solid waste disposal needs. But at some point in time, an alternate disposal facility will be required. Proper planning therefore entails: 1) the development of a detailed closure plan before the landfill reaches capacity, and 2) provision of an alternate disposal facility by the time the closing landfill shuts its gates.

Depending on the complexity of the situation, preparation of a closure plan can take from several months to more than one year to complete. If environmental studies are needed before the initiation of engineering for closure plans and specifications, the entire process can extend to several years. In the case of planning and developing an alternate facility, a period of five years or more from inception to implementation is considered to be realistic in the United States -- especially if site selection and scientific investigations are yet to be conducted.

Planning for landfill closure requires careful consideration of waste quantities in relation to available capacity. In Chapter 10, the importance of monitoring the filling rate was emphasized. This information should be used to periodically estimate and adjust the anticipated date when the landfill will reach capacity and, therefore, be closed. As the landfill approaches its limit of capacity, the specific date of closure may shift, so the planning for an alternate facility should provide some flexibility with respect to timing. When the landfill finally does close, a sign should be posted stating this fact and providing instructions for using the alternate disposal facility.

17.2.2 New Landfill vs. Existing Landfill

The closure plan should be regarded as integral to the overall plan for developing and managing the landfill. For any proposed (new) landfill, the closure plan should be a part of the original landfill design. The design engineer should anticipate the manner in which systems providing service during the active life of the landfill (e.g., drainage or gas management systems) will be integrated into the closure design or replaced at the time of closure. An example would be channeling of runoff from the landfill cap to a previously constructed sediment basin.

In the case of an existing landfill, either active or inactive, a closure plan may not have been considered nor prepared. Environmental monitoring at such facilities also may not have been conducted, or the data may be lacking or deficient. Under these types of circumstances, the site conditions must be characterized before the closure design can be developed because any closure plan must be designed to minimize environmental impacts and, possibly, to restore the affected resources. The required scientific investigations (hydrogeologic, hydrologic, etc.) should form the basis of the closure plan design. The procedures for closing an existing landfill are considered further in Subsection 17.6.

17.2.3 Elements of a Closure Plan

The following elements are essential to closure plan development:

- hydrogeologic report, describing the physical relationships between the landfill and the hydrogeology of the site and any observed effects on groundwater quality;

- final site topographic plan, showing finished contours of the landfill and adjoining area, and important planimetric features such as streams, wooded areas, roads, buildings, and boundary lines;

- final cover system design, including plans and specifications for all system components and details of construction;

- sources of final cover materials, both earthen and synthetic (where applicable);

- final landscaping or site redevelopment plan, including construction specifications and details;

- preparatory grading plan, describing the requirements for filling and grading to achieve the desired landfill contours and the required degree of surface preparation for subsequent placement of the final cover system;

- operating plan, to be applied during the active and final stages of the landfill to show how closure construction will be phased (not applicable to smaller landfills where closure construction will be performed all at once);

- surface water management plan, including design of surface drainage systems and erosion and sedimentation controls;

- groundwater management plan, for modification of the natural water table and groundwater flow paths, where necessary, to mitigate impacts from the landfill;

- leachate management plan, required for lined landfills and for unlined landfills needing remediation of contaminated groundwater;

- landfill gas management plan;

- environmental monitoring plan for groundwater, surface water, gas migration, erosion, and sedimentation;
- cost estimates for closure construction and post-closure care (i.e., long-term operation, maintenance, and monitoring); and
- implementation schedule, notification procedures, and regulatory review.

Not all of these elements will be required for every site; however, most of the listed items will be pertinent to most landfill closures.

17.2.4 Implementation

The entity responsible for closing a landfill must provide some means of procuring the necessary labor, materials, and equipment and must have the financial and technical resources to complete the work. In certain cases, the entity itself may provide the workforce and purchase construction materials directly for all or a portion of the project. Larger entities may also have in-house technical staff who can be called upon to oversee construction to ensure that the work is performed in conformance to the design engineer's plans and specifications. It is more likely, however, that larger and more complex landfill closures would be implemented using the resources of private construction contractors and technical experts, including testing laboratories, construction managers, and resident engineers. The resident engineer on a project typically would be a representative from the firm that prepared the closure design.

Even if the responsible entity uses its own personnel and equipment for all construction associated with closure, there may be major portions of the work that require the expertise of specialty contractors. A prime example would be any landfill cap that employs a geomembrane liner. The installation of a geomembrane liner must be performed by skilled workers using special equipment and testing procedures to make the required field seams. If the liner warranty is to remain valid, generally these installations must be performed by factory-authorized workers in strict adherence to the manufacturer's recommendations.

Other specialized services for landfill closure might include surveying, well drilling, installation and startup of landfill gas equipment, and geotechnical testing of materials.

For the most part, the closure construction will resemble other types of civil engineering projects in which large quantities of earth materials are excavated, hauled, placed, graded, and compacted. The construction should proceed in accordance with the engineer's plans and specifications. However, minor adjustments to closure grades may be made in the field as long as minimum and maximum slope criteria and drainage design requirements are met. Critical elements of the work, particularly the installation of the final cover system, should conform to the standards established under a quality assurance program (see Chapter 8).

Conventional methods of construction management generally are applicable. Where large quantities of earth materials are to be imported, the scheduling of deliveries will be important to the progress of the work. The impact of truck traffic on neighboring areas and transportation routes must also be considered. Where special materials such as geosynthetics are required for the project, their availability and timely shipment from the vendor to the site will be essential to maintaining the project schedule.

The single most important factor in the schedule is likely to be the weather. Clay liners and geomembrane liners, in particular, can be installed only under certain conditions. As a rule, construction activities should be avoided during the wet and cold seasons. Excessively hot periods also present problems for construction.

17.3 Post-Closure Plan

A post-closure plan is needed to ensure the long-term integrity of the closed landfill. This type of plan contains elements that relate to operation, maintenance, and monitoring of the various components of the closed facility. The typical elements of a post-closure plan include:

- maintenance of the landfill surface and vegetation cover, including restoration of eroded areas, reseeding, regrading of settled areas, and periodic cutting and mowing;
- maintenance of drainage channels, drainage control structures, sediment basins, etc.;
- operation and maintenance of leachate management facilities (including liners), where applicable;
- operation and maintenance of gas control/recovery facilities, where applicable;
- surface water monitoring program;
- groundwater monitoring program;
- landfill gas (migration) monitoring program;
- cost estimates and financing options for implementation of the post-closure plan; and
- deed clause changes, land use restrictions, and zoning restrictions (commonly encountered in the United States, but may also be relevant to landfill closures in some economically developing countries).

The post-closure plan should take effect immediately following closure construction and should continue for an unknown period of years until regulatory authorities have determined that the landfill no longer represents a significant threat to human health and safety and to the environment.

17.4 Costs of Closure and Post-Closure

The costs of closure and post-closure will vary from site to site, but normally represent a substantial percentage of the total cost of landfilling. In the United States, the capital costs of landfill closure may exceed \$200,000/ha. To these costs must be added the present worth of post-closure care, which can approach, or even exceed, the costs of closure construction. The variability of post-closure costs is particularly large. A site that requires operation and maintenance of leachate and gas management facilities will have far greater post-closure costs than one requiring only maintenance of the landfill cap and occasional environmental monitoring.

It is important to recognize that the costs of closure and post-closure will be incurred without a self-sustaining revenue stream (unlike an operating landfill, which can generate revenue through tipping fees). The goal of landfill administrators, therefore, should be to capture the necessary funds for closure and post-closure in advance, during the active life of a landfill. This is appropriately done through the tipping fee structure, so that the users of the landfill are the ones who pay for its closure. Fees will need to be adjusted from time to time to reflect the most current estimates of closure and post-closure costs.

In fact, an analysis of closure and post-closure costs should be performed during the original planning of a landfill and included in the project's cost estimates that accompany the construction documents. The cost analysis should include:

- capital costs of closure;
- post-closure costs for operation, maintenance, and monitoring; and
- projected cash flow from the date of closure through the end of the post-closure period (assume 30 years, minimum).

The cost estimates should be developed to a level of accuracy comparable to other, similar engineering projects. Possible information sources available to the estimator are:

- owners/operators of other landfills,
- contractors who have performed this type of work,
- cost estimating handbooks, and
- existing cost files of the owner/operator.

Cost estimates typically are derived using a number of different sources and methods for any given project. Estimates may be constructed from consideration of labor, material, and equipment costs for each component of the work. In evaluating future costs, values must be adjusted for inflation as well as for accrued interest on accumulated funds. For an operating landfill, collected tipping fees should be sufficient to cover current debt retirement and operating costs, plus all estimated future costs, with a modest additional allowance for contingencies. However, for an existing landfill that has not previously included closure costs in its fee structure, it may be impractical to recover all such costs through tipping fees. (The fees could be exorbitant if the time to closure is relatively short.) In such instances, other cost recovery mechanisms, such as general taxation, must be found to supplement tipping fee revenues.

17.5 Site Use/Development Issues

Closed landfills are a potential resource, as well as a potential source of major problems. They are a potential resource because, due to their open land area, they may be put to beneficial use. The potential source of problems is represented by the contents in the fill, as well as the potential of hazards from the wastes extending beyond the boundary of the landfill site. The major limitations that closed landfills bring to site redevelopment are:

- the need to preserve the integrity of the landfill cap;
- the hazards of landfill gas; and
- the probability of differential settlement, which can result in structural damage to buildings on the landfill.

The extent of these limitations will depend on several factors, including the types of waste landfilled, age of the landfill, degree of compaction, and climate. In general, relatively new landfills showing substantial methane generation and continuing settlement will be poor candidates for reuse. Older landfills, which have achieved relative stability in terms of gas generation and waste consolidation, will be more viable for redevelopment.

Despite the limitations and risks noted above, many closed landfill sites have been used for various functions -- some with success and others with unfortunate consequences. Past uses have included:

- passive recreation areas or open space -- parks, green belts;
- active recreation uses -- athletic fields, golf courses;
- commercial development -- storage areas, parking lots, lightweight metal buildings; and
- residential development -- conventional housing, apartments.

Because of the explosion hazard that results from the accumulation of landfill gas in enclosed spaces, residential housing and commercial office buildings should not be considered except for completely stabilized landfills. Even then, particular caution must be exercised in providing for gas ventilation, gas monitoring, and proper foundation design. Because they are safer alternatives, passive or active recreation areas are more likely applications for the redevelopment of landfill sites.

Agricultural uses may also be feasible, but the quality of the topsoil and subsoil layers of the landfill cap may not be conducive to productive crop yields. Irrigation in many cases would be impractical, and the additional water burden might compromise the performance of the final cover system.

The following is a summary of basic guidelines for planning the post-closure use of a landfill site:

1. The major issues to be considered in the reuse of landfill sites are:

   * hazards of methane accumulation in confined spaces (explosion potential),
   * production of malodorous gases,
   * differential settlement,
   * low load-bearing capacity of landfills, and
   * public acceptance.

2. The safest approach is to wait until the landfill mass has achieved complete biochemical and structural stability. A substantial time duration may be required to reach a degree of stability that is necessary for certain types of uses.

3. In all cases, site reuse must be designed to preserve the integrity and function of all landfill systems -- especially the cap and bottom liner.

4. End uses that do not require construction of buildings pose less risk than those uses that involve construction of buildings on a completed fill. Relatively low-risk land uses include recreational open spaces, parks, golf courses, and agriculture.

5. Any recreational use of a landfill, such as a park or playing field, must ensure that gas emissions are either properly controlled or sufficiently diminished or diffused so as to pose no significant risk of explosion or hazard to human health and safety.

6. Although landfill gas may not always present a hazard to public health or safety, it can stress vegetation growing on the landfill surface.

7. Land uses that require irrigation have the potential to increase leachate generation and should be given careful consideration if leachate management is a problem.

8. A closed landfill represents potentially valuable property, especially in urban areas.

9. The owner may wish to develop the property with some type of building construction, as opposed to simple use as open space. However, construction on landfills is problematic for the following reasons:

   * the low load-bearing capacity of solid waste limits foundation loads to less than 25 to 40 kN/m^2;

   * solid waste typically will settle 10 to 30% of its original volume due to settlement; and

   * induced loads will increase, in many cases, the degree and rate of settlement.

10. Special design techniques are available to reduce or overcome the effects of landfill settlement. The most reliable method is to drive pilings through the waste into solid geologic material underneath the landfill. However, steel and concrete pilings are subject to degradation from chemicals in the refuse.

11. If the landfill has a bottom liner and leachate collection system, pilings will disrupt them.

12. Pilings can also damage the final cover system of a landfill. Consideration must be given to maintaining a good seal around piling penetrations so as to prevent water infiltration and the unwanted venting of gas.

13. Differential settlement can also affect the physical integrity and alignment of utilities -- electric, water, sewer, and gas lines -- installed on or below the landfill surface.

14. Any excavations into the landfill must be done with caution, since such work may encounter potentially odorous (sometimes, toxic) gases and explosive conditions. Also, slopes around excavations may be unstable.

15. Any structure built on a landfill must be designed to prevent gas accumulation in enclosed spaces and to include provisions for monitoring the presence of gas.

17.6 Closure of Dumps/Corrective Action

17.6.1 General

A dump is an uncontrolled refuse disposal area in which the waste is placed on or into the ground without regard for modern sanitary landfill procedures. Improperly designed or operated landfills may have many of the characteristics of a dump. In either case, there are likely to be adverse environmental impacts from improper land disposal of waste. This subsection of the guidance document discusses problem identification, data acquisition, and remedial alternatives for mitigating undesirable impacts resulting from improper practices of land disposal. The guidance also applies to correction of problems that may occur at fills that are designed, operated, and closed as part of a modern landfill project but at which adverse environmental impacts occur despite the best of intentions.

Open dump sites are by definition uncontrolled or poorly controlled operations. The sites were not selected through the conduct of a rigorous process of analysis, and they are not or have not been operated in an environmentally safe manner. Compounding the problem, dumps may be located near residential and commercial developments, sensitive environmental areas, or both. As a consequence, open dumps can and do represent unacceptable risks to humans and to the environment.

The typical dump is characterized by all or most of the following conditions:

- poor site selection;
- no order, no plans;
- abundance of physical hazards;
- uncontrolled scavenging;
- no daily cover;
- no intermediate or final cover;
- little, if any, compaction;
- no site drainage or erosion control;
- no leachate management;
- no landfill gas management;
- fires;
- presence of disease carriers; and
- foraging by animals.

In short, the site and operation have so many shortcomings and problems that the only recourse may be to close it, remediate it, and replace it with a disposal facility that meets modern engineering standards for landfills.

17.6.2 Procedures for Corrective Action

Because of the variable nature of dumps, the specific procedures for closure and mitigation of impacts will differ from site to site. In the simplest case, a small site might be readily excavated and all the material hauled to an approved landfill, such as in the case of illegal dumps characteristic of many communities in economically developing countries. In the worst case, the situation might require an expensive capping system plus extensive measures for leachate and gas management.

Whatever the case, the methods and decisions surrounding closure or corrective action should be based on accepted engineering principles. The challenge will be in finding solutions that satisfy the basic criteria for environmental protection while also heeding political realities and economic constraints. Adaptation and innovation will play important roles in formulating workable solutions. However, the general methodology will be the same in each case, involving the following steps:

1. problem identification/data acquisition,
2. evaluation of alternatives, and
3. plan selection.

17.6.2.1 Problem Identification/Data Acquisition

Before undertaking any corrective action, it is imperative to have a thorough understanding of the site and its surrounding environment. For example, specific information on the waste types and existing groundwater quality would be needed before remedial alternatives could be considered. In all but the simplest cases of dump closure, substantial amounts of data on the landfill operation and its environment will be required to characterize the site and to define the extent of the problem. If no data are available, as is often the case, the effort to collect the necessary information can be time-consuming and expensive. Typical data requirements for corrective action are listed in Table 17-1. All or most of this information will be needed for the closure and remediation of all but the simplest dump sites.

The acquisition of data may be an iterative process. After the initial phase of data gathering, additional data requirements may become apparent. For example, specific data may be needed to support the evaluation of a particular remedial alternative being considered. Once the essential data have been collected, it should be possible to define the magnitude and extent of the problem.

17.6.2.2 Evaluation of Alternatives

After defining the problem, the next step is to develop conceptual ideas or alternatives for correction of the problem. Each alternative will actually be a series of connected actions leading to a desired result. To illustrate:

Alternative A: Excavate the refuse and contaminated soil, and dispose of these materials at the new landfill. Backfill the excavation and reclaim the site for recreational use.

Alternative B: Cap the site to reduce leachate generation and continue to monitor the site for impacts to groundwater. Install security measures to exclude public entry.

Specific alternatives may be tied to particular technologies or variations in technology. For example, in the case of landfill capping, one alternative might rely on a local soil material for construction of the barrier layer, while a second alternative would use a geosynthetic material for this purpose. As another example, leachate treatment might be accomplished using different site-built or commercially available treatment processes.

Table 17-1. Typical Data Requirements for Corrective Action

Site Location
- Topography
- Proximity to population centers
- Proximity to surface water
- Site access
- Site size
- Areas of contamination

Climatic Information
- Rainfall -- maximum, minimum, average, number of events, intensity
- Temperature -- maximum, minimum, average
- Evapotranspiration data

Geologic, Geochemical, and Hydrogeologic Information
- Geologic setting and generalized soil profiles
- Soil physical and chemical characteristics
- Depth of bedrock
- Depth of groundwater and aquifers
- Existence of perched zones
- Groundwater flow patterns and volume
- Existing monitoring well locations and installation procedures
- Groundwater quality test results and testing frequency

Waste Characterization and Disposal Practices
- Types, characteristics, and quantities of waste present
- Variability of wastes within the site
- Fill methods
- Fill thickness
- Cover materials and vegetation
- Period of time site was active
- Period of time since the last waste was placed

Other Information
- Definition of current contamination -- groundwater, surface water, leachate production, soil contamination, migration
- Types of studies performed (by whom)
- Corrective actions previously taken (if any)

Once the available alternatives have been identified and described, they should be developed further by listing their advantages and disadvantages and their approximate costs. Conceptual cost estimates for each alternative should show both capital and operating costs. It should be remembered that operating costs should include the long-term maintenance and monitoring costs of post-closure. In many instances, the operating or long-term costs may exceed capital costs. So that cost differences between alternatives are fairly considered, it will be useful to express capital and operating costs as a combined present worth. The calculation of present worth should consider both the rate of inflation and the cost of borrowed money.

A range of other factors needs to be considered in the evaluation and comparison of alternatives. The following is a list of important evaluation criteria:

- technical feasibility,
- capital and operating costs,
- reliability/history of previous applications/risks,
- short- and long-term environmental effects,
- construction impacts,
- ability to reuse site,
- secondary economic impacts,
- compliance with regulatory standards, and
- aesthetic factors.

This list is not intended to be all-inclusive. Depending on the situation, other criteria may also be important to corrective action at a site. In cases where numerous alternatives may be applicable, it would be most efficient to perform a brief evaluation early in the process to identify a shortlist of better alternatives. Detailed evaluations would then be performed on the smaller number of alternatives having the greatest probability of success.

17.6.2.3 Plan Selection

The selected alternative forms the basis of a remedial action plan. Plan selection does not imply that the best alternative will always be chosen. In many cases, economic constraints may lead to a solution that is less than ideal -- one in which the degree of environmental remediation is less than the desired ideal. Each situation will be unique and will impose its own set of practical limitations. The goal in selecting a plan should be to maximize benefits to human health and the environment within the framework of those limitations.

As indicated, economic realities will factor heavily in the decision-making. It will be important to establish the available level and sources of funding for any corrective action. Once the "affordable" limit is known, the practical options for corrective action are likely to be clear. Careful consideration of capital vs. operating costs will be necessary, as will the sources and timing of funds to cover those costs. In an economically developing country, it may be unrealistic to depend on future commitment of funds to implement a plan that would have high operating costs over a period of many years.

It is common practice to document the plan selection and the process that led up to it -- problem identification, data acquisition, and evaluation of alternatives -- in a feasibility study report. The report typically represents the cumulative effort of the many contributors and decision-makers. It serves to validate, and provides a public record of, the plan selection process.

17.6.3 Overview of Issues and Alternatives

The issues concerning dumps and poorly operated or abandoned land disposal sites are virtually the same as those for new and properly performing landfills. That is, the same types of environmental controls ultimately are needed to protect land, water, and air quality, as well as the health and safety of human populations. The environmental controls and corrective actions necessary and available for remediating uncontrolled disposal sites can be categorized as follows:

- control of surface water run-on,
- control of erosion and sedimentation,
- control of leachate generation and migration,
- management of landfill gas, and
- collection/consolidation/relocation of waste.

The following is a brief review of causes, effects, and corrective action alternatives for each category of controls. For convenience, the description of alternatives is presented in tabular form.

17.6.3.1 Control of Surface Water Run-on

The flow of surface water onto a waste disposal site can occur as a result of: 1) flooding, 2) improper siting within a natural drainage way, or 3) failure of run-on diversion channels. The possible consequences of run-on include:

- an increase in leachate generation,
- contamination of downstream water resources,
- erosion of the landfill cover (if originally present) and exposure of the refuse,
- dispersion of refuse into bodies of water and populated areas, and
- damage to access roads and other infrastructure.

Alternatives available for correcting run-on include diversion structures and detention/retention basins, as described in Table 17-2.

Table 17-2. Corrective Action Alternatives for Control of Surface Water Run-on

Technique	Functions/Description	Applications/Restrictions
Diversion Structures	• Located upslope of landfill • Divert surface runoff around landfill via dikes, channels, etc. • Divert flow through solid waste via culverts only as a last resort, where diversion around landfill is not feasible	• For landfills subject to flooding or run-on from other sources • Most applicable for small watershed • Should be designed for 100-year storm since failure could lead to catastrophic environmental damage
Detention/ Retention Basins	• Located upslope of landfill • Detention basins attenuate peak flow rates to prevent unmanageable flow rates downstream • Retention basins prevent any downstream runoff	• For landfills subject to run-on from upstream drainage • Periodic maintenance of basins required to maintain their efficiency • Retention basins require high evaporation rates or highly permeable substrate to allow seepage (may be undesirable if effect on water table would increase leachate generation in landfill)

17.6.3.2 Control of Erosion and Sedimentation

Erosion of drainage channels and slopes is a common problem, even at managed landfills. The problem may be especially acute, therefore, at an uncontrolled disposal site. If erosion is not controlled, it may degrade any landfill soil cover that is present, thereby increasing the amount of infiltration into the landfill and the quantity of leachate generated. Because erosion may lead to exposure of the waste, additional contamination can occur.

In more severe cases of erosion, sediment may be transported off-site, causing degradation of water quality in the receiving waters. If sedimentation is heavy, the affected water bodies or wetlands may be permanently damaged. Alternatives for correcting erosion control problems are presented in Table 17-3.

17.6.3.3 Control of Leachate Generation and Migration

In a landfill or dump, leachate is generated by two primary routes: 1) passage of infiltrating water from the surface through the waste, and 2) contact between the buried refuse and subsurface sources of water. The first of these pathways occurs to varying degrees at all sites but will be of greater consequence to sites where precipitation is high and the cover over the waste is relatively permeable or lacking entirely. The second pathway is applicable to sites where the refuse was placed either in direct contact with water or below the groundwater table. This is commonly the situation in swampy areas that have been filled to reclaim the area for some other purpose.

Leachate generation generally is a difficult problem to solve. Most sites do not have provisions for controlling the movement of groundwater through the waste or for containing the leachate that is generated. As a result, the leachate is free to escape the site and contaminate the groundwater resource. Where groundwater controls and/or leachate collection and treatment are necessary, the costs can be prohibitive. In the case of buried refuse that is not in contact with groundwater, leachate formation usually can be mitigated with a properly designed and constructed landfill cap. For a developing country, the costs of capping are more likely to be manageable than costs of leachate collection and treatment.

The alternatives available for controlling leachate generation and leachate migration are summarized in Tables 17-4 and 17-5, respectively.

17.6.3.4 Management of Landfill Gas

At most sites where organic solid waste has been buried, landfill gas is generated in sufficient quantities to present potential problems. Often, the gas rises through the landfill and vents harmlessly into the atmosphere. However, if anything impedes the flow of gas to the surface,

Table 17-3. Corrective Action Alternatives for Erosion Control Problems

Technique	Functions/Description	Applications/Restrictions
Channel Lining	• Prevents excessive erosion • Lining may be grass, rock, erosion control mats, asphalt, or other anthropogenic materials	• For unlined drainage channels experiencing erosion of bottom and/or sides • Some techniques are expensive • Larger channels require more resistant lining
Channel Grade Control	• Reduces flow velocity to non-erosive levels • Check dams, drop structures, and erosion checks may be used	• For natural or artificial channels experiencing high flow velocities due to steep gradients • Sedimentation and flooding impacts should be evaluated when check dams are employed • Drop structures may be costly for greater flow rates and depths of drop
Channel Realignment	• Alters channel alignment to improve stability of channel bottom and banks	• For natural channels experiencing erosion from changes to watershed or other cause • May require extensive earthwork if realignment is required for long length of stream • Effects of realignment must be carefully modeled and evaluated
Energy Dissipators	• Reduce flow velocity and energy of discharges from channels, culverts, and ditches • Level spreaders, hydraulic jumps, discharge aprons, and drop inlets may be used	• For outlets discharging on erodible soil • Discharge from energy dissipator must be onto stabilized surface • Hydraulic jump is only effective when inlet flow is supercritical • Drop structure is used at head of channel or culvert to reduce hydraulic gradient

(continued)

Table 17-3. Corrective Action Alternatives for Erosion Control Problems (cont.)

Technique	Functions/Description	Applications/Restrictions
Detention/ Retention Basins (Sediment Basins)	• Attenuate peak flow rates from watershed • Allow controlled release of water to prevent excessive flows through drainage ways • Prevent transport of sediment to downstream locations	• For areas subject to erosion from high flows during major storm events • Periodic removal of sediment is required to maintain design efficiency of basin • Most appropriate where landfill grading significantly increases runoff from site
Dikes and Interceptor Ditches	• Divert and route runoff away from slopes • May be either temporary or permanent structures	• For slopes subject to overland flow • Flow must be diverted to controlled drainage path • Ditches must be lined to prevent channel erosion
Slope Drains	• Direct runoff down slope in controlled structures, temporary or permanent • Flexible down drains, pipe drops, and chutes may be used	• For slopes subject to concentrated runoff • Runoff must be directed to inlet of slope drain • Outlet of slope drain often requires energy dissipator or stabilized surface to prevent erosion from high flow velocity discharge
Mulches	• Provide protective cover over soil to dissipate the erosive force of rainfall and overland flow • Straw, wood chips, sawdust, and other materials may be used	• For exposed slopes subject to rainfall impact and overland flow • Many mulches require anchoring on slopes steeper than 3H:1V with netting or similar material • Should be combined with establishing vegetation • Can be applied with seed, fertilizer, and lime in one operation by hydroseeding technique

(continued)

Table 17-3. Corrective Action Alternatives for Erosion Control Problems (cont.)

Technique	Functions/Description	Applications/Restrictions
Bending or Scarifying Slopes	• Provides series of small terraces to slow overland flow and provide flat surfaces for seed and mulch to prevent their being washed off • Scarifying of slope can be done with special attachment on bulldozer or other grading equipment • Horizontal surfaces on micro-terraces are typically 25 cm wide. Benching with terraces up to a few meters in width may also be used	• For steep slopes subject to overland flow • Should be combined with establishing vegetation cover • Effective in cohesive soils only
Vegetation Cover	• Provides protective cover over soil; root system helps bind soil particles and prevents their washoff • Wide variety of seed mixes and methods of application are available • Hydroseeding combines seeding, fertilization, and mulching in one operation	• For exposed slopes, channels, and other areas where soil is susceptible to erosion • Subject to climatic restrictions • Time of year is important in seeding • Some plant species may be sensitive to landfill gas accumulating in root zone • Compatibility should be demonstrated prior to seeding whole area

Table 17-4. Corrective Action Alternatives for Control of Leachate Generation

Technique	Functions/Description	Applications/Restrictions
Covers	• Decrease amount of precipitation infiltrating into the waste and generating leachate • Low permeable barrier layer is placed over waste in conjunction with other layers of total cover system	• Applicable to closed landfills or filled areas of operating landfills • Cover must include landfill gas vent system and erosion control protection • Expensive procedure that should be part of an overall closure plan
Impermeable Barriers	• Located upgradient or around perimeter of landfill • Prevent movement of uncontaminated groundwater into refuse • Slurry trenches, grout curtains, or sheet piling are used to construct barrier	• For landfills located in shallow groundwater flow systems • Barriers must be deep enough to ensure that groundwater cannot pass beneath barrier and flow up into refuse • More effective if they can be keyed into underlying low-permeable soil • Not effective in groundwater discharge area
Interceptor Trenches	• Located upgradient or around perimeter of landfill • Capture groundwater and divert it around landfill; depress water table near landfill • Perforated collection pipes are backfilled with gravel	• For landfills located in shallow groundwater flow systems • Trenches must be deep enough to effectively lower water table • Discharge area is required for flow collected by pipes • Not effective in groundwater discharge areas, nor in soils of low permeability
Groundwater Pumping	• Located upgradient of landfill • Lowers local water table below refuse level • Well point or deep extraction wells are used	• For landfills located in shallow groundwater flow systems • Can be effective in groundwater discharge areas • Not effective in low permeable soils • Discharge area is required for pumped groundwater • Operating and maintenance costs associated with wells and pumps are high

Table 17-5. Corrective Action Alternatives for Control of Leachate Migration

Technique	Functions/Description	Applications/Restrictions
Impermeable Barriers	• Prevent migration of leachate from site • Slurry trenches, grout curtains, sheet piling, and geomembrane liners are used	• Located around perimeter of landfill • Effective against only shallow, subsurface leachate flow • Must be combined with some type of collection system to remove leachate generated within landfill
Subsurface Drains	• Collect leachate migrating from landfill beneath the surface or through seeps on the surface • Typically consist of trenches laid with perforated pipe, backfilled with gravel, and covered	• Located around perimeter of landfill or at base of slopes experiencing leachate seeps • Leachate must be transported to treatment system
Ditches	• Collect surface seeps of leachate	• Located at base of leachate seeps • Leachate must be transferred to treatment system • Treatment costs are increased since ditches also capture surface runoff which becomes contaminated and must be treated • Ditch should be lined • Useful only for temporary control
Groundwater Pumping	• Creates cone of depression beneath landfill to prevent leachate from migrating with groundwater flow system beyond site boundary • Deep extraction wells are used	• For landfills experiencing subsurface migration of leachate in groundwater flow system • Located beneath landfill or on downgradient side of groundwater flow system • Extracted water must be transferred to leachate treatment system • Maintenance and long-term operating costs are high

it will migrate laterally along the path of least resistance until it can vent to the atmosphere. Physical barriers such as low-permeability soils and final cover systems can lead to unwanted migration unless specific measures for venting the gas are provided.

Uncontrolled gas migration may result in the accumulation of gas in structures on or near the site. Where gas concentrations indicate a potential explosion hazard, or noxious gas odors are present, appropriate corrective actions will be required. These may include passive control measures, such as vents and barriers, or active control measures, such as forced ventilation and gas treatment systems. Alternatives for correcting gas migration problems are described in Table 17-6.

17.6.3.5 Collection/Consolidation/Relocation of Waste

In most open dumps, the waste has simply been discharged into a general area, with no consideration as to how the fill would be placed, compacted, covered, and graded. The result is a highly inefficient disposal operation that, even if the usual environmental impacts are absent, could benefit from certain improvements. At any uncontrolled disposal site, the appropriate corrective actions should be based on the type of analysis discussed earlier. However, it is reasonable to anticipate that many situations would benefit from collection/consolidation/relocation of the waste. Such measures may be used to improve environmental controls and to reduce operating and closure costs at the same time. Alternatives for collection/consolidation/relocation include the following:

- excavation or collection of waste deposits from around the outside of the site to reduce the size of the waste disposal area, immediately followed by placement, compaction, and covering of the collected material within the remaining area;
- excavation of all waste (particularly if the dump site is small) and hauling the material to an approved disposal facility;

Table 17-6. Corrective Action Alternatives for Control of Landfill Gas Migration

Technique	Functions/Description	Applications/Restrictions
Pipe Vents	• Provide flow path for landfill gas to atmosphere or to header pipe for burning or recovery • Vertical or horizontal perforated pipe in borings or trenches backfilled with gravel are used	• Located in or around perimeter of landfill • Active system is more effective than passive system in controlling lateral migration • Monitoring is required to ensure system is effective
Trench Vents	• Provide flow path for landfill gas to atmosphere or collection system • Narrow trenches backfilled with gravel are used • Should be combined with impermeable barrier on outer wall of trench	• Located around perimeter of landfill • Can be free venting or part of collection/recovery system • Can be passive or active, although active is more effective • Depth should be 60 cm below water table, low permeability layer, or bottom of landfill, whichever is shallower • Monitoring is required to ensure effectiveness
Impermeable Barriers	• Prevent lateral migration of landfill gas • Slurry trench, clay, or geomembrane liner are used	• Located around perimeter of landfill • Same depth requirements as trench vents apply • Should be combined with vent system to be effective • Monitoring is required
Gas Burning	• Oxidizes volatile, odorous gases to non-odorous components • Flaring of gases at controlled combustion points is used	• For landfills generating nuisance levels of odorous gases • Maintenance of flares is required • Adequate methane must be present in gas to support combustion

- excavation of all material, temporarily stockpiling it nearby with appropriate environmental controls, constructing a new landfill on the original site in conformance with modern sanitary landfill standards, and disposal of the excavated material in the new facility; and

- excavation of the material, processing it, reclaiming recyclable materials, upgrading the site, and disposing of residues in the new site (landfill mining and reclamation).

Depending on the particular circumstances, the site would then be operated or closed as necessary. Operation would entail bringing the site up to modern landfilling standards with respect to filling, compacting, and covering the waste; site drainage; management of leachate and gas; environmental monitoring; general administration; etc.

17.7 Landfill Mining and Reclamation

17.7.1 Background

Landfill mining and reclamation (LFMR) is a planned and controlled method of excavating and processing disposed solid wastes. LFMR can be used as a measure to upgrade open dumps and poorly designed or improperly operated landfills that do not meet applicable or acceptable environmental and public health specifications [1]. LFMR technology can range from low-capacity, labor-intensive systems to high-capacity, mechanical systems. High-technology processing (e.g., 50 to 100 Mg/hr of excavated material) typically involves a series of mechanical, or mechanical and manual, processing operations. Typical equipment used in simple, high-technology LFMR operations are excavators, screens, and conveyors. Low-technology processing usually involves the use of very few and simple pieces of equipment (e.g., screens) and of substantial manual labor. Regardless of the level of the technology, the systems have a common element of portability so that they can easily be moved from a completed excavation to a new location.

Applications of LFMR that have potential and relevance in economically developing countries include: 1) the excavation and processing of wastes in an open dump to recover disposal capacity and to convert the site to a modern landfill; and 2) remediation of land disposal areas that suffer from adverse environmental impacts, through excavation, processing, and removal of waste materials. The potential of LFMR for recovery of materials (e.g., soil) is discussed in Chapter 15.

Landfill mining was first described in 1953 in an article that documented the processes used at a landfill operated by the City of Tel Aviv, Israel [2]. The primary objective of the LFMR operation was to excavate the waste for the recovery of a soil amendment. Excavation and processing equipment included a front-end loader, several conveyors, and a rotating (i.e., trommel) screen. According to literature, the operation in Tel Aviv remained the only application of LFMR until the 1980s.

Two developments took place between 1950 and 1980 that impacted landfill mining. One was the emergence of a modular processing system designed to process mixed waste as it arrived at landfills or at transfer stations, primarily for the purpose of recovering steel containers. The second development took place in the late 1960s/early 1970s, and concerned an assessment of the technical feasibility of composting landfilled municipal solid waste *in situ*. Although the landfilled waste composting project was not commercialized, it provided information on the acceleration of the degradation of organic matter in a landfill as well as emphasized the importance of a cellular structure in a sanitary landfill. The modular concept of processing wastes at disposal facilities, in conjunction with *in situ* processing of landfilled wastes, has become the basis of many current and planned LFMR systems.

During the 1980s, two major trends brought about renewed interest in landfill mining. The first trend was the shortage of landfill space in some areas and the second was the emphasis on resource recovery. In 1982, a proposal was made to the Metro Manila Commission in the

Philippines [3]. The proposal called for the application of landfill mining in the upgrading of one of Metro Manila's disposal sites on the Island of Balut, Tondo. However, the project was not implemented, primarily due to a shortage of funds. During the early 1990s, the use of LFMR as a method of remediating disposal sites to current environmental standards gained the interest of municipalities, as well as the use of the technology to reduce the area of completed landfills in order to reduce the cost of closure and of post-closure activities.

17.7.2 Status

Relatively few written evaluations of landfill mining have been prepared. However, some processing of land-disposed wastes has occurred in the Philippines and in the Republic of China. In the United States, about one dozen landfills have been or are being mined. A brief description of two of the projects that have been conducted in the United States is presented below. The descriptions of the projects and their results serve to illustrate the variety of reasons for considering and implementing an LFMR operation, and to illustrate design aspects and operating experience.

17.7.2.1 Collier County, Florida

A comprehensive field test evaluation [1] of the Collier County landfill mining system was conducted in 1992 under the U.S. EPA's Municipal Innovation Technology Evaluation (MITE) Program. The LFMR system is operated as a means to reuse a previously unlined land disposal area as a modem sanitary landfill. An added benefit of the LFMR operation is the recovery of a soil-like material that can be used as cover material, which would normally have to be purchased from off-site sources. The process consists of excavation and processing of the excavated wastes using mechanical equipment. The key piece of processing equipment is a trommel screen. The mined wastes are relatively well decomposed. Consequently, as shown in Table 17-7, the soil fraction recovered from the process (i.e., cover material plus finely sized, decomposed wastes) accounts for about 60% of the excavated material.

Table 17-7. Mass Balance and Efficiency in Stream Concentrations – Collier LFMR Demonstration Project

Fraction	Mass Fraction (wt %)	Stream Purity (wt %)
Non-processible	18	N/A[a]
Soil	60	94
Ferrous	2	82
Plastics	2	75
Residue and Other[b]	18	–
	100	

[a] Not applicable.
[b] Includes heavies, finger-screen unders, and aluminum.

The properties of several of the recovered streams from the Collier County LFMR system were determined through laboratory analyses. In the case of the soil fraction, the concentrations of metals were found to be low. Environmental monitoring of the LFMR operation was conducted during the technology assessment. No significant occupational or public health and safety problems occurred or were identified during the demonstration project.

17.7.2.2 Barre, Massachusetts

As part of an expansion of a land disposal site, a private operator excavated and processed a section of the site that had been filled with waste in an unlined area between the mid-1950s and 1970. The wastes in the unlined areas were excavated and relocated while the excavated area was lined to serve as new disposal capacity. The soil fraction recovered from the processing of the excavated wastes was retained for use as cover material for the new facility.

17.7.3 Technology

The discussion on technology is preceded by a paragraph on accelerated decomposition, because stability of buried organic wastes is preferable prior to landfill mining and reclamation.

17.7.3.1 Accelerated Decomposition

Excavating and processing insufficiently decomposed wastes poses the risk of unacceptable generation of nuisances and adverse consequences with regard to human health and safety and to the environment. If landfill mining and reclamation is attempted before the landfilled wastes are sufficiently stabilized, precautions must be taken to protect the health and safety of the workforce and to protect the environment. Leachate recirculation is one of the means employed to accelerate the process of decomposition.

17.7.3.2 Process Design

Process design focuses on the attainment of the following four goals: 1) excavation of the landfilled material; 2) processing of the excavated material to remove recyclable or reusable materials, such as ferrous metals, stabilized organic matter, and soil; 3) transport of the process residues to a landfill; and 4) remediation of the excavated area. Depending on the plan, the excavated area could be properly lined and serve as a landfill.

One aspect of processing design is the recovery of material resources. In the case of those economically developing countries where relatively large percentages of the wastes are putrescible, cellulosic, or both, the materials worthy of recovery include biologically stable organic fines for use as landfill intermediate cover material, final cover material, soil amendment, or a combination of these. Other material fractions for consideration for recovery could be ash and other inorganic fines in those instances where these types of materials are present at relatively high concentrations in a disposal site. Potential uses of these materials include road and building construction materials. For example, at one disposal site in the Republic of China, brick material, ash, and other fines are recovered from landfilled wastes for the manufacture of new bricks.

17.7.3.3 Excavation

The technology involved in the excavation of landfilled waste has not changed much since the Tel Aviv experience in the 1950s. Generally, excavation is conducted using techniques similar to those used for open face mining. Equipment involved may be a front-end loader, a clamshell, a backhoe, a hydraulic excavator, or a combination of these. Excavated material either may be directly processed on-site or be stockpiled for later processing, either on-site or at a processing facility.

Processing begins with the segregation of the excavated mass into discrete streams. As indicated earlier, processing can be mechanical, manual, or both.

Processing at a large landfill site is best accomplished by means of equipment that is characteristically portable. The equipment usually consists of conveyor belts and a screen.

The number of separated streams and the degree of processing involved depend upon several factors. Not the least of the factors is whether the processed material is to serve as a resource or is to be rendered innocuous (remediation or upgrading of a disposal site).

The quantities and characteristics of the material fractions (streams) that are generated by a LFMR operation depend upon: 1) the physical and chemical properties of the excavated material, 2) the effectiveness of the type of mining technology, and 3) the efficiency with which the technology is applied. Judging from available information, and assuming a practical range of stabilities of the mined material and of mechanical processing efficiencies, recovery of soil-like material could be expected to be in the neighborhood of 30 to 70% of the excavated mass. The ratio of soil to other materials depends upon the type of waste landfilled, landfill operating procedures, and the extent of degradation of the disposed wastes.

17.7.4 Feasibility of LFMR

Site-specific conditions determine whether or not LFMR can be used as a method of corrective action. Key conditions include:

- composition of the waste initially put in the landfill;

- landfill geometry;
- historic operating conditions, if any;
- extent of degradation of the waste; and
- quantities of processed materials that, because of their characteristics (e.g., toxic wastes), require extraordinary means to transport and dispose of them.

In the case of economically developing countries, LFMR has potential utility in the remediation of open dumps and in the conversion of an open dump to a landfill. It can also be employed to recover landfilled resources such as a soil fraction for use on-site as cover material.

Based on the few analyses reported thus far for LFMR projects in the United States, the heavy metal content and other characteristics of the recovered soil fraction indicate that the fraction is suitable for use as landfill cover. However, it should be emphasized that the characteristics of the recovered materials are substantially a function of the composition of the buried waste -- including concentrations of heavy metals and of other potentially toxic compounds. The percentage of recovered materials and their characteristics and properties are functions of the composition of the landfilled material and the configuration and operating conditions of the landfill mining process. Analyses of the characteristics of landfilled wastes are required to properly assess the feasibility of LFMR and to properly design and operate an LFMR system.

References

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Chapter 18

Economic Considerations

18.1 Introduction

The coverage in this chapter of the economics of waste disposal is limited to the costs directly related to construction and operation. Omitted from the discussion are other costs that are sometimes charged to the landfill account. The other costs include those for operating recycling programs and non-regulated hazardous waste management programs, and fees for external solid waste programs (i.e., state, province, or national governmental).

The cost of land disposal of solid wastes is obviously a function of the complexity of the construction and of the operation of the facility. For a given location, the cost increases as the complexity of the design increases in response to governmental and public desire for greater protection of the public health and of the environment. An example of the influence of increased complexity of landfill disposal facilities in the United States is shown by the data in Table 18-1.

The data in Table 18-1 illustrate the average trend among the major cost elements of landfill disposal costs in the United States from the 1970s to the 1990s. In the 1970s, the major fraction of the costs for landfilling was that associated with site operation. Since a large number of economically developing countries do not have regulations which require liner and capping systems and closure and post-closure care, their current cost histories and trends correspond approximately to those in the United States in the 1970s. As the environmental performance requirements for land disposal sites became more stringent (around the middle of the 1980s) and the public awareness of the environmental impacts of inadequately designed disposal facilities increased in the United States, the cost of constructing landfills increased; conversely, the operational costs as a percentage decreased. In addition, long-term post-

Table 18-1. Changes in Landfill Development Costs in the United States[a]

Item	Typical Cost (%) 1975[b]	1986[c]	1990[d]
Pre-development	5.9	5 to 10	7.0
Construction	12.3	25 to 35	35.0
Operation	75.7	40 to 50	36.0
Closure	6.1	1 to 5	3.0
Post-closure Care	0	10 to 15	11.0
Unanticipated	0	0	8.0
Total	100	100	100

Adapted from Reference 1.

[a] Profit is not included, 16-ha site, 1 million Mg, 15-year site life.
[b] Includes 117 cm soil liner and leachate collection system.
[c] Includes 150 cm clay liner (available on-site) and 30-year post-closure.
[d] Includes 150 cm clay liner (available on-site), 30 mil synthetic liner, leachate collection system, increased monitoring.

closure care of the disposal facility was also required and, therefore, the cost of the care had to be added to the overall cost. More recently, in the United States (in the early to mid-1990s), the average cost of construction and operation of landfills has reached a plateau. Not illustrated in the table for the time period shown is the wide variation in the magnitude of landfill disposal costs from region to region, primarily due to differences in mandated performance requirements and the availability of land.

The cost of landfilling depends on many factors. Among the more important factors are: the characteristics and quantities of waste to be disposed, in-place density of waste and ratio of cover material to solid waste, availability of suitable soil for use as cover and liner materials, ruggedness of the terrain and ease of access to the site, and whether or not the construction will be phased. All other factors being equal, phased landfill construction generally is cheaper than construction of the entire landfill site at one time. Site conditions and regulatory requirements for landfill construction are major determinants of the magnitude of landfill construction costs and differences among them can result in large differences in costs of construction.

One method of estimating landfill costs is to examine past and current landfill operations in the general vicinity of the proposed disposal area and to obtain or estimate the costs. An estimation of both capital cost and operating cost is required. Additionally, the estimate must be adjusted to reflect the differences between the reviewed disposal operations and the proposed operation.

The cost of landfill disposal contributes to the total cost of waste management of a community. When landfill costs become a relatively high percentage of the cost of waste management, they also can have a substantial influence on the extent and nature of the processing to which the wastes might be subjected prior to ultimate disposal. For example, salvaging and recycling of materials may compete for discarded materials and divert them prior to land disposal.

The cost of operating a landfill can be recovered by means of a user fee, i.e., the user bears the cost of the service. The fee typically is known as a "tipping fee." Tipping fees are commonly, but not exclusively, used to recover the cost of operating landfill in industrialized countries. Tipping fees generally are charged according to the weight or volume of the waste and to the type of waste.

18.2 Potential Methods of Cost Reduction

In those instances and locations in which land suitable for landfill disposal is available at low cost and development costs are low, the cost of landfilling is a relatively small fraction of the total disposal cost. Under such circumstances, landfilling solid wastes without processing usually would be the least expensive method of management. On the other hand, some form of waste processing to reduce amounts and volumes of wastes destined to be landfilled may be economically justifiable in a location in which suitable landfill sites are expensive to develop.

One method of determining the financial performance of a landfill disposal system and operation is to analyze the unit cost (i.e., cost per Mg disposed) over the economic life of the fill. By virtue of this method of analysis, potential optimization or reductions in unit cost can be identified and secured by considering two alternatives: 1) implementing measures that reduce the overall cost without sacrificing the quality and performance of service, and 2) increasing the quantity of wastes that are landfilled. In those cases in which the costs have been optimized, only the second alternative represents potential for decreasing the unit cost. This alternative is sometimes overlooked as a potential means of improving system performance. A disadvantage of using this strategy, of course, is a reduction in the lifespan of the fill.

Reductions in the unit cost of landfilling, or its optimization, can be realized by operating the landfill such that the density of solid wastes placed in the fill is the highest technically achievable value. As discussed in Chapter 10, in-place density is a function of several operating variables (e.g., number of passes of compacting machinery). In the case of existing disposal operations, reductions in the unit cost of disposal (assuming that the accounting of cost is performed over the economic life of the improvement) can be improved if the operational procedures are conducted so that the density of the in-place waste is maximized.

Shredding and baling are two of the more common methods of processing wastes to achieve high in-place densities in a landfill. Either method, if applicable and under appropriate conditions, can increase the density of the collected waste, thereby reducing the volume occupied by the buried waste. Thus, these two methods of processing can increase the mass of waste that can be placed in the fill. Additionally, less cover soil normally is required. Expanding the mass capacity of the landfill and reducing the cover requirements can lower landfill disposal costs if the savings exceed the cost of processing.

Removal of recyclable materials (e.g., scavenging, composting) is a form of waste processing that is comparable to shredding and baling in terms of reduction of amount of waste destined to be landfilled. The scavenging may take place before, during, or after collection.

In addition to methods of reducing the quantities and volumes of wastes entering a land disposal site, the cost of land disposal can be contained in some cases by upgrading the quality of the waste to a level that does not require extraordinary landfilling or containment measures for the protection of the public health and of the environment. Examples of extraordinary measures are those prescribed for a "hazardous waste" landfill (Chapter 8). Among the approaches to upgrading are detoxification of toxic wastes, encapsulation or solidification of hazardous or toxic substances, and acceptance of semi-solid wastes only in those cases where the moisture content is less than the acceptable moisture content (e.g., 60%).

The large-scale processing of waste for recovery of valuable materials prior to land disposal may be justifiable according to technical and/or financial criteria in areas where landfill capacity is scarce and alternate sites are remote from the area of waste generation (i.e., more than 50 km away). Depending on the circumstances and conditions, the large-scale processing could be feasible near the point of collection (i.e., in conjunction with a transfer station) or on the site of the landfill itself. In either case, the outcome of materials recovery is a reduction in the types and quantities requiring land disposal and, therefore, in disposal costs.

18.3 Capital and Operating Costs

Among the principal capital costs are those of land, structures, site preparation and access, vehicles, and heavy equipment. These capital costs usually are fixed costs in that, as a general rule, they do not vary (thus, the use of the term "fixed") during the course of the landfill operation. Labor required for maintenance, fuel costs, and cost of cover material emplaced during the operation of the landfill are all generally classified as operational costs. Operational costs are variable in that they generally increase with the quantities of wastes that are disposed.

A major difficulty in developing a method of estimating the cost of landfill disposal in an economically developing country is the scarcity of reliable data. Thus, data collection is an important first step in accurate cost estimating. The task of data collection can be facilitated considerably by following an organized method. In brief, the method consists of tabulating the applicable components, or elements, of cost (e.g., cost elements such as site preparation), estimating the magnitude of the cost of each cost element, and performing some arithmetic calculations to total and analyze the costs. One representation of the cost components of landfilling is illustrated in Table 18-2. Also shown for illustrative purposes in the table is a relative distribution of the costs among the components.

Table 18-2. Individual Component Cost Relative to Total Landfill Cost[a]

Component	% of Total Cost
Pre-development	3.6
Construction Costs	35.5
Operation Costs	46.0
Closure	0.9
Long-term Care	11.5
Other	2.5

[a] Adapted from References 1, 2, and 3.

A guide, or alternatively model, for cost accounting is presented in Table 18-3. The guide is presented in the form of a worksheet for calculating the cost of landfill disposal.

Table 18-3. Worksheet for Estimating Landfill Costs
(40 ha net disposal area, 180 Mg/day facility) (1995 US Dollars)

Pre-Development Costs	
Siting the facility (engineering, legal fees, and preliminary geotechnical investigations)	$106,000
Site mapping (topographic/boundary surveys) and final geotechnical investigation	106,000
Engineering design and regulatory permit application	141,000
Legal and public hearings	70,000
Land purchase	352,000
Regulatory permitting fees	7,000
Administrative support services	35,000
Contingency	70,000
[a] **Total Pre-Development Cost**	**$887,000**
Initial Construction Costs	
Entrance and access roads	$141,000
General site excavation and land clearing	1,055,000
Erosion and sediment control facilities	70,000
Liners and liner cushion system	774,000
Leachate collection and landfill gas venting system	70,000
Leachate treatment system	141,000
Site landscaping	70,000
Scale system	70,000
Scalehouse and office building	28,000
Equipment maintenance facility	106,000
Public convenience area	42,000
Miscellaneous site paving	42,000
Miscellaneous (lighting, gates, signs, etc.)	70,000
Construction engineering and quality control testing	70,000
Subtotal	2,749,000
Contingency	63,000
[b] **Total Initial Construction Cost**	**$2,812,000**
Annual Operational Costs	
Site personnel and management	$281,000
Facility overhead (e.g., building and ground, site maintenance, and electricity)	70,000
Equipment operations and maintenance	70,000
Equipment rental	211,000
Road maintenance	35,000
Routine environmental monitoring (e.g., groundwater, surface water, and landfill gas)	35,000
Engineering services	42,000
Site and equipment insurance/closure bonding	70,000
Ongoing development and construction costs	352,000
Leachate treatment at a municipal sewer system	14,000
Pre-treatment of leachate prior to disposal into municipal system	70,000
Unanticipated costs	70,000
[c] **Total Operational Costs**	**$1,320,000**

(continued)

Table 18-3. Worksheet for Estimating Landfill Costs
(40 ha net disposal area, 180 Mg/day facility) (1995 US Dollars) (cont.)

Closure and Post-Closure Costs
This assumes that the final cap on the landfill is part of the cost while the landfill is operating. The annual amount should be set aside during the operational years of the landfill.

Costs include the following:

- Engineering fees for preparation of a closure plan
- Regulatory approvals of the closure plan
- Final site grading and revegetation
- Maintenance of erosion and sediment control facilities
- Operation and maintenance of leachate collection and treatment system

[d]	**Annual Closure/Post-Closure Costs**	**$70,000**
Annual Cost		
[e]	Capital costs (a + b)	$3,699,000
[f]	Amortization of capital costs - straight line depreciation over 20 years at 9%	401,000
[g]	Annual operating cost	1,323,000
[h]	Annualized closure and post-closure costs (d)	70,000
[i]	Total annual cost (f + g + h)	1,794,000
[j]	Annual tons per year (200 tons/day x 6 days/week x 52 weeks/yr)	56,160 Mg
[k]	Cost per ton (i/j)	32/Mg
[l]	Host community fee for capital improvements	–
[m]	State or local fee	–
[n]	Total Tipping Fee (k + l + m)	$32/Mg
Cost per Household per Month		
[o]	Annual cost (I)	$1,794,000
[p]	Population (people)	100,000
[q]	Cost per person (o/p)	$18/yr
[r]	Persons per household	4
[s]	Cost per household (q x r)	$6/month

Adapted from Reference 4.

Although the model and worksheet are based on conditions in the United States, they can be adapted easily for use in economically developing countries. The adaptation is possible because the model is based on generic rather than specific cost elements and principles. The costs, as listed in the table, can be interpreted as being "indicators" of the relative costs among the capital and operating cost elements. When adapted for use for another country and set of circumstances, the costs of the cost elements similarly will be indicators of cost allocation for that application.

The cost accounting worksheet presented in Table 18-3 encompasses the main elements of a modern landfill project -- namely, pre-development, initial construction (i.e., capital improvements), annual operation, and closure and post-closure.

The costs listed in the worksheet are an example of those for a 180 Mg/day landfill operation designed to serve a population of 80,000 to 100,000 people, operating in the United States. The facility is situated on a site which has a fill area of about 40 ha, and 60 ha dedicated to disturbed (roads, etc.) and non-disturbed buffer areas. The average excavation depth is about 9 m. The costs also include a double-liner system and a leachate collection and detection system. The facility operates 6 days per week, 52 weeks per year.

Having established the cost elements that apply to a particular landfill site and operation, the estimation process is reduced to properly estimating their costs. The effort placed on determining the magnitude of the costs depends on the objective of the analysis. The objective can range from estimates of costs for general planning and evaluation of alternatives to final cost estimates for: facility design and operation, financing, and specification of cost recovery schedules. Obviously, the greatest effort to determine and establish accurate costs is in those cases where inaccurate cost estimates cause the greatest risks and financial exposures, e.g., the case of estimating costs for purposes of securing financing for capital equipment, and setting rates for recovery of cost.

Cost estimation using general models, formats, and non-site specific data is appropriate for general planning and estimating the range of the potential magnitudes of construction and of all the other costs associated with landfill design and operation. This method of cost analysis is useful in making initial or conceptual design decisions and for comparing various disposal options.

Approximate magnitudes of costs for the development and operation of modern sanitary landfills can be gained by observing those for facilities in the United States over a range of landfill sizes. The magnitudes of costs are provided in Table 18-4 for landfill sites having 100, 200, 300, and 400 ha in total area.

18.4 Costs Associated with Landfill Equipment

In the case of most large landfills, the capital costs of heavy equipment used for landfilling solid waste constitute a major cost component for the development and operation. As was mentioned in Chapter 9, "Equipment Selection," the two principal uses for landfill equipment are to move and compact wastes and to move and compact soil. An indication of the magnitude of the cost of equipment can be gained from the data presented in Table 18-5. Because of the high costs associated with the heavy equipment required for landfilling, the acquisition of a sufficient number of the appropriate equipment for the efficient and continuous operation of a fill oftentimes is not carried out in economically developing countries.

Under the conditions of operation in the United States, the economic lifespan of mobile landfill equipment generally is estimated to be about 5 years (i.e., about 10,000 hours of operation) [5].

In an industrialized nation, the annual cost of maintaining heavy landfill equipment (lubrication, tire repair, replacement parts, etc.) is estimated as being 16 to 18% of the original capital cost of the equipment; the economic life of the equipment is typically 5 to 7 years. The ratio of

Table 18-4. Summary of Landfill Development and Annual Costs in the United States (1995 US Dollars)

Cost Element	Active Landfill Area			
	100 ha	200 ha	300 ha	400 ha
Pre-development ($) [a]	430,000	520,000	610,000	700,000
Site Preparation ($)				
Clay (on-site)	8,700,000	18,300,000	29,500,000	42,200,000
Clay (16 km-haul)	10,600,000	21,800,000	34,600,000	49,300,000
Membrane/Clay (on-site)	11,900,000	24,400,000	38,500,000	54,400,000
Membrane/Clay (16-km haul)	12,900,000	26,400,000	41,700,000	58,600,000
Operations ($/yr)	220,000	380,000	530,000	580,000
Closure ($) [b]	1,400,000 to 2,300,000	2,800,000 to 4,600,000	4,200,000 to 7,000,000	5,700,000 to 9,300,000
Post-closure ($/yr)[c]	170,000 to 340,000	240,000 to 480,000	350,000 to 700,000	460,000 to 920,000

[a] Items included in Pre-development Costs: environmental impact analysis/report, feasibility report, design and plan of operation, administration. Land costs are omitted.

[b] Items included in Closure Costs: earth work, seeding, gas collection.

[c] Items included in Post-closure Costs: monitoring (groundwater, gas, leachate), leachate treatment, site maintenance, liability insurance, seeding, gas collection.

maintenance to capital cost increases substantially if the equipment is operated beyond its economic life. The cost of maintenance of equipment in economically developing countries is obviously dependent upon the prices charged locally for parts and supplies. The actual cost in an economically developing country would depend very strongly upon the age of equipment, type of equipment, maintenance procedures, as well as on a variety of other factors that are particular to the country. However, as an approximate estimation, the ratio of annual maintenance cost to capital cost probably would be on the order of 15 to 20% until the equipment's economic life is exceeded.

Table 18-5. Capital Costs of Landfill Equipment

Type of Equipment	Flywheel Power (kW)	Approx. Wt[a] (Mg)	Range of Cost[b] (US$)	Comments
Crawler Dozer	<60	8 to 10	56,000 to 126,000	Standard/landfill blade
	67 to 97	12 to 16	80,000 to 186,000	Standard/landfill blade
	104 to 130	14 to 20	145,000 to 194,000	Standard blade
	186 to 209	26 to 34	352,000 to 441,000	Landfill blade
Crawler Loader	<68	9 to 11	68,000 to 92,000	GPB:[c] 0.8 m^3
	75 to 97	12 to 16	108,000 to 182,000	GPB: 1.5 m^3
	75 to 97	12 to 16	108,000 to 182,000	MPB:[d] 1.3 m^3
	119 to 142	16 to 22	238,000 to 377,000	GPB: 2.3 m^3
	119 to 142	20 to 24	238,000 to 377,000	MPB: 1.9 m^3
Rubber-tired Loader	<75	7 to 10	98,000	GPB: 1.3 m^3
	<75	8 to 11	115,000	MPB: 1.1 m^3
	89 to 119	9 to 12	138,000 to 212,000	GPB: 3.0 m^3
	89 to 257	10 to 13	138,000 to 212,000	MPB: 1.7 m^3
Landfill Compactor	141 to 161	<21	215,000 to 279,000	Landfill blade
	224 to 235	29 to 32	300,000 to 451,000	Landfill blade
	250 to 392	31 to 46	365,000 to 569,000	Landfill blade

Source: equipment manufacturers.

[a] Basic machine plus engine sidescreens; radiator guards; reversible fan; roll bar; and either a landfill blade, general-purpose bucket, or multiple-purpose bucket as noted.

[b] January 1996. The range of costs reflects differences regarding the equipment supplied by the manufacturer and regarding specifications of options supplied. Equipment costs in economically developing countries may be between 5 to 60% more than the costs of the same equipment in the United States. The additional costs of equipment in economically developing countries can be due to any or a combination of the following: transportation costs, taxes, custom clearance, and import duties.

[c] General-purpose bucket.

[d] Multiple-purpose bucket.

As is the case with the cost of maintenance, the cost of fuel varies with type, condition, and use of the equipment. The cost is fundamentally related to the rate of fuel consumption. As an approximation, total fuel consumption for a mechanically intensive landfill operation averages about 35 liters fuel/Mg waste disposed [6]. Considering this estimate as the basis, the fuel consumption per piece of heavy equipment probably would be on the order of 100 liters per day.

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16. ABSTRACT The report offers guidance on all aspects of the planning, design, and implementation of landfills in economically developing countries. The intended audience includes municipal officials, solid waste managers, engineers, and planners. The report's 18 chapters include critical technical areas such as siting, design, and operation of landfills. Equally important non-technical aspects such as social, economic, and institutional topics relevant to developing landfills in economically developing countries are also discussed. The guiding principle of the report is the application of acceptable landfill practices within the conditions and availability of resources prevailing in both large urban cities and small communities in economically developing countries.

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Earth Fills		13C
Sites		
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