LDCRS FLOW FROM DOUBLE-LINED LANDFILLS AND SURFACE IMPOUNDMENTS

by

Rudolph Bonaparte and Beth A. Gross
GeoSyntec Consultants
Atlanta, Georgia 30342

Contract No. 68-C0-0068

Project Officer

Mr. Robert E. Landreth
Risk Reduction Engineering Laboratory
Cincinnati, Ohio 45268

RISK REDUCTION ENGINEERING LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

DISCLAIMER

The information in this document has been funded by the U.S. Environmental Protection Agency (EPA) under Contract No. 68-C0-0068, Work Assignment No. 35 to Eastern Research Group, Inc. It has been subjected to the Agency's peer and administrative reviews, and it has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resource. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Risk Reduction Engineering Laboratory is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities.

This report provides the field data to support the Agency's recent final rule on liner leak detection (40 CFR 260, 264, 265, 270, and 271). The data illustrates that waste management facilities can be constructed with minimal leakage rates provided that quality control and quality assurance programs are used.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

ABSTRACT

This report presents field data on the measured flows of liquid from the leakage detection, collection, and removal systems (LDCRSs) of 28 double-lined landfill facilities and eight double-lined surface impoundment facilities. For each facility, information on design and operation is presented, as is an evaluation of the sources of the measured flow. Potential sources include leakage through the top liner, precipitation that percolates into the LDCRS during construction, water that infiltrates through the bottom liner and enters the LDCRS, and consolidation of any clay component of the top liner. From the evaluation, conclusions are drawn regarding the frequency of occurrence, sources, and rates of liquid flows from the LDCRSs of double-liner systems. Conclusions are as follows:

- LDCRSs frequently exhibit flows from one or several of the aforementioned sources;
- all of the landfill cells constructed with geomembrane top liners appear to have exhibited top liner leakage; cells with composite top liners typically exhibited LDCRS flows attributable to consolidation water, except for composite liners constructed with geosynthetic-clay liners (GCLs) for which there is little, if any, consolidation water;
- about 60 percent of the surface impoundment ponds constructed with geomembrane top liners appear to have exhibited top liner leakage; the lower incidence of top liner leakage for ponds than for landfill cells may be attributed to the use of ponding tests and/or leak location surveys during construction of the ponds to identify geomembrane defects and allow their repair;
- flow rates from the LDCRSs of the landfills are generally within the range that would be expected, based on currently available methods of analysis for liner system performance; flow rates from the LDCRSs of ponds constructed with geomembrane top liners are lower than would be calculated using available analysis methods because the use of ponding tests and leak location surveys, followed by geomembrane repair, resulted in fewer geomembrane liner defects than assumed in the analysis methods; and
- facilities constructed with a rigorous construction quality assurance program typically meet EPA recommended action leakage rates (ALRs) of 1,000 lphd (100 gpad) for landfills and 10,000 lphd (1,000 gpad) for ponds; however, flow rates higher than these ALRs occasionally occur at landfills with composite top liners and ponds that have geomembrane top liner defects.

This report was submitted in fulfillment of Contract No. 68-C0-0068, Work Assignment No. 35, by GeoSyntec Consultants under the sponsorship of EPA. The report covers work completed through September 1992.

CONTENTS

CONTENTS (continued)

FIGURES

TABLES

ACKNOWLEDGEMENTS

This report was prepared under the guidance of the EPA, Office of Research and Development. The EPA Task Manager overseeing preparation of the report was Mr. Robert E. Landreth. An earlier version of this report was prepared for the EPA Office of Solid Waste. EPA Task Managers for the earlier report were Messrs. Alessi D. Otte and William Kline. The support and contributions of Messrs. Landreth, Otte, and Kline to this work are appreciated. The authors would also like to thank Dr. J.P. Giroud of GeoSyntec Consultants for his review of the report.

SECTION 1

INTRODUCTION

1.1 PURPOSE OF THE REPORT

Liquid flows have been observed from the leakage detection, collection, and removal systems (LDCRSs) of many double-lined landfill and surface impoundment units. Regulatory authorities and others have sometimes assumed that these flows are due solely to leakage through the top liner and are, therefore, a cause for concern and action. The flows, however, can be due to sources other than top liner leakage.

The purpose of this report is to summarize and evaluate field data on the measured flows of liquid from the LDCRSs of 28 double-lined landfills and eight double-lined surface impoundments. The report was originally prepared to provide technical support for EPA's proposed Liner/Leak Detection System Rule of 29 May 1987. In this proposed rule, EPA introduced the concept of action leakage rate (ALR) which was defined as (52 FR 20222) "*the rate of leakage from the top liner into the LDCRS that triggers interaction between the owner or operator and the Agency to determine the appropriate response action for the leakage*". Under the proposed rule, the facility owner or operator could establish an ALR as a value specified by EPA or by developing a site-specific ALR. The ALR value specified by EPA was proposed to be in the range of 5 to 20 gallons/acre/day (gpad). This report was initiated to provide technical support to EPA for selection of a specific ALR value. Interim results of the investigation of LDCRS flow rates were presented by Bonaparte and Gross [1990]. In their paper, Bonaparte and Gross conclude that while an ALR of 50 lphd (5 gpad) is too restrictive, an ALR of 200 lphd (20 gpad) appears to be reasonable for facilities constructed to present standards with rigorous construction quality assurance. (NOTE: For simplicity, in this report it is assumed that 1 gpad = 10 lphd. More precisely, however, 1 gpad = 9.3 lphd.)

The proposed Liner/Leak Detection System Rule was finalized on 29 January 1992 (57 FR 3462). The original ALR concept was not included in the final rule, and the ALR was redefined as (57 FR 3462) "*the maximum design leakage rate that the leak detection system can remove without the fluid head on the bottom liner exceeding one foot*". The value of the ALR in the final rule is site-specific. Additionally, as stated in the preamble to the final rule (57 FR 3474), "*the Agency believes that units meeting the minimum technical requirements would not require action leakage rates below 100 gpad for landfills and waste piles and 1000 gpad for surface impoundments*". These flow rates, which are referred to as EPA's "*recommended action leakage rates*" in the preamble to final rule, are significantly higher (i.e., approximately one to two orders of magnitude higher) than the ALR values considered under EPA's proposed rule of 29 May 1987. As will be shown in this report, the facilities considered in this report typically exhibited LDCRS flows less than the ALR values in the final rule.

1.2 ORGANIZATION OF THE REPORT

The organization of this report is as follows:

- conclusions on the analysis and interpretation of the LDCRS flow rate data are presented in Section 2;
- recommendations for future research related to the information presented herein are presented in Section 3;
- potential sources of liquid flows from LDCRSs are described in Section 4;
- data on measured flows from the LDCRSs of double-lined landfills and surface impoundments are presented in Section 5; and
- analysis and interpretation of the LDCRS flow rate data is presented in Section 6.

The regulatory developments that led to the final ALR concept are presented in Appendix A of this report.

1.3 DEFINITIONS

1.3.1 Landfills and Surface Impoundments

Landfills and *surface impoundments* are land-based units that contain solid wastes, and liquid wastes or sludges, respectively. The goal of the lining system in these units is to minimize, to the extent achievable, the migration of hazardous constituents out of the units.

1.3.2 Liner, Lining System, and Double-Liner System

A *liner* is a low-permeability barrier used to impede liquid or gas flow. As discussed in Giroud [1984] and EPA [1987], no currently available liner is totally impermeable. Since no liner is impermeable, liquid containment within a landfill or surface impoundment unit can only result from a combination of liners and drainage layers performing complementary functions. Liners impede the flow of liquid out of the unit. Drainage layers collect and convey the liquid towards controlled collection points (sumps) where the liquid can be removed from the unit. Combinations of liners and drainage layers in the units are called *lining systems*.

A *double-liner system* is a lining system which includes two liners with a leakage detection, collection, and removal system (LDCRS) between the liners. For landfills, a leachate collection and removal system (LCRS) is placed above the top liner. For surface impoundments, there is no need or regulatory requirement for a LCRS above the top liner. The majority of double-liner systems being constructed today have either geomembrane or composite top and bottom liners (where a composite liner consists of a geomembrane placed directly on top of a low-permeability soil layer or geosynthetic clay liner (GCL)) with a LDCRS between the two liners. Older lining systems constructed with low-permeability soil liners alone are not considered in this report.

1.3.3 Double-Liner System Components

Figure 1 illustrates typical double-liner systems used to contain leachate in landfills. Double-liner systems used to contain liquid in surface impoundments are similar to those shown in Figure 1, except that surface impoundments do not require an LCRS drainage layer above the top liner. (Waste piles are a third type of land-based containment unit and are similar to landfills except that they only contain solid wastes temporarily. Waste piles are mentioned briefly in this report for completeness since they are subject to most of the same regulations as landfills.) The double-liner systems shown in Figure 1 incorporate the liner types (i.e., geomembrane liners and composite liners) and the drainage materials types (i.e., granular materials, geonets, or other geosynthetics) used to construct landfills, waste piles, and surface impoundments. The types of liners and drainage materials used in double-liner systems significantly influence the frequencies of occurrence, sources, and rates of flow from LDCRSs. Therefore, different liner and drainage material types will be considered in this report.

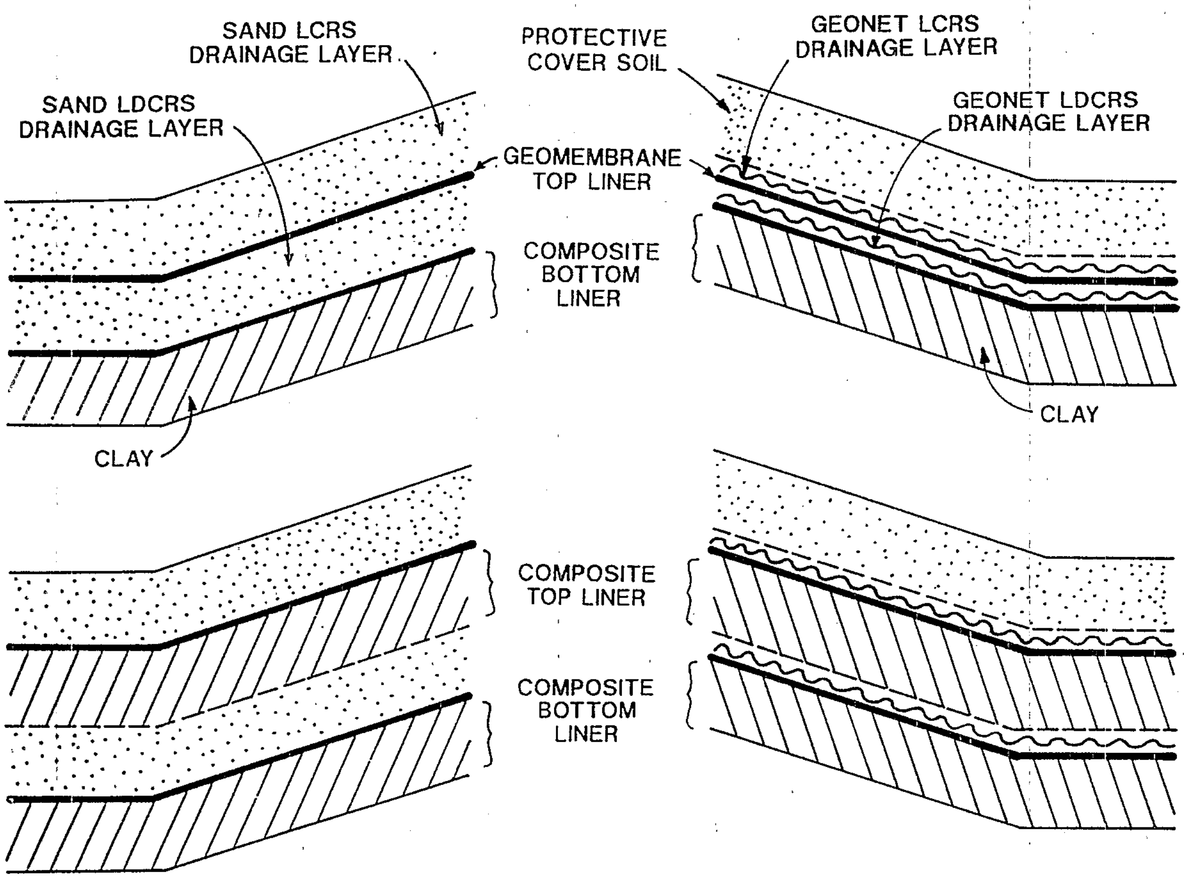


Figure 1. Typical double-liner systems for leachate containment in landfills.

In this report, the parameters used to describe the design features of double-liner systems are (Figure 2): i = slope gradient (dimensionless); k_{dt} = hydraulic conductivity of the LCRS drainage material (cm/s); T_{dt} = thickness of the LCRS drainage material (m (ft)); T_{gt} = thickness of the geomembrane component of the top liner (mm (mil)); k_{st} = hydraulic conductivity of the compacted low-permeability soil or geosynthetic clay liner (GCL) component of the top liner (cm/s); T_{st} = thickness of the compacted low-permeability soil or GCL component of the top liner (m (ft)); k_{db} = hydraulic conductivity of the LDCRS drainage material (cm/s); T_{db} = thickness of the LDCRS drainage material (m (ft)); T_{gb} = thickness of the geomembrane component of the bottom liner (mm (mil)); k_{sb} = hydraulic conductivity of the compacted low-permeability soil component of the bottom liner (cm/s); and T_{sb} = thickness of the compacted low-permeability soil component of the bottom liner (m (ft)).

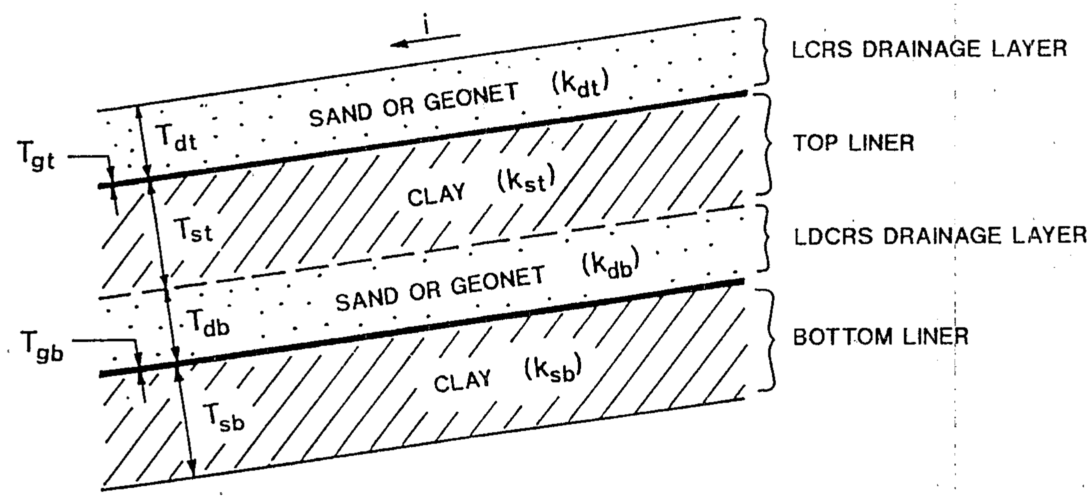


Figure 2. Definitions and terminology for double-liner system components. (Note: k = hydraulic conductivity; T = thickness; and i = slope gradient.)

SECTION 2

CONCLUSIONS

Using the data for landfills and surface impoundments presented in Section 5 of this report, and the data analysis and interpretation presented in Section 6, the following conclusions are drawn with respect to LDCRS flows from double-lined waste containment facilities.

- LDCRSs frequently exhibit flows that may be due to top liner leakage or other sources such as construction water, consolidation water, and infiltration water. LDCRS flow rate data presented in Tables 4 and 7, for landfills and surface impoundments, respectively, demonstrate the frequencies of occurrence and rates of flow from these sources.

- All of the landfill cells reviewed in this report that were constructed with geomembrane top liners appear to have exhibited top liner leakage. Based on the available data, the average and maximum flow rates attributable to top liner leakage at active cells that had geomembrane top liners and construction quality assurance (CQA) programs were less than 1,000 lphd (100 gpad). Typically, flow rates from these units were less than 200 lphd (20 gpad). For cells without CQA programs, both average and maximum flow rates attributable to top liner leakage were frequently more than 1,000 lphd (100 gpad). Maximum flow rates, which often occurred shortly after storm events, were typically several times greater than the average flow rates.

- Only about 60 percent of the surface impoundment ponds reviewed in this report that were constructed with geomembrane top liners appear to have exhibited top liner leakage. In general, the measured flows from the ponds were less than 300 lphd (30 gpad). The lower incidence of top liner leakage for ponds than for landfill cells may be attributed to the use of ponding tests and/or leak location surveys during construction of the ponds to identify geomembrane defects and allow their repair. Additionally, when flows were observed during operation of a pond, defects were often located and repaired. Thus, significant LDCRS flows from ponds were often of limited duration (i.e., until the pond was repaired).

- Facilities having a composite top liner incorporating a layer of clay almost always exhibited LDCRS flows due to consolidation water. Flows attributable to primary consolidation of the clay occurred while the facilities were active. Continuing flows after facility closure are potentially attributable to water expelled during secondary compression of the clay layer (secondary compression water). Average measured flow rates attributable to consolidation water ranged up to 1,300 lphd (130 gpad), although most rates were less than 300 lphd (30 gpad); average measured flow rates potentially attributable to secondary compression water ranged from 30 to 380 lphd (3 to 38 gpad).

- Leakage rate calculations performed using the method of Giroud and Bonaparte [1989a,b] provide a reasonable upper bound on observed flow rates attributable to top liner leakage at landfills with geomembrane top liners. However, the method greatly overpredicts top liner leakage rates at impoundments with geomembrane top liners. It appears that the primary reason for the overprediction is that the number and/or frequency of geomembrane holes assumed by Giroud and Bonaparte are too high for the considered surface impoundments and period of monitoring. Based on the data in this report, the use of ponding tests and leak location surveys, followed by geomembrane repair, reduces the frequency and/or size of geomembrane holes below the number often assumed for leakage rate calculations (i.e., 3 to 5 per hectare (1 to 2 per acre)).

- The calculation methods presented by Gross et al. [1990] for estimating consolidation water and construction water flow rates appear to give reasonable order-of-magnitude estimates of flows attributable to these sources.

- Based on an analysis of the data presented in Tables 4 and 7, facilities with double-liner systems constructed with a rigorous CQA program will typically meet the EPA recommended action leakage rates of 1,000 lphd (100 gpad) for landfills and 10,000 lphd (1,000 gpad) for surface impoundments. For landfills with composite top liners, flows due to consolidation water may occasionally be greater than 1,000 lphd (100 gpad). For surface impoundments that have defects in the geomembrane top liner, flow rates may temporarily be higher than 10,000 lphd (1,000 gpad). However, repair of the defects will usually decrease flows to below triggering levels (i.e., less than 10,000 lphd (1,000 gpad)).

SECTION 3
RECOMMENDATIONS

3.1 INTRODUCTION

The information contained in this report is intended to provide a preliminary understanding of how landfill and surface impoundments are performing with respect to liquid containment and environmental protection. To increase this understanding, it is recommended that additional studies be undertaken. The purpose of this section of the report is to present recommendations for future studies to expand the information contained in this report. In developing the recommendations, emphasis is placed on those studies appearing to have the best potential to provide useful results and that can be performed with data currently accessible to EPA.

3.2 AVAILABLE DATA

As a starting point for the additional studies, data should be obtained from the waste management units described in this report and other units that have designs meeting, or at least reasonably consistent with, existing EPA regulations. Information should be collected directly from the owners/operators of the units, as well as from EPA files. The data that should be gathered for each unit include:

- type of unit and design details, geographic location, hydrogeologic setting, waste characteristics, key dates in the life of the unit (e.g., construction, operation, closure), and operations and maintenance information;
- LCRS monitoring data (liquid quantity and chemical quality);
- LDCRS monitoring data (liquid quantity and chemical quality);
- unsaturated zone monitoring data (liquid quantity and chemical quality), if it exists;
- ground-water quality monitoring data;
- rainfall monitoring data; and
- results of any special evaluations or testing, such as geomembrane coupon testing.

3.3 DATA EVALUATION

The available data for landfills, waste piles, and surface impoundments should be collected, analyzed, interpreted and cataloged. The cataloging effort should be designed to create a permanent data base, available for interested parties, that can be periodically updated in the future. The analyses and interpretation of the data should be intended to systematically address the following questions.

- What quantity and chemical quality of leachate is generated in the units, both during and after closure?
- How does the quantity and chemical quality of leachate vary geographically?
- What impact is EPA's land disposal restrictions (i.e., 40 CFR 268) having on leachate quantity and chemical quality?
- What is the quantity and chemical quality of the liquid flows from the LDCRSs of the units?
- What are the sources of the liquid flows from the LDCRSs?
- What conclusions can be drawn from the available LDCRS data on the performance of top liners and, by extrapolation, on the performance of the entire liner system?
- What is the risk of the liquid flows from the LDCRS on human health and the environment?
- Is there any indication from the available data that the LCRSs or LDCRSs are clogged or otherwise not functioning adequately?
- Is there any indication that units with one type of LCRS or LDCRS design are performing better than units with a different type of design?
- Does available ground-water quality monitoring data or other available monitoring data (such as unsaturated zone monitoring data) provide any indication of leakage from a unit?

SECTION 4

POTENTIAL SOURCES OF LIQUIDS IN LDCRSs

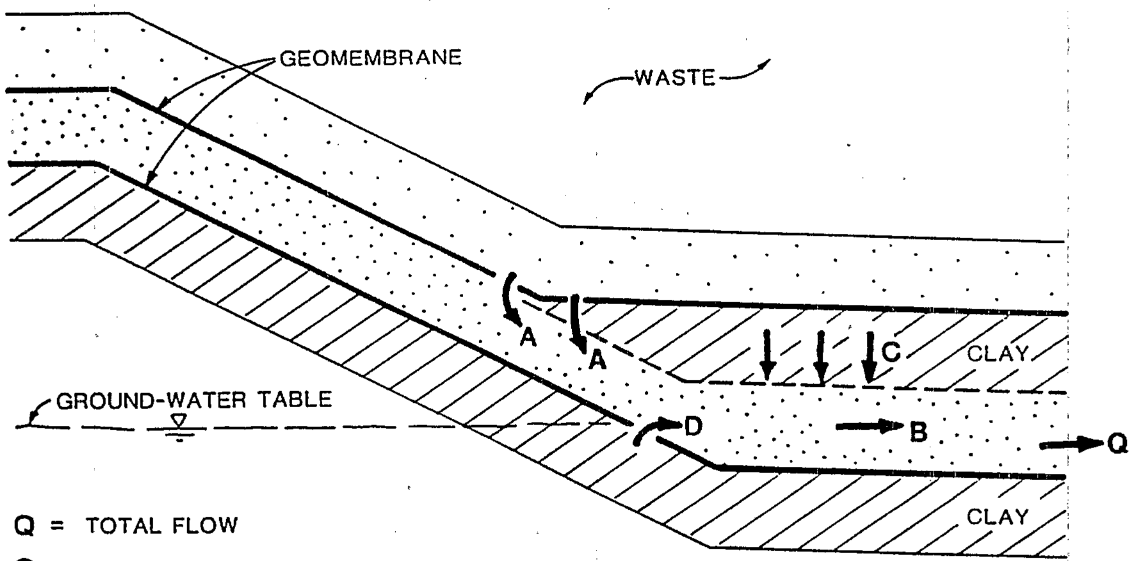
4.1 INTRODUCTION

To evaluate LDCRS flow data, the potential sources of flow must first be identified. Flow can be due to top liner leakage, water from precipitation or other sources that percolates into the LDCRS during construction ("construction water"), water expelled from a granular LDCRS due to compression of the LDCRS ("compression water"), water squeezed out of the clay component of a composite top liner as a result of clay consolidation ("consolidation water"), and water that infiltrates the bottom liner and enters the LDCRS ("infiltration water") [Gross et al., 1990]. Each of these potential sources of flow is depicted in Figure 3 and is described below.

4.2 TOP LINER LEAKAGE

All of the top liners considered in this report include geomembranes (i.e., they are either geomembrane liners or composite liners). Leakage through liners constructed with geomembranes occurs essentially as a result of flow through defects in the geomembrane. Occasional small defects in geomembranes may result from manufacturing, but are more likely to result from during or after geomembrane installation. Equations to calculate steady-state leakage rates through liners constructed with geomembranes due to flow through holes were developed in EPA [1987], based on the analytical and experimental studies by Faure [1979, 1984], Sherard [1985], Fukuoka [1985, 1986], and Brown et al. [1987]. The equations were later modified by Bonaparte et al. [1989], Giroud and Bonaparte [1989a,b], and Giroud et al. [1989; 1992]. Based on these equations, the rate of flow through geomembrane holes is dependent on the liquid head on the geomembrane, the hydraulic conductivities of the soil layers immediately underlying and overlying the geomembrane, the size and frequency of occurrence of holes in the geomembrane, and, for composite liners, the quality of the contact between the geomembrane and underlying soil layer (which is a function of the quality of construction).

Table 1 presents the results of calculations using the equations for flow through holes in a geomembrane to obtain top liner leakage rates per unit area of liner. For the calculations, it was assumed that the soil layer underlying the geomembrane is 0.9 m (3 ft) thick, and the GCL underlying the geomembrane is 6 mm (0.25 in.) thick. It was further assumed that the geomembrane was carefully constructed and had only five small holes per hectare (2 small holes per acre), with each hole having an area of 3×10^{-6} m^2 (5×10^{-3} in^2), and that good quality contact existed between the geomembrane and underlying soil layer or GCL (assumptions consistent with those of Giroud and Bonaparte [1989a,b]).



Q = TOTAL FLOW

Q = A+B+C+D

POTENTIAL SOURCE:

A = TOP LINER LEAKAGE

B = CONSTRUCTION WATER AND COMPRESSION WATER

C = CONSOLIDATION WATER

D = INFILTRATION WATER

Figure 3. Potential sources of flow from LDCRSs (from Bonaparte and Gross [1990]).

Table 1. Calculated top liner leakage rates due to leakage through holes in a geomembrane (q_T, lphd). (Values obtained using equations from Bonaparte et al. [1989] and Giroud et al. [1992], and the following input parameters: N = number of geomembrane holes per unit area = 5 holes/hectare (2 holes/acre); a = area of geomembrane hole = 3 x 10^{-6} m^2 (5 x 10^{-3} in^2); k_{min} = minimum of k_{db} or k_{st}; and h_t = liquid head on liner. Good quality contact exists between the geomembrane and underlying soil layer or geosynthetic clay liner (GCL). The thickness of the soil layer is 0.9 m (3 ft), and the thickness of the GCL is 6 mm (0.25 in.).)

Hydraulic Conductivity k_{min} (cm/s)	Liquid Head on Liner, h_t (m (ft))					
	0.03 (0.1)		0.3 (1)		3.0 (10)	
	Soil Layer	GCL	Soil Layer	GCL	Soil Layer	GCL
10^{-9}	-	0.01	-	0.2	-	10
10^{-8}	0.05	0.06	0.4	1	3	80
10^{-7}	0.3	-	2	-	20	-
10^{-6}	1	-	10	-	90	-
10^{-5}	8	-	60	-	500	-
10^{-4}	40	-	300	-	2600	-
10^{-3}	200	-	1000	-	5200	-
10^{-2}	400	-	1500	-	6200	-
10^{-1}	600	-	2000	-	6300	-
1	600	-	2000	-	6300	-

From inspection of Table 1, it can be seen that calculated steady-state top liner leakage rates through composite liners (based on a hydraulic conductivity (k_{min}) of the clay or GCL component of the composite liner of 10^{-7} cm/s or less) range from 0.01 to 90 lphd (0.001 to 9 gpad). In contrast, calculated leakage rates through geomembrane liners underlain by drainage materials (with the hydraulic conductivity of the drainage material $k_{min} > 10^{-2}$ cm/s) range from 400 to 6,300 lphd (40 to 630 gpad). The calculated leakage rates for geomembrane top liners are about two to five orders of magnitude greater than those calculated for composite top liners. A further contrast between composite liners and geomembrane liners lies in the fact that it can take from several months to many years for liquid to flow through the clay component of a composite liner or several days to several years for liquid to flow through the GCL component of a composite liner, whereas flow through a hole in a geomembrane liner underlain by a drainage material occurs almost instantaneously. It can also be observed from Table 1 that composite liners incorporating GCLs are most effective at minimizing leakage when subjected to liquid heads of 0.3 m (1 ft) or less, which are typical for landfills. When subjected to higher liquid heads, such as those that occur in surface impoundments (e.g., 3 m (10 ft)), the effectiveness of composite liners incorporating GCLs decreases somewhat due to the high hydraulic gradient across the GCL [Giroud et al., 1992].

4.3 CONSTRUCTION WATER

The primary source of construction water in a LDCRS is precipitation that percolates into the LDCRS prior to placement of the top liner. Of this water, some may be retained in the drainage material by capillary tension, and the rest will flow by gravity from the LDCRS.

The maximum time required for gravity drainage of construction water from a LDCRS can be estimated using Darcy's equation, as follows:

$$t_c = L_f \, n_{db} \, / (k_{db} i) \qquad \text{(Equation 1)}$$

where: t_c = maximum time for gravity drainage of construction water (s); L_f = maximum length of flow path (m (ft)); i = slope gradient (dimensionless); and n_{db} = porosity of the LDCRS drainage material (dimensionless).

The maximum volumetric moisture content of a drainage material due to capillarity is referred to as its specific retention, s_r. The specific retention of a drainage material is dependent on the size distribution and shape of the material's pores. The specific retention of a geonet drainage layer is zero; the specific retention of a coarse gravel is almost zero. A medium to coarse sand has a specific retention on the order of 0.08 [Linsley et al., 1975]. If the volumetric moisture content, w_v, of the

LDCRS drainage material at the end of construction is less than its specific retention (i.e., if $w_v < s_r$), there will be no drainage of construction water. If, however, the volumetric moisture content of the material at the end of construction is greater than its specific retention (i.e., if $w_r > s_r$), water will drain from the layer until the volumetric moisture content equals the specific retention (i.e., $w_r = s_r$).

The volume of water per unit area of liner that drains from the LDCRS by gravity can be estimated using the following equation:

$$v_C = T_{db}\ (w_v - s_r) = T_{db}\ (S\ n_{db} - s_r) \qquad \text{(Equation 2)}$$

where: v_C = volume of construction water per unit area of liner that drains from the LDCRS by gravity (m (ft)); w_v = volumetric moisture content of drainage material at end of construction (dimensionless); s_r = specific retention of drainage material (dimensionless); and S = degree of saturation of drainage material at end of construction (dimensionless).

The average LDCRS flow rate per unit area of liner, q_C (lphd (gpad)), due to construction water is given by:

$$q_c = v_C\ /\ t_C \qquad \text{(Equation 3)}$$

Gross et al. [1990] presented the results of calculations to quantify potential construction water flow rates and durations for a typical landfill cell. The results indicate that the flow rate is directly proportional to k_{db} and the duration of flow is inversely proportional to k_{db}. Thus, with a high-permeability drainage material, such as a clean gravel or geonet (e.g., $k_{db} > 1$ cm/s), the flow rate after a precipitation event can be large (e.g., 200,000 lphd (20,000 gpad)) but of very short duration (e.g., less than one day). In contrast, with a lower-permeability drainage material, such as a fine to medium sand (e.g., $k_{db} = 10^{-2}$ cm/s), the rate of flow of construction water will be smaller (e.g., 2,000 lphd (200 gpad)), but the duration of flow will be quite long (e.g., more than 100 days). In the latter case, construction water may still be draining from a facility well after the start of operation.

4.4 COMPRESSION WATER

As a LDCRS constructed of a granular material compresses under the weight of the overlying waste or impounded liquid, the pore volume and porosity of the LDCRS decrease. Simultaneously, the capillary tension of water in the pores of the material increases as the soil particles take on a denser packing.

When a granular LDCRS material retaining water by capillary tension compresses, the volume of water per unit area of liner that drains from the LDCRS can be calculated using the following equation:

$$v_E = \epsilon_v \, s_r \, T_{db} = (\Delta\sigma_v \, / \, E_c) s_r \, T_{db} \qquad \text{(Equation 4)}$$

where: v_E = volume of water per unit area of liner that drains from the LDCRS by gravity (m (ft)); ϵ_v = compressive strain of the LDCRS drainage material (dimensionless); $\Delta\sigma_v$ = change in vertical stress due to placement of waste (kPa (psf)); and E_c = constrained modulus of the drainage material (kPa (psf)). Equation 4 was derived using the conservative assumption that there is no increase in specific retention of the granular material as it compresses under the weight of the overlying waste. Equation 4 can only be used if the volumetric water content of the material is greater than or equal to its specific retention (i.e., $w_v \geq s_r$). If the volumetric water content of the material is less than the material's specific retention (i.e., $w_v < s_r$), Equation 4 is not valid since liquid may not be released as a result of compression.

Calculations in Gross et al. [1990] indicate that the flow rate of compression water from a granular drainage material initially at its specific retention is small (e.g., 1 to 20 lphd (0.1 to 2 gpad)) and is frequently negligible in comparison to potential flow rates from other sources.

4.5 CONSOLIDATION WATER

Two general categories of low-permeability soil layers must be considered: (i) relatively thick (0.5 to 1.5-m (1.5 to 5-ft) thick) layers of compacted natural clay or bentonite-treated soil; and (ii) thin (6-mm (0.25 in.) thick) GCLs. During filling of a landfill or surface impoundment, soil layers in the first category will consolidate and expel water into the adjacent LDCRS drainage layer. GCLs, however, are placed in a dry state and will not contribute additional liquid to the LDCRS.

An upper bound of the rate at which water is expelled from a clay layer can be obtained by assuming the clay layer is initially saturated. With this assumption, the occurrence of consolidation water can be quantified using the classical theory of one-dimensional consolidation [Terzaghi, 1943]. This theory uses the consolidation time factor, T, defined as:

$$T = \frac{c_v t}{H^2} \qquad \text{(Equation 5)}$$

where: T = consolidation time factor at time t (dimensionless); t = elapsed time since instantaneous load application (s); H = length of drainage path (m (ft)); and c_v = coefficient of consolidation (m^2/s

(ft^2/s)). The theory also establishes a relationship between the consolidation time factor T and the degree of consolidation U.

Schiffman [1957] modified the classical theory of one-dimensional consolidation to account for a constant rate of load application. In his work, Schiffman established a relationship between the degree of consolidation U and the consolidation time factor T. This relationship was later used by Giroud [1983] to determine the maximum rate of consolidation R_{max} (defined as dU/dT) for a constant rate of load application. For flow rate calculations, it can be assumed that the rate of filling of a unit is constant between t = 0 and t = t_f, where t_f is the time required to fill the landfill or surface impoundment. It can also be assumed that the pore water within the clay layer drains to the LDCRS drainage layer (i.e., the maximum length of the drainage path for pore water is equal to the thickness of the clay layer).

For most landfill and many surface impoundment applications, the time factor, T_f, at the end of filling (obtained using Equation 5 with t = t_f) is larger than one. As shown by Giroud [1983], when $T_f > 1$, almost all of the consolidation water has been expelled at time t = t_f (i.e., at the end of waste placement or surface impoundment filling) and $R_{max} = 1/T_f$.

Giroud [1983] has established the following equation to calculate the maximum rate of water expulsion from a consolidating clay layer subjected to a constant rate of load application:

$$q_S = \frac{\Delta\sigma_v \, k_{st}}{\rho_w \, g \, T_{st}} R_{max} \qquad \text{(Equation 6)}$$

where: q_S = maximum flow rate from the LDCRS per unit area of liner due to consolidation water (m/s (ft/s)); $\Delta\sigma_v$ = vertical stress due to the weight of waste (kPa (psf)); ρ_w = density of water (kg/m^3 (lb/ft^3)); g = acceleration of gravity (m/s^2 (ft/s^2)); and R_{max} = maximum rate of consolidation. Equation 6 is conservative because it assumes that the clay is initially saturated. In most cases, clay layers are compacted to a degree of saturation between 75 and 90 percent.

Calculations presented in Gross et al. [1990] suggest that the flow rate due to consolidation water may range from 10 to 1,500 lphd (on the order of 1 to 150 gpad). Higher flow rates are associated with more compressible soils, faster rates of load application, and larger consolidation stresses. The calculations also indicate that, for most landfills that receive waste at a steady rate over one or more years, the end of primary consolidation will approximately coincide with the end of the active life of the landfill.

It should be noted that, as described by Bonaparte and Gross [1990], water from secondary compression of a clay layer may persist after the end of primary consolidation. In general, soils that exhibit relatively high consolidation, such as high plasticity clays, will also exhibit relatively high secondary compression. As a consequence, for some plastic clay materials compacted wet of optimum moisture content, water due to secondary compression may be a significant source of liquid flow after the end of a facility's active life. Calculated secondary compression flow rates are in the range of 10 to 100 lphd (on the order of 1 to 10 gpad). These flow rates may persist over the entire post-closure period of the facility, albeit at a progressively decreasing rate.

4.6 INFILTRATION WATER

Infiltration water can migrate through defects in the geomembrane component of the bottom liner into the LDCRS if there is a sustained ground-water table above the base of the bottom liner or if the bottom liner is a composite liner with a clay layer that is undergoing consolidation or secondary compression. The calculation results given in Table 1 can be used to estimate infiltration rates if it is assumed that the rate of flow through the liner is independent of the direction of flow (i.e., up or down). In this case, k_{min} in Table 1 corresponds to the hydraulic conductivity of the soil immediately underlying the geomembrane component of the bottom liner. From Table 1, the quantity of infiltration through composite bottom liners (i.e., $k_{sb} < 10^{-6}$ cm/s) constructed with clay layers will be relatively small and will only occur after water saturates the clay layer. In contrast, infiltration rates through geomembrane bottom liners underlain by relatively permeable soils can be very large and will occur quickly.

SECTION 5

DATA FROM LDCRSs OF OPERATING UNITS

5.1 DATA COLLECTION METHODOLOGY

The data presented in this report were obtained from engineering drawings, project specifications, operation records, and interviews with facility owners and operators and regulatory agencies. With respect to flow data, in most cases only data on LDCRS flow rates were available; data on LCRS flow rates and on the chemical quality of flows from the LDCRS and LCRS were typically not available. Efforts were made to obtain data from operating and closed landfills and from facilities constructed with different types of lining systems (e.g., geomembrane top liners versus composite top liners, and sand LDCRS drainage layers versus geonet LDCRS drainage layers), constructed with and without third-party construction quality assurance (CQA) programs, and located in different climatic regions. For the purpose of this report, a facility was considered to be closed if it was covered with a soil layer or geomembrane. Very little data were obtained from closed facilities, and approximately 86 percent of the facilities were constructed under a third-party CQA program. In addition, approximately 96 percent of the landfill facilities are located in relatively moist climatic regions. All other things being equal, larger flow rates would be expected from the LDCRSs of operating or closed landfills located in relatively moist climatic regions than from operating or closed landfills, respectively, located in drier climatic regions, since there is less leachate production in drier climates. Based on the characteristics of the data base, the measured flow rates presented in this report likely represent the higher end of the range of flows that might occur from landfills constructed under third-party CQA programs.

5.2 DESCRIPTION OF OPERATING UNITS

LDCRS flow rate data have been collected from 28 double-lined landfill facilities (containing 76 individually monitored landfill cells) and eight double-lined surface impoundment facilities (containing 17 individually monitored ponds). The data, along with information on each of the facilities, are presented in Tables 2 through 7. These tables include all of data reported by Bonaparte and Gross [1990], as well as additional data that the authors were able to obtain since the preparation of the cited reference. Tables 2 and 3 present general information and double-liner system properties, respectively, for the 28 landfill facilities. Tables 5 and 6 present the same information for the eight surface impoundment facilities. It should be noted that the double-liner system properties given in Tables 3 and 6 were obtained from the previously-listed sources; they are not measured properties.

Table 2. General information on double-lined landfills.

Landfill (Group)	Location (U.S.)	Average Annual Rainfall (mm)	Ground Water Separation Distance (m)	Area of Cell (hectares)	Maximum Waste Height (m)	LDCRS Collector Spacing (m)	Base Slope Gradient	End of Construction	Third-Party CQA of Gmb Installation	Method of Flow Rate Measurement
A(IV)	Unknown	Unknown	Unknown	3.6	Unknown	Unknown	Unknown	5/1986	Yes	Weekly pumping if liquid present in sump, liquid volume recorded from accumulating flow meter
B(IV)	Unknown	Unknown	Unknown	4.4	Unknown	12	Unknown	3/1986	Yes	Weekly pumping if liquid present in sump, liquid volume recorded from accumulating flow meter
C(III)	Unknown	Unknown	2	1.2	Unknown	Unknown	Unknown	9/1985	Yes	Liquids pumped from sump, liquid volume recorded daily
D(IV)	Unknown	Unknown	6	1.1	Unknown	Unknown	Unknown	1986	Unknown	Unknown
E(III)-Cell 1	North Central	790	3	3.3	20	30	0.02	9/1986	No	Periodic pumping if liquid present in sump, liquid volume recorded monthly from accumulating flow meter
Cell 2				2.7		30	0.02	10/1987		
Cell 3				2.3		30	0.02	6/1988		
Cell 4				2.1		30	0.02	10/1989		
F(III)-Cell 1	North East	970	0	0.6	21	60	0.02	3/1986	Yes	Weekly pumping with manually operated electric pumps, liquid volume recorded from accumulating flow meter
Cell 2				0.5		60	0.02	3/1986		
Cell 3				0.5		60	0.02	3/1986		
Cell 4				0.6		60	0.02	3/1986		
G(III)-Cell 1	North East	970	0	0.7	21	60	0.02	9/1986	Yes	Weekly pumping with manually operated electric pumps, liquid volume recorded from accumulating flow meter
Cell 2				0.5		60	0.02	9/1986		
Cell 3				0.8		60	0.02	9/1986		
Cell 4				0.8		60	0.02	9/1986		
Cell 5				0.5		60	0.02	9/1986		
Cell 6				0.8		60	0.02	9/1986		
H(III)-Cell 1	South West	280	90	4.6	30	30	0.02	3/1987	Yes	Daily pumping with jet pump if liquid depth in sump > 0.3 m, liquid volume recorded from accumulating flow meter
Cell 2				4.2	30	30	0.02	12/1987		
Cell 3				4.6	30	30	0.02	6/1989		
Cell 4				3.8	30	30	0.02	7/1989		
I(IV)-Cell 1	North East	1,040	1	2.0	24	30	0.02	7/1988	Yes	Daily pumping if liquid present in sump, liquid volume recorded from accumulating flow meter
Cell 2				2.0	24	30	0.02	7/1988		
Cell 3				1.7	24	30	0.02	8/1988		
Cell 4				1.7	24	30	0.02	8/1988		
Cell 5				2.8	24	30	0.02	9/1988		
Cell 6				3.9	24	30	0.02	11/1988		
Cell 7				2.6	24	30	0.02	1/1989		

Table 2. (continued)

Landfill (Group)	Location (U.S.)	Average Annual Rainfall (mm)	Ground Water Separation Distance (m)	Area of Cell (hectares)	Maximum Waste Height (m)	LDCRS Collector Spacing (m)	Base Slope Gradient	End of Construction	Third-Party CQA of Gmb Installation	Method of Flow Rate Measurement
J(II)-Cell 1	Gulf Coast	1,630	2	0.4	8	37	0.02	9/1985	Yes	Liquid volume from sump measured and recorded weekly by opening drain lines and allowing gravity flow into a graduated container
Cell 2				0.3	8	37	0.02	9/1985		
Cell 3				0.2	8	37	0.02	6/1987		
Cell 4				0.4	8	37	0.02	6/1987		
K(I)	North Central	790	3	5.6	20	30	0.02	8/1985	No	Periodic pumping if liquids present in sump, liquid volume measured indirectly by multiplying pumping time by pump capacity
L(II)-Cell 1	North East	1,040	5	2.4	40	46	0.013	3/1988	No	Automatic pumping of liquid from sump, liquid volume measured indirectly by multiplying pumping time by pump capacity
Cell 2				2.4	40	46	0.013	10/1987		
Cell 3				1.2	40	46	0.013	5/1990		
Cell 4				1.2	40	46	0.013	7/1990		
M(I)-Cell 1	South East	1,520	0.6	4.3	8	15	0.02	8/1988	Yes	Liquid volume pumped from sump recorded periodically from accumulating flow meter
Cell 2				4.9	8	15	0.02	2/1989		
N(I)-Cell 1	North East	1,070	0.9	1.9	26	21	0.027	7/1986	Yes	Flow rate measurements to sump taken continuously with automated flow monitoring system and weekly using a 0.9 l container and stopwatch
Cell 2				2.6	26	46	0.04	1/1987		
Cell 3				1.5	24	Unknown	Unknown	11/1987		
Cell 4				1.9	23	Unknown	Unknown	3/1988		
O(II)-Cell 1	North East	990	1.2	2.7	5	30	0.02	8/1987	Yes	Flow rate measurements to sump taken continuously with automated flow monitoring system
Cell 2				2.3	8	30	0.02	10/1987		
Cell 3				1.9	8	30	0.02	4/1988		
P(II)-Cell 1	North East	1,040	1.5	4.0	50	5	0.005	2/1987	Yes	Automatic pumping of liquid from sump if liquid depth in sump > 1.5 m, liquid volume recorded from accumulating flow meter
Cell 2			1.5	4.0	50	5	0.005	2/1987		
Q(II)-Cell 1	North East	1,040	1.5	3.3	21	38	0.005	12/1985	No	Liquid volume pumped from sump estimated by multiplying the sump area by the change in liquid depth in the sump
Cell 2			1.5	3.5	21	38	0.005	12/1985		
R(IV)	North East	1,040	1.5	6.4	25	30	0.02	7/1987	No	Liquid volume pumped from sump recorded from accumulating flow meter
S(IV)	North East	1,040	1.5	2.4	25	30	0.02	4/1991	No	Liquid volume pumped from sump recorded from accumulating flow meter

Table 2. (continued)

Landfill (Group)	Location (U.S.)	Average Annual Rainfall (mm)	Ground Water Separation Distance (m)	Area of Cell (hectares)	Maximum Waste Height (m)	LDCRS Collector Spacing (m)	Base Slope Gradient	End of Construction	Third-Party CQA of Gmb Installation	Method of Flow Rate Measurement
T(III)-Cell 1	South East	1,350	0	0.6	20	30	0.02	5/1985	Yes	Liquid volume pumped from sump recorded from accumulating flow meter
Cell 2				0.6	20	30	0.02	7/1985		
Cell 3				0.6	20	30	0.02	11/1985		
Cell 4				0.6	20	30	0.02	11/1985		
Cell 5				0.5	20	30	0.02	6/1986		
Cell 6				0.9	20	30	0.02	6/1986		
Cell 7				1.5	25	53	0.025	9/1987		
Cell 8				1.4	25	53	0.025	4/1988		
Cell 9				1.3	25	53	0.025	12/1988		
Cell 10				1.3	25	53	0.025	12/1988		
Cell 11				1.1	25	53	0.025	8/1989		
Cell 12				1.1	25	53	0.025	8/1989		
Cell 13				1.1	25	53	0.025	10/1990		
Cell 14				1.1	25	53	0.025	10/1990		
U(III)	Gulf Coast	1,420	0.6	1.0	35	Unknown	0.03	12/1988	Yes	Liquid volume pumped from sump several times a week recorded from accumulating flow meter
V(II)-Cell 1	North East	1,140	2.4	3.0	53	46	0.02	5/1989	Yes	Flow rate measurements taken with pail and stopwatch
Cell 2				1.6	53	46	0.02	5/1989		
W(II)	North East	1,140	7.6	2.7	30	27	0.02	9/1989	Yes	Liquid volume pumped from sump recorded from accumulating flow meter
X(IV)	North East	1,140	1.5 - 6	1.6	13	90	0.015	1/1990	Yes	Liquid volume pumped from sump recorded from accumulating flow meter
Y(IV)	North East	1,140	>6	7.2	37	30	0.02	9/1990	Yes	Liquid volume pumped from sump recorded from accumulating flow meter
Z(III)	South East	1,090	1.5	4	9	60	0.04	12/1990	Yes	Liquid volume pumped from sump once a month recorded from accumulating flow meter
AA(III)	Midwest	740	6	1.1	11	43	0.02	12/1987	Yes	Liquid volume pumped from sump and recorded weekly
AB(III)	North East	910	15	2.3	9	5	0.04	11/1989	No	Automatic pumping if liquid depth in sump > 0.3 m, liquid volume recorded from accumulating flow meter

Table 3. Details of landfill double-liner system[a].

LANDFILL (GROUP) AND LINING SYSTEM DESCRIPTION	LCRS[b]			TOP LINER[b]				LDCRS[b] (base slope)			BOTTOM LINER (base slope)[b]			
	Material	k_{dt} (cm/s)	D_{dt} (m)	k_{st} (cm/s)	D_{st} (m)	Polymer	T_{gt} (mm)	Material	k_{db} (cm/s)	D_{db} (m)	k_{sb} (cm/s)	D_{sb} (m)	Polymer	T_{gb} (mm)
A(IV) composite/composite	Sand	10^{-2}	0.3	2×10^{-8}	0.6	HDPE	1.5	Sand	10^{-2}	0.3	2×10^{-8}	0.9	HDPE	1.5
B(IV) composite/composite	Sand	10^{-2}	0.3	2×10^{-8}	0.45	HDPE	1.5	Sand	10^{-2}	0.3	2×10^{-8}	0.9	HDPE	1.5
C(III) composite/composite	Geonet	10^{-1}	0.009	10^{-7}	0.6	HDPE	1.5	Geonet	>1	0.009	10^{-7}	0.9	HDPE	1.5
D(IV) composite/composite	Sand	10^{-3}	0.3	10^{-7}	0.3	HDPE	2	Sand	10^{-3}	0.3	10^{-7}	0.9	HDPE	2
E[c](III) composite/composite	Sand	2×10^{-2}	0.3	10^{-8}	1.5	HDPE	2	Geonet	>1	0.01	10^{-8}	3	HDPE	1.5[c] 2[c]
F(III) composite/composite	Gravel Overlying Geonet	1 >1	0.3 0.005	10^{-7}	0.45	HDPE	2	Sand Overlying Geonet	10^{-2} >1	0.3 0.005	10^{-7}	0.9	HDPE	1.5
G(III) composite/composite	Gravel Overlying Geonet	1 >1	0.3 0.005	10^{-7}	0.45	HDPE	2	Gravel Overlying Geonet	1 >1	0.3 0.005	10^{-7}	0.9	HDPE	2
H[g](III) composite/composite	Gravel Overlying Geonet	5×10^{-1} >1	0.3 0.005	10^{-7}	0.45	HDPE	1.5	Gravel Overlying Geonet	5×10^{-1} >1	0.3 0.005	10^{-7}	0.9	HDPE	1.5
I[d][g](IV) composite/composite	Sand	10^{-2}	0.6	10^{-9}	0.006	HDPE	1.5	Sand	10^{-2}	0.3	10^{-9}	0.15	HDPE	1.5
J[e,f](II) geomembrane/composite	Sand	10^{-2}	0.3	--	--	HDPE	2	Sand	10^{-2}	0.3	10^{-7}	0.9	HDPE	1[f] 1.5[f]
K(I) geomembrane/composite	Sand	4×10^{-3}	0.3	--	--	HDPE	1.5	Geonet	>1	0.005	10^{-8}	5	HDPE	1.5
L(II) geomembrane/composite	Sand	10^{-3}	0.6	--	--	CSPE	0.9	Sand	10^{-3}	0.6	10^{-3}	0.6	PVC	0.8
M(I) geomembrane/composite	Sand	10^{-3}	0.3	--	--	HDPE	2	Sand Overlying Geonet	10^{-3} >1	0.6 0.005	10^{-6}	0.6	HDPE	1
N(I) geomembrane/composite	Sand	10^{-2}	0.6-0.9	--	--	HDPE	1.5	Geonet	>1	0.005	10^{-5}	0.3	HDPE	1.5
O(II) geomembrane/composite	Sand	10^{-1}	0.6	--	--	HDPE	1.5	Sand	10^{-1}	0.4	10^{-5}	0.3	HDPE	1.5

Table 3. (continued)

LANDFILL (GROUP) AND LINING SYSTEM DESCRIPTION	LCRS[b]			TOP LINER[b]				LDCRS[b] (base slope)			BOTTOM LINER (base slope)[b]			
	Material	k_{dt} (cm/s)	D_{dt} (m)	k_{st} (cm/s)	D_{st} (m)	Polymer	T_{gt} (mm)	Material	k_{db} (cm/s)	D_{db} (m)	k_{sb} (cm/s)	D_{sb} (m)	Polymer	T_{gb} (mm)
P(II) geomembrane/composite	Sand	10^{-3}	0.6	--	--	CSPE	0.9	Sand	10^{-3}	0.6	10^{-7}	0.6	PVC	0.8
Q(II) geomembrane/geomembrane	Sand	10^{-2}	0.45	--	--	CSPE	0.9	Sand	10^{-2}	0.45	10^{-3}	0.15	PVC	0.8
R(IV) composite/composite	Sand	10^{-2}	0.45	10^{-7}	0.6	CSPE	0.9	Sand	10^{-2}	0.45	10^{-7}	0.15	PVC	0.8
S(IV) composite/composite	Sand	10^{-2}	0.45	10^{-7}	0.6	HDPE	1.5	Sand	10^{-2}	0.45	10^{-7}	0.15	HDPE	1.5
T[a](III) composite/composite	Sand Overlying Geonet	10^{-2} >1	0.09 0.005	10^{-7}	0.9	HDPE	1.5	Geonet	>1	0.005	10^{-7}	0.9	HDPE	1.5
U(III) composite/composite	Geonet	>1	0.009	10^{-7}	0.9	HDPE	2	Geonet	>1	0.009	10^{-7}	0.9	HDPE	2
V(II) geomembrane/composite	Sand	5×10^{-3}	0.6	--	--	HDPE	1.5	Sand	5×10^{-3}	0.3	10^{-8}	0.6	HDPE	1.5
W(II) geomembrane/composite	Sand	10^{-3}	0.6	--	--	HDPE	2	Sand	10^{-3}	0.3	10^{-7}	0.6	LLDPE	1.5
X(IV) composite/composite	Sand	10^{-2}	0.45	10^{-7}	0.45	HDPE	1.5	Sand	10^{-2}	0.3	10^{-7}	0.08	HDPE	2
Y(IV) composite/composite	Sand	10^{-2}	0.6	10^{-7}	0.45	HDPE	2	Sand	10^{-2}	0.3	10^{-7}	0.6	HDPE	2

Table 3. (continued)

LANDFILL (GROUP) AND LINING SYSTEM DESCRIPTION	LCRS[b]			TOP LINER[b]				LDCRS[b] (base slope)			BOTTOM LINER (base slope)[b]			
	Material	k_{dt} (cm/s)	D_{dt} (m)	k_{st} (cm/s)	D_{st} (m)	Polymer	T_{gt} (mm)	Material	k_{db} (cm/s)	D_{db} (m)	k_{sb} (cm/s)	D_{sb} (m)	Polymer	T_{gb} (mm)
Z[d](III) composite/geomembrane	Sand	10^{-2}	0.6	10^{-9}	0.006	HDPE	1.5	Geonet	>1	0.005	--	--	HDPE	1.5
AA(III) composite/composite	Sand	10^{-2}	0.3	10^{-7}	0.45	HDPE	1.5	Geonet	>1	0.005	10^{-7}	0.9	HDPE	1.5
AB[g](III) composite/composite	Sand	10^{-1}	0.6	10^{-7}	0.8	HDPE	2	Stone	10^{-1}	0.3	10^{-7}	0.9	HDPE	2

Notes: [a] The reported properties were obtained from engineering drawings, project specifications, operation records, and interviews with landfill owners and operators and regulatory agencies. If the properties of a project-specific geonet drainage layer could not be determined, the geonet was assumed to have a hydraulic conductivity greater than 1 cm/s and a thickness of 5 mm.

[b] Abbreviations are as follows: k_{dt} = hydraulic conductivity of LCRS drainage material; D_{dt} = thickness of LCRS drainage material; k_{st} = hydraulic conductivity of compacted low-permeability soil component of top liner; D_{st} = thickness of compacted low-permeability soil component of top liner; T_{gt} = thickness of geomembrane component of top liner; k_{db} = hydraulic conductivity of LDCRS drainage material; D_{db} = thickness of LDCRS drainage material; k_{sb} = hydraulic conductivity of compacted low-permeability soil or geosynthetic clay liner component of bottom liner; D_{sb} = thickness of compacted low-permeability soil or geosynthetic clay liner component of bottom liner; and T_{sb} = thickness of geomembrane component of bottom liner.

[c] The geomembrane component of the bottom liner is 1.5 mm thick for Cells 1 through 3 and 2 mm thick for Cell 4.

[d] The soil component of the composite top liner is a geosynthetic clay liner.

[e] For this lining system, the order of components of the bottom composite liner is reversed (the compacted low-permeability soil component of the bottom liner was placed on top of the geomembrane component) from the order normally used for a composite liner.

[f] The geomembrane component of the bottom liner is 1 mm thick for Cells 1 and 2 and 1.5 mm thick for Cells 3 and 4.

[g] On the side slope the top liner is a geomembrane.

Table 4. Measured flow rates from the LDCRSs of the double-lined landfills.

Landfill (Group)	QUANTITY OF LIQUIDS MEASURED — END OF CONSTRUCTION: Time[a] (months)	END OF CONSTRUCTION: Average Flow (lphd)	END OF CONSTRUCTION: Maximum Flow (lphd)	END OF CONSTRUCTION: Potential Sources of Flow	DURING ACTIVE LIFE: Time[a] (months)	DURING ACTIVE LIFE: Average Flow (lphd)	DURING ACTIVE LIFE: Maximum Flow (lphd)	DURING ACTIVE LIFE: Potential Sources of Flow
A(IV)	-	-	-	-	11	40	(c)	Water from consolidation of clay component of top liner
B(IV)	1	15	(c)	Construction water draining from sand	-	-	-	
C(III)	-	-	-	-	6	110	(c)	Water from consolidation of clay component of top liner
D(IV)	-	-	-	-	8	190	(c)	Water from consolidation of clay component of top liner and construction water draining from sand
E(III)-Cell 1	0.5	1,700	6,400(i)	Construction water draining from granular collection trenches of Cells 1 and 4, and, for Cell 1 which is being loaded with waste, water from consolidation of clay component of top liner	3	840	(c)	Water from consolidation of clay component of top liner for Cells 1 through 4
					34-52	150	710(b)	
Cell 2	-	-	-		21-27	130	340(b)	
					28-39	40	90(b)	
Cell 3	-	-	-		13-22	440	1,040(b)	
					23-31	150	200(b)	
Cell 4	0.5	1,900	(c)		3-14	260	350(b)	
F(III)-Cell 1	-	-	-	-	18-20	720	2,330(i)	For Cells 1 through 4, while the cells are open, water from consolidation of clay component of top liner; for Cells 1 through 4 after closure, water from consolidation/secondary compression of clay component of top liner (See Note j which is applicable to cells at 40 to 50 months or more after the end of construction.)
					21-24	180	320(i)	
					34-39(f)	280(f)	570(i)(f)	
					40-45(f)	170(f)	260(i)(f)	
					46-57(f)	130(f)	320(i)(f)	
					58-60(f)	230(f)	290(i)(f)	
Cell 2	-	-	-	-	18-19	1,180	3,240(i)(f)	
					20-24	380	570(i)	
					34-39(f)	250(f)	520(i)(f)	
					40-45(f)	220(f)	480(i)(f)	
					46-60(f)	140(f)	340(i)(f)	
Cell 3	-	-	-	-	18-19	1,300	2,560(i)	
					20-24	350	530(i)	
					34-39(f)	380(f)	1,370(i)(f)	
					40-51(f)	260(f)	1,530(i)(f)	
					52-60(f)	200(f)	430(i)(f)	
Cell 4	-	-	-	-	18-21	90	230(i)(f)	
					22-24	220	370(i)(f)	
					35-51(f)	200(f)	510(i)(f)	
					52-57(f)	140(f)	340(i)(f)	
					58-60(f)	220(f)	480(i)(f)	

Table 4. (continued)

Landfill (Group)	QUANTITY OF LIQUIDS MEASURED							
	END OF CONSTRUCTION				DURING ACTIVE LIFE			
	Time[a] (months)	Average Flow (lphd)	Maximum Flow (lphd)	Potential Sources of Flow	Time[a] (months)	Average Flow (lphd)	Maximum Flow (lphd)	Potential Sources of Flow
G(III)-Cell 1	-	-	-	-	12-14	130	210(i)	For Cells 1 through 6, while active, water from consolidation of clay component of top liner; for Cells 1 through 6 after closure, water from consolidation/secondary compression of clay component of top liner
					15-18	20	990(i)	
					28-33	100	270(i)	
					34-39	60	230(i)	
					40-45(g)	50(g)	160(i)(g)	
					46-51(g)	260(g)	1,270(i)(g)	
					52-54(g)	170(g)	620(i)(g)	(See Note j, which is applicable to cells at 40 to 50 months or more after the end of construction.)
Cell 2	-	-	-	-	12-18	0	0(i)(g)	
					28-33(g)	350(g)	820(i)(g)	
					34-39(g)	300(g)	700(i)(g)	
					40-54(g)	240(g)	670(i)(g)	
Cell 3	-	-	-	-	12-18	50	150(i)	
					28-33	90	200(i)	
					34-39(g)	50	100(i)	
					40-45(g)	60(g)	130(i)(g)	
					46-51(g)	210(g)	1,010(i)(g)	
					52-54(g)	80(g)	140(i)(g)	
Cell 4	-	-	-	-	12-18	10	20(i)	
					28-33	150	440(i)	
					34-39	40	110(i)	
					40-51(g)	170(g)	750(i)(g)	
					52-54(g)	60(g)	110(i)(g)	
Cell 5	-	-	-	-	12-18	8	40(i)	
					28-33	50	120(i)	
					34-39	20	50(i)	
					40-44	60	230(i)	
					45-51(g)	110(g)	400(i)(g)	
					52-54(g)	80(g)	250(i)(g)	
Cell 6	-	-	-	-	12-18	9	40(i)	
					28-33	20	50(i)	
					34-39	30	50(i)	
					40-44	20	50(i)	
					45-51(g)	160(g)	1,010(i)(g)	
					52-54(g)	40(g)	80(i)(g)	

Table 4. (continued)

Landfill (Group)	QUANTITY OF LIQUIDS MEASURED: END OF CONSTRUCTION: Time[a] (months)	Average Flow (lphd)	Maximum Flow (lphd)	Potential Sources of Flow	DURING ACTIVE LIFE: Time[a] (months)	Average Flow (lphd)	Maximum Flow (lphd)	Potential Sources of Flow
H(III)-Cell 1	1	50	160(i)	Construction water draining from granular collection trenches of Cells 1, 3, and 4 water from consolidation of clay component of top liner, and leakage through geomembrane top liner on side slope of cells	2-5	20	100(i)	For all active cells, water from consolidation of clay component of top liner and leakage through geomembrane top liner on side slope of cells; for Cell 1 after being covered with a geomembrane at 19 months after construction, water from consolidation/secondary compression of clay component of top liner, and leakage through geomembrane top liner on side slopes as leachate is still present in the LCRS
					6-13	150	420(i)	
					21-44(e)	70(e)	100(i)(e)	
Cell 2	1	0	0(i)		2-8	4	50(i)	
					12-29	60	120(i)	
					30-43	110	180(i)	
Cell 3	1	170	740(i)		2-11	90	370(i)	
					12-20	160	170(i)	
					21-25	80	90(i)	
Cell 4	0.5	390	770(i)		2-9	0	0(i)	
					10-12	290	710(i)	
					13-23	80	100(i)	
I(IV)-Cell 1	1	0	0(i)	Construction water draining from sand for Cells 2 through 7, and leakage through defects in geomembrane top liner on side slope (GCL does not extend up the side slope) (See Note j, which is applicable to cells at 1 month or more after the end of construction)	2-23	0	0(i)	For Cells 2 through 7, construction water draining from sand over several months after construction, compression water draining from sand, and leakage through defects in geomembrane top liner on side slope (GCL does not extend up the side slope) (See Note j, which is applicable to cells at 1 month or more after the end of construction)
Cell 2	1	40	130(i)		2	30	60(i)	
					3-9	0	0(i)	
					10-14	7	50(i)	
					15-23	1	4(i)	
Cell 3	1	160	390(i)		2-4	8	20(i)	
					5-8	0.3	5(i)	
					9-10	30	150(i)	
					11-22	0.3	3(i)	
Cell 4	1	890	2,900(i)		2-7	40	130(i)	
					8-11	0	0(i)	
					12	120	430(i)	
					13-22	4	40(i)	
Cell 5	1	60	260(i)		2-11	40	320(i)	
					12-21	5	30(i)	
Cell 6	1	60	200(i)		2-9	50	170(i)	
					10-19	0	0(i)	
Cell 7	1	30	50(i)		2-3	50	110(i)	
					4-10	30	80(i)	
					11-17	5	9(i)	

Table 4. (continued)

Landfill (Group)	QUANTITY OF LIQUIDS MEASURED: END OF CONSTRUCTION: Time[a] (months)	Average Flow (lphd)	Maximum Flow (lphd)	Potential Sources of Flow	DURING ACTIVE LIFE: Time[a] (months)	Average Flow (lphd)	Maximum Flow (lphd)	Potential Sources of Flow
J(II)-Cell 1	1	17,000	32,000(i)	For Cells 1 through 4, construction water draining from sand and top liner leakage	3	1,700	4,300(i)	Water from consolidation of clay component of bottom liner from all active cells experiencing flow; for Cell 1 after closure and for Cell 4, top liner leakage; leakage determination based on chemical analysis of flow
					9-45	0	0(i)	
					46(f)	20(f)	30(f)(i)	
					52(f)	140(f)	200(f)(i)	
Cell 2	1	4,700	17,000(i)		6-16	0	0(i)	
					24	110	130(i)	
					36(f)	6(f)	10(f)(i)	
					40-52(f)	0(f)	0(f)(i)	
Cell 3	1	200	620(i)		6	2	6(i)	
					12	6	7(i)	
					30	270	320(i)	
Cell 4	1	60	470(i)		6-23	0	0(i)	
					24	120	1,300(i)	
					30	270	320(i)	
K(I)	-	-	-	-	10	60	(c)	Top liner leakage
L(II)-Cell 1	1-6	2,600	5,400(b)	For Cells 1 through 4, construction water draining from sand and top liner leakage	7-14	940	2,600(b)	For Cells 1 through 4, construction water draining from sand and top liner leakage; the higher LDCRS flow rates correspond with higher flow rates from the LCRS associated with storm events
					15-22	2,200	3,300(b)	
					23-28	960	1,300(b)	
					29-40	780	1,100(b)	
Cell 2	1	6,600	(c)		4-19	170	320(b)	
	3	590	(c)		20-28	1,600	2,600(b)	
					29-34	570	650(b)	
					35-39	340	420(b)	
					40-45	820	990(b)	
Cell 3	1-4	1,810	2,100(b)		5-8	1,630	1,900(b)	
					12-14	1,660	1,900(b)	
Cell 4	1-4	1,910	2,500(b)		5-8	840	1,100(b)	
					9-12	450	670(b)	
M(I)-Cell 1	-	-	-	Top liner leakage and construction water draining from sand	7-16	3	20(b)	Top liner leakage for Cells 1 and 2, and for Cell 2 at 2-3 months construction water draining from sand
					17-26	2	4(b)	
					27-33	1	4(b)	
Cell 2	1	3	(c)		2-3	140	160(b)	
					4-10	20	50(b)	
					11-18	2	3(b)	
					19-27	1	2(b)	

Table 4. (continued)

Landfill (Group)	QUANTITY OF LIQUIDS MEASURED							
	END OF CONSTRUCTION				DURING ACTIVE LIFE			
	Time[a] (months)	Average Flow (lphd)	Maximum Flow (lphd)	Potential Sources of Flow	Time[a] (months)	Average Flow (lphd)	Maximum Flow (lphd)	Potential Sources of Flow
N(I) -Cell 1	-	-	-	Top liner leakage and construction water draining from granular collection trenches of Cells 2 through 4	12-23	220	820(i)	Top liner leakage for Cells 1 through 4
					24-35	160	580(i)	
					36-41	130	260(i)	
Cell 2	1	470	560(i)		6-11	160	420(i)	
					12-23	100	860(i)	
					24-35	30	60(i)	
Cell 3	2-3	140	170(i)		4-11	150	240(i)	
					12-23	140	350(i)	
					24-25	10	60(i)	
Cell 4	2-3	5	10(i)		4-6	20	110(i)	
					7-21	0	0(i)	
O(II)-Cell 1	1	450	(c)	For Cells 1 through 3, construction water draining from sand and top liner leakage	2-4	160	170(b)	Top liner leakage for Cells 1 through 3
					29-31	5	8(b)	
					32-37	7	9(b)	
					38-43	7	10(b)	
					44-46	5	10(b)	
Cell 2	1	130	(c)		8-11	30	30(b)	
					27-29	3	3(b)	
					30-35	3	5(b)	
					36-41	4	10(b)	
					42-44	5	7(b)	
Cell 3	1	200	(c)		4-5	50	70(b)	
					21-23	9	9(b)	
					24-29	7	10(b)	
					30-35	6	8(b)	
					36-38	5	7(b)	
P(II)-Cell 1	-	-	-		16-22	20	90(b)	Top liner leakage for Cells 1 and 2
					23-31	20	20(b)	
					32-41	20	30(b)	
					42-46	3	10(b)	
Cell 2	-	-	-		16-22	10	200(b)	
					23-31	5	20(b)	

Table 4. (continued)

Landfill (Group)	QUANTITY OF LIQUIDS MEASURED							
	END OF CONSTRUCTION				DURING ACTIVE LIFE			
	Time[a] (months)	Average Flow (lphd)	Maximum Flow (lphd)	Potential Sources of Flow	Time[a] (months)	Average Flow (lphd)	Maximum Flow (lphd)	Potential Sources of Flow
Q(II) -Cell 1	1-8	260	440(b)	Construction water draining from sand and top liner leakage	9-20	420	860(b)	Top liner leakage for Cells 1 and 2; for Cell 2, water from construction of a new cell adjacent and hydraulically connected to Cell 2 at 61 to 67 months after construction
					21-35	810	1,520(b)	
					36-44(f)	130(f)	240(b)(f)	
					51-60(f)	210(f)	270(b)(f)	
					61-67(f)	300(f)	330(b)(f)	
Cell 2	1-8	490	610(b)	-	9-20	1,100	1,830(b)	
					21-35	610	1,190(b)	
					36-44(f)	210(f)	420(b)(f)	
					51-60(f)	410(f)	520(b)(f)	
					61-67(f)	1,420(f)	1,560(b)(f)	
R(IV)	0.5	23,300	(c)	Construction water draining from sand and water from consolidation of clay component of top liner	6-17	210	450(b)	Water from consolidation of clay component of top liner
					19-29	110	160(b)	
					30-41	500	2,140(b)	
					42-48	200	300(b)	
S(IV)	0-3	0	0	-	-	-	-	-
T(III)-Cell 1	-	-	-	-	44-71(f)	30(f)	50(b)(f)	
Cell 2	-	-	-	-	42-53(f)	40(f)	50(b)(f)	
					54-65(f)	30(f)	50(b)(f)	
Cell 3	-	-	-	-	36-47(f)	100(f)	130(b)(f)	
					48-53(f)	80(f)	160(b)(f)	
					54-65(f)	40(f)	70(b)(f)	

Table 4. (continued)

Landfill (Group)	QUANTITY OF LIQUIDS MEASURED							
	END OF CONSTRUCTION				DURING ACTIVE LIFE			
	Time[a] (months)	Average Flow (lphd)	Maximum Flow (lphd)	Potential Sources of Flow	Time[a] (months)	Average Flow (lphd)	Maximum Flow (lphd)	Potential Sources of Flow
T(III)-Cell 4	-	-	-	-	36-47(f)	40(f)	50(b)(f)	For Cells 1 to 6 which are closed, water from consolidation/secondary compression of clay component of top liner and for Cells 7 through 14, water from consolidation of clay component of top liner and leakage through the geomembrane top liner on the landfill side slope; for Cell 7 at 28-33 months after construction and Cell 8 at 21-25 months, surface water entering LDCRS at anchor trench; flows decreased after the anchor trench soil was removed and recompacted; for Cell 7 at 33 months, leakage through the geomembrane top liner on the side slops after the geomembrane top liner on the landfill side slope was damaged; the damage was repaired that same month; for Cell 11 at 7-13 months, leakage through the geomembrane top liner on the side slopes based on the results of a dye test; top liner defects were identified and repaired at 14 months after construction
					48-65(f)	50(f)	90(b)(f)	
Cell 5	-	-	-	-	31-42(f)	50(f)	70(b)(f)	
					43-48(f)	90(f)	190(b)(f)	
					49-54(f)	50(f)	80(b)(f)	
					56-60(f)	110(f)	170(b)(f)	
Cell 6	-	-	-	-	31-42(f)	60(f)	90(b)(f)	
					43-48(f)	50(f)	100(b)(f)	
					49-60(f)	40(f)	60(b)(f)	
Cell 7	-	-	-	-	16-27	30	50(b)	
					28-33	220	420(b)	
					34-39	70	250(b)	
					41-45	20	20(b)	
Cell 8	-	-	-	-	9-20	120	200(b)	
					21-25	840	1,360(b)	
					26-32	120	190(b)	
					34-38	50	60(b)	
Cell 9	-	-	-	-	1-6	100	240(b)	
					7-12	230	330(b)	
					13-18	150	300(b)	
					19-24	50	110(b)	
					26-30	20	20(b)	
Cell 10	-	-	-	-	1-6	330	450(b)	
					7-12	150	250(b)	
					13-18	230	440(b)	
					19-24	160	290(b)	
					26-30	70	90(b)	
Cell 11	-	-	-	-	1-6	140	270(b)	
					7-13	600	1,170(b)	
					14-16	140	230(b)	
					18-22	130	230(b)	
Cell 12	-	-	-	-	1-6	40	70(b)	
					7-10	310	400(b)	
					11-16	100	130(b)	
					18-22	80	110(b)	
Cell 13	-	-	-	-	1-8	50	70(b)	
Cell 14	-	-	-	-	1-8	40	50(b)	

Table 4. (continued)

Landfill (Group)	QUANTITY OF LIQUIDS MEASURED							
	END OF CONSTRUCTION				DURING ACTIVE LIFE			
	Time[a] (months)	Average Flow (lphd)	Maximum Flow (lphd)	Potential Sources of Flow	Time[a] (months)	Average Flow (lphd)	Maximum Flow (lphd)	Potential Sources of Flow
U(III)	1	500	1,370(i)	Construction water draining from sand	2-5 6-10 11-18 19-22 23-26 27-32	3 250 30 100 30 10	8(i) 410(i) 70(i) 150(i) 220(i) 30(i)	Water from consolidation of clay component of top liner
V(II) -Cell 1 Cell 2	6(h) 6(h)	1,390 250	4,730(i) 920(i)	For Cells 1 and 2, construction water draining from sand and top liner leakage; top liner leakage is known to be occurring for Cell 1, which had a localized lining system failure on the landfill side slope shortly after the end of construction	22 22	200 20	(c) (c)	For Cells 1 and 2, top liner leakage
W(II)	6(h)	160	1,350(i)	Construction water draining from sand and top liner leakage	20	70	(c)	Top liner leakage
X(IV)	-	-	-	-	18	40	(c)	Water from consolidation of clay component of top liner
Y(V)	-	-	-	-	10	120	(c)	Water from consolidation of clay component of top liner
Z(III)	-	-	-	-	4 5-7 8	4 8 0	(c) 9(b) (c)	Water from consolidation of clay component of top liner
AA(III)	-	-	-	-	9-12 13-16 17-34	5 1 0	9(b) 1(b) 0(b)	Water from consolidation of clay component of top liner
AB(III)	-	-	-	-	1-3 4-6 8-10	770 1,030 320	(c) 1,350(b) 420(b)	Consolidation water and leakage through geomembrane top liner on side slope; leakage was known to be occurring from 4 to 7 months based on chemical analysis of flows; observed geomembrane defects (two approximately 10 mm diameter holes) were repaired at seven months after the end of construction

Notes:
(a) Time interval between end of construction and flow measurements.
(b) Maximum monthly flow rate.
(c) Data is too limited to evaluate.
(d) Waste not yet placed in cell.
(e) Cell 1 was covered with an HDPE geomembrane at 19 months after construction.
(f) Cell was closed with a final cover system.
(g) Cell was covered with intermediate cover.
(h) The data is reported as end of construction because the hydraulic conductivities of the LDCRS of these facilities are so low (i.e., 10^{-3} cm/s) that significant water may still be flowing from the LDCRS at six months after construction
(i) Maximum weekly flow rate.
(j) Theoretically, minor leakage could be occurring through the composite top liner, as the time period for monitoring exceeds the calculated breakthrough time for the soil component of the top liner. However, no direct evidence is available to confirm or eliminate leakage as a source.

Table 5. General information on double-lined surface impoundments.

Surface Impoundment (Group)	Location (U.S.)	Average Annual Rainfall (mm)	Ground Water Separation Distance (m)	Area of Cell (hectares)	Maximum Liquid Height (m)	LDCRS Collector Spacing (m)	Base Slope Gradient	End of Construction	Third-Party CQA of Gmb Installation	Method of Flow Rate Measurement
A(III)	Unknown	Unknown	120	0.5	Unknown	Unknown	Unknown	6/1986	Unknown	Daily pumping if liquid present in sump, liquid volume recorded from accumulating flow meter
B(IV)-Pond 1 Pond 2	South West	280	90	0.5 0.4	2.8 2.1	24 55	0.02 0.02	6/1984 12/1984	Yes	Daily pumping with jet pump if liquid depth in sump > 0.3 m, liquid volume recorded from accumulating flow meter
C(III)-Pond 1 Pond 2 Pond 3	South West	280	90	0.5 0.7 0.3	4.2 3.0 3.6	23 30 17	0.02 0.02 0.02	6/1985 12/1985 6/1986	Yes	Daily pumping with jet pump if liquid depth in sump > 0.3 m, liquid volume recorded from accumulating flow meter
D(II)	East Central	1,120	Unknown	0.2	6.1	12	0.02	1985	Yes	Unknown
E(I)-Pond 1 Pond 2 Pond 3 Pond 4 Pond 5	South Central	480	Deep	0.4 0.6 0.4 1.1 1.1	3.7 3.7 3.7 4.9 4.9	46 46 46 7 7	0.02 0.02 0.02 0.02 0.02	11/1988 12/1988 1/1989 4/1990 6/1990	Yes	Daily pumping if liquid present in sump, liquid volume measured indirectly by multiplying pumping times by pump capacity
F(I)	Gulf Coast	1,550	20	0.8	4.5	12	0.003	12/1983	Unknown	Daily observation of flow from LDCRS collector pipe to sump
G(II)	North Central	890	Unknown	1.9	5	30	0.01	1/1989	Yes	Liquid volume removed from sump estimated by multiplying the number of times the pump is automatically activated by the volume of liquid that is stored in the sump between the "pump on" and "pump off" levels
H(II)-Pond 1 Pond 2 Pond 3	North Central	1,040	3	0.6 0.4 0.6	1.4	46 34 61	0.01 0.01 0.01	11/1988 11/1988 11/1988	Yes	Automatic pumping of liquid from sump based on depth of liquid sump; flow is measured using accumulating flow meter and is automatically totaled, recorded, and printed daily

Table 6. Details of surface impoundment double-liner system[a].

SURFACE IMPOUNDMENT (GROUP) AND LINING SYSTEM DESCRIPTION	TOP LINER[b],[e]				LDCRS[b] (side slope)			LDCRS[b] (base slope)			BOTTOM LINER[b] (base slope)			
	k_{st} (cm/s)	D_{st} (m)	Polymer	T_{gt} (mm)	Material	k_{db} (cm/s)	D_{db} (m)	Material	k_{db} (cm/s)	D_{db} (m)	k_{sb} (cm/s)	D_{sb} (m)	Polymer	T_{gb} (mm)
A(III) composite/composite	10^{-8}	0.45	HDPE	1.5	Geonet	>1	0.005	Geonet	>1	0.005	10^{-7}	0.9	HDPE	1.5
B[f](IV) composite/composite	10^{-7}	0.45	HDPE	1.5	Sand	10^{-3}	0.45	Sand	10^{-3}	0.45	10^{-7}	0.6	HDPE	1.5
C(III) composite/composite	10^{-7}	0.45	HDPE	2.5	Geonet	>1	0.005	Gravel Overlying Geonet	5×10^{-1} >1	0.3 0.005	10^{-7}	0.9	HDPE	1.5
D(II) geomembrane/composite	--	--	HDPE	1.5	Geonet	>1	0.005	Sand	10^{-3}	0.3	10^{-7}	0.6	HDPE	1
E(I) geomembrane/composite	--	--	HDPE	2.5	Geonet	>1	0.005	Geonet	>1	0.005	10^{-7}	0.9	HDPE	2
F(I) geomembrane/geomembrane	--	--	CSPE-R	1.1	Geotextile[c]	3×10^{-1}	0.003	Geotextile[c]	3×10^{-1}	0.003	1	0.3	PVC	0.8
G(II)[d] geomembrane/geomembrane	--	--	Ethylene Interpolymer Alloy	0.9	Sand	$>10^{-3}$	0.3	Sand	$>10^{-3}$	0.3	Needlepunched Geotextile		HDPE	1
H(II) geomembrane/geomembrane	--	--	HDPE	2	Geonet	>1	0.005	Sand	10^{-2}	0.3	10^{-7}	0.3	HDPE	1.5

Notes: [a] The reported properties were obtained from engineering drawings, project specifications, operation records, and interviews with surface impoundment owners and operators and regulatory agencies. If the properties of a project-specific geonet drainage layer could not be determined, the geonet was assumed to have a hydraulic conductivity greater than 1 cm/s and a thickness of 5 mm.

[b] Abbreviations are as follows: k_{st} = hydraulic conductivity of compacted low-permeability soil component of top liner; D_{st} = thickness of compacted low-permeability soil component of top liner; T_{gt} = thickness of geomembrane component of top liner; k_{db} = hydraulic conductivity of LDCRS drainage material; D_{db} = thickness of LDCRS drainage material; k_{sb} = hydraulic conductivity of compacted low-permeability soil component of bottom liner; D_{sb} = thickness of compacted low-permeability soil component of bottom liner; and T_{sb} = thickness of geomembrane component of bottom liner.

[c] For the groupings in the paper, the geotextile drainage layer is assumed to be equivalent to the geonet drainage layer.

[d] For this surface impoundment, the geomembrane bottom liner is underlain by a needlepunched geotextile drainage layer which drains to a sump. The geotextile in turn is underlain by a 0.45-m thick compacted low-permeability soil layer.

[e] For all of the facilities, the geomembrane top liner is exposed.

[f] On the side slope the top liner is a geomembrane.

Table 7. Measured flow from the LDCRSs of the double-lined surface impoundments.

SURFACE IMPOUNDMENT (GROUP)	QUANTITY OF LIQUID MEASURED							
	END OF CONSTRUCTION				DURING ACTIVE LIFE			
	Time[a] (months)	Average Flow (lphd)	Maximum Flow (lphd)	Potential Sources of Flow	Time[a] (months)	Average Flow (lphd)	Maximum Flow (lphd)	Potential Sources of Flow
A(III)	2	53	(c)	Water from consolidation of the clay component of the top liner	-	-	-	-
B(IV)-Pond 1	-	-	-	-	26-28	2	7(b)	For Pond 1, water from consolidation of the clay component of the top liner and leakage through the geomembrane top liner on the side slope; at 36 months after construction, top liner leakage for Pond 1 was apparent based on chemical analysis of flows; flows decreased after 37 months as the liquid height in the pond was decreased; Pond 1 was decommissioned at 49 months after construction; no flow was observed from Pond 2 during 20-43 months after construction; Pond 2 was cleaned out at 43 months after construction (see Note h, which is applicable to ponds at 4 to 12 months or more after the end of construction)
					29-31	210	250(b)	
					32-34	530	790(b)	
					35-37	1,120	1,340(b)	
					38-42	310	450(b)	
					43-49	60	170(b)	
Pond 2	-	-	-	-	20-43	0	0(b)	
C(III)-Pond 1	-	-	-	Water from consolidation of the clay component of the top liner and construction water draining from granular collection trenches	15-16	870	1,070(b)	For Ponds 1 through 3, water from consolidation of the clay component of the top liner; for Pond 2, top liner leakage at 38-39 months after construction when the liquid height in the pond was increased; a geomembrane liner defect was found on the side slope of Pond 2 and repaired at 40 months after construction (see Note h, which is applicable to ponds at 4 to 12 months or more after the end of construction)
					17-24	0	0(b)	
					25-28	220	240(b)	
					29-60	10	210(b)	
					61-72	50	120(b)	
Pond 2	-	-	-		8-9	870	1,000(b)	
					10-15	40	100(b)	
					16-20	210	250(b)	
					21-24	50	90(b)	
					25-28	670	1,380(b)	
					29-31	140	300(b)	
					35-37	4	10(b)	
					38-39	960	1,020(b)	
					40-66	40	130(b)	
Pond 3	2	1,590	(c)		3-5	100	200(b)	
					6-10	4	20(b)	
					11-15	180	370(b)	
					16-24	10	40(b)	
					28-46	10	60(b)	
					47-49	120	210(b)	
					50-59	4	30(b)	
D(II)	-	-	-	-	7(d)	60	(c)	At 7 months after construction, construction water draining from sand and top liner leakage; based on the results of chemical analysis of LDCRS flow, the flow contained constituents found in the pond liquid; from 8 to 78 months after construction, the operator reported that insignificant amounts of liquid were in the LDCRS
					8-78	Small	Small	

Table 7. (continued)

SURFACE IMPOUNDMENT (GROUP)	QUANTITY OF LIQUID MEASURED: END OF CONSTRUCTION				QUANTITY OF LIQUID MEASURED: DURING ACTIVE LIFE			
	Time[a] (months)	Average Flow (lphd)	Maximum Flow (lphd)	Potential Sources of Flow	Time[a] (months)	Average Flow (lphd)	Maximum Flow (lphd)	Potential Sources of Flow
E(I)-Pond 1	1	0	0(g)	No flow recorded; the ponds were constructed during a period with little precipitation	2-19	0	0(g)	For Pond 2, top liner leakage due to 20-mm long defect at a geomembrane seam on side slope of pond 15 months after construction; the defect was repaired at 15 months
Pond 2	1	0	0(g)		2-14	0	0(g)	
					15	30,000	(c)	
Pond 3	1	0	0(g)		18	0	0(g)	
Pond 4	1	0	0(g)		17	0	0(g)	
Pond 5	1	0	0(g)		3	0	0(g)	
					3	0	0(g)	
F(I)	0-0.5	1,380	3,000(g)	Construction water draining from granular collection trenches and, at 0-0.5 months after construction, top liner leakage; a geomembrane defect was found at one month after construction and repaired; no top liner leakage at 2 months after construction based on the results of a ponding test performed with water containing dye	3-8	2	(c)	Construction water slowly draining through geotextile drainage layer from 3 to many months after construction; no top liner leakage from 3-8 months after construction based on chemical analysis of LDCRS flow for a primary chemical constituent in the pond liquids; at 9 months top liner leakage due to damage to top liner; the damage was repaired, the LDCRS was flushed with water, and a ponding test was performed to locate any additional geomembrane defects; the flow rates from the pond decreased after the top liner was repaired and remained relatively constant until 53 months after construction; based on chemical analyses of LDCRS flow, the flows from 10-53 months after construction are attributed to top liner leakage and LDCRS flush water that entered the LDCRS at 9 months and slowly drained from the LDCRS and, potentially, water from another source, such as water entering the LDCRS at the anchor trench; based on chemical analysis of LDCRS flow, leakage occurred again at 53 months after construction, when the maximum liquid height in the pond was increased; the chemical characteristics of the leakage went back to normal (i.e., a primary chemical constituent in the pond liquids was not detected) when the liquid height was decreased and the LDCRS was flushed with water; a primary chemical constituent in the pond liquids was again detected in the LDCRS flow during 81-88 months; at 88 months after construction, the flow rates increased dramatically, and the facility was taken out service; an investigation of the CSPE-R top liner indicated that the geomembrane had a number of pinholes which were located primarily on the base of the pond
	2	50	300(g)		9	950	(c)	
					10	10	(c)	
					11-30	3	(c)	
					31-52	3	6(b)	
					53	10	(c)	
					54-60	5	7(b)	
					61-80	20	40(b)	
					81-87	30	50(b)	
					88	250	(c)	
G(II)	-	-	-	-	6-9	110(e)	140(b)(e)	Construction water draining from sand and top liner leakage
					10	20(e)	(c)	

Table 7. (continued)

SURFACE IMPOUNDMENT (GROUP)	QUANTITY OF LIQUID MEASURED							
	END OF CONSTRUCTION				DURING ACTIVE LIFE			
	Time[a] (months)	Average Flow (lphd)	Maximum Flow (lphd)	Potential Sources of Flow	Time[a] (months)	Average Flow (lphd)	Maximum Flow (lphd)	Potential Sources of Flow
H(II)-Pond 1	2-3	990	1,230(b)	Construction water draining from sand during first 3 months of operation for Ponds 1 and 2; for Pond 3, flow instrumentation malfunction for first 3 months of operation; analysis of chemical constituents of flow indicated top liner leakage for Pond 3 occurred immediately after the pond became operational	4-7	250	310(b)	For all ponds, construction water draining from sand up to 7 months after construction, and as described below, top liner leakage in all ponds; analysis of chemical constituents of flow indicate top liner leakage from Pond 2 at 7 to 25 months after construction, and from Pond 3 at 1 to 25 months after construction; at 25 months, geomembrane defects were located in Ponds 2 and 3 and repaired; for Pond 3 flows decreased significantly after geomembrane defects were repaired, and for Pond 2 flows increased after the repairs when the liquid level in the pond was increased; for Ponds 1 and 3, reduced flow rates over time are believe to be due to build-up of sludge over the top liner; this sludge could impede the flow of liquid through a geomembrane defect
					8-10	200	240(b)	
					13-16	150	210(b)	
					17-22	50	90(b)	
					23-28	70	190(b)	
					29-31	60	100(b)	
Pond 2	2-3	1,020	1,300(b)		4-7	380	450(b)	
					9	1,180	(c)	
					15-19	230	300(b)	
					20-25	240	690(b)	
					26-31	400	670(b)	
Pond 3	3	(f)	(f)		5-7	19,780	27,440(b)	
					13-17	6,550	9,650(b)	
					24-25	1,640	2,120(b)	
					26-31	440	660(b)	

Notes: [a] Time interval between end of construction and flow measurements.
[b] Maximum monthly flow rate.
[c] Data is too limited to evaluate.
[d] No flows have been detected after the eight months of operation.
[e] The flow rates include flows from the sand LDCRS and flows from the geotextile drainage layer that underlies the geomembrane bottom liner.
[f] Data not available due to instrumentation malfunction.
[g] Maximum weekly flow rate.
[h] Theoretically, minor leakage could be occurring through the composite top liner, as the time period for monitoring exceeds the calculated breakthrough time for the soil component of the top liner. However, no direct evidence is available to confirm or eliminate leakage as a source.

Tables 4 and 7, respectively, present the LDCRS flow rate data for the landfill and surface impoundment facilities. Data are summarized for two different time periods: (i) just after the end of construction, when the influence of construction water on the flow rates would be greatest; and (ii) during the active life of the facility. Where possible, flow rates are reported at different time intervals during the active life. The authors found only limited data on flow rates after landfill closure. The data corresponding to closed landfill conditions are specially noted in Table 4.

A characterization of the monitored cells and ponds is presented in Table 8. It can be seen that about 40 percent of the monitored cells and ponds have geomembrane top liners, while the remaining 60 percent have composite top liners. About 40 percent of the monitored cells and ponds have sand LDCRSs, while the remaining 60 percent have geonet LDCRSs. (Some of the facilities listed in Table 8 as having a geonet LDCRS may actually have a geocomposite LDCRS consisting of a geonet with a geotextile bonded to its top surface. However, for the purposes of this report, geocomposite LDCRSs are considered functionally equivalent to geonet LDCRSs.) Most of the units are located at sites where the ground-water table is below the unit base; however, in a few cases, the relationship between the unit base and the ground-water table is unknown. For purposes of this report, it is assumed that infiltration of ground water did not contribute to the LDCRS flows at any of the units. For all units, the bottom liner included a geomembrane; in most cases, the bottom liner was a composite. Therefore, for most facilities, a small amount of the water expelled during consolidation of the soil component of the bottom liner could infiltrate the LDCRS through a hole in the geomembrane component of the bottom liner. This small amount of water is considered to be negligible for the purpose of this report. Also, for most facilities, the collection efficiency of the LDCRSs at the monitored facilities should be very high (i.e., very little of the liquid in the LDCRS should have migrated into the bottom liner).

It should be noted that only 13 of the 28 landfill facilities and three of the eight surface impoundment facilities have lining systems that appear to meet the minimum design requirements of EPA's final rule of 29 January 1992 (described in Appendix A). The minimum design requirements of the final rule include the following: (i) a composite bottom liner consisting of a geomembrane and a 0.9 m (3 ft) thick compacted clay layer with a hydraulic conductivity no greater than 1×10^{-7} cm/s; (ii) a minimum LDCRS bottom slope of 1 percent; (iii) for granular LDCRS drainage media, a minimum thickness of 30 cm (12 in.) and a minimum hydraulic conductivity of 1×10^{-2} cm/s for landfills and 1×10^{-1} cm/s for surface impoundments; and (iv) for synthetic LDCRS drainage media, a minimum

Table 8. Characterization of 93 individually monitored cells and ponds. [Note: Gmb = geomembrane; Cmp = composite; Below = ground-water table below base of facility.]

	Top Liner		LDCRS		Ground-Water Table	
	Gmb	Cmp	Sand	Geonet	Below	Unknown
Cells	25	51	32	44	74	2
Ponds	11	6	7	10	15	2
Cells and Ponds	36	57	39	54	89	4

Table 9. Number of facilities in each group.

Group No.	Top Liner	LDCRS	Number of Cells and Ponds
I	Geomembrane	Geonet	13
II	Geomembrane	Sand	23
III	Composite	Geonet	41
IV	Composite	Sand	16

hydraulic transmissivity of 3×10^{-5} m^2/s for landfills and 3×10^{-4} m^2/s for surface impoundments. The main reason that some of the facilities do not meet the requirements of the final rule is that the compacted clay component of the bottom liner is less than 0.9 m (3 ft) thick or has a hydraulic conductivity greater than 1×10^{-7} cm/s.

To interpret the data, it is convenient to group the monitored facilities by the type of top liner (i.e., geomembrane versus composite) and type of LDCRS (i.e., sand versus geonet). With this grouping, the potential sources of flow for cells and ponds in any group are basically the same (Table 9). The flow rate data are interpreted for each group of facilities in Section 6.

5.3 MEASUREMENT OF FLOW FROM LDCRSs

Under EPA's final rule of 29 January 1992, owners and operators of hazardous waste landfills and surface impoundments are required to monitor the rate of flow from the LDCRS of the facilities on a weekly basis during the active life of the facilities (including the closure period) and monthly or quarterly during the post-closure period. For the majority of the facilities presented in this report, liquid flows from the LDCRSs of operating units were measured daily or weekly. However, the available data were typically weekly or monthly flow volumes, or flow rates.

The flow rate data for each facility are given in Table 4 for landfills and Table 7 for surface impoundments. Where there is sufficient data to evaluate the temporal variation in flow, both average and maximum flow rates are reported. Average flow rates are typically reported for one or more months. Maximum flow rates are reported as the maximum weekly or monthly flow rate over a given time interval, except as noted. When possible, the maximum flow rates are based on a maximum weekly flow rate. It is preferable to report the maximum flow rates based on a weekly time interval, as this is the time interval required by EPA for monitoring of LDCRS flow rates at active units. With this information, conclusions can be drawn on the maximum LDCRS flow rates that may occur on a weekly basis at other land disposal units.

The techniques for measuring LDCRS flow rates at the landfill and surface impoundment facilities presented in this report range from the relatively simple, such as calculating the flow quantities based on changes in liquid depth in the LDCRS sump, to relatively complex, such as measuring flows using tipping buckets and flumes and recording the flow data with automated data-logging systems. The different methods used to measure LDCRS flow rates at the facilities in the report were as follows:

- estimating the volume of liquid pumped from the sump by multiplying the sump area by the change in the liquid depth in the sump and dividing volume of liquid by the time between liquid depth measurements;

- measuring volume indirectly by multiplying the pumping time by the pump capacity and dividing by the time since the last pumping event;

- estimating the volume of liquid removed from the LDCRS sump during a certain period of time by multiplying the number of times the pump automatically activated by the volume of liquid that is stored in the sump between the "pump on" and "pump off" levels, and dividing the estimated volume of liquid by the length of the considered time period;

- measuring the flow rate manually at a given point in time, using a bucket and stopwatch (at gravity flow outlets);

- measuring the liquid volume in the LDCRS by opening the drain lines and allowing the liquid to flow by gravity into a graduated container and dividing the volume of liquid by the time since the last measurement event (at gravity flow outlets);

- using flow meters equipped with mechanical accumulators or automatic data-logging systems and dividing the change in flow volume by the time since the last measurement event; and

- using tipping buckets and flumes, with automatic flow data acquisition systems (at gravity flow outlets).

The most common method used to measured LDCRS flow rates at the facilities presented in this report involved using a flow meter equipped with a mechanical accumulator and dividing the change in flow volume by the time since the last measurement event.

SECTION 6

RESULTS AND DISCUSSION

6.1 METHODOLOGY FOR EVALUATING MEASURED FLOW

In this section of the report, the sources of flow from the LDCRSs of operating facilities within each of the four groups identified in Table 9 are evaluated by comparing the measured flow rates for a specific time period with the calculated flow rates from different sources during the same time period. This methodology for evaluating the source of measured flow has been described by Gross et al. [1990] as follows.

- Identify the potential sources of flow based on double-liner system design, climatic and hydrogeologic setting, and operating history.
- Calculate the flow rates from each potential source.
- Calculate the time frame for flow from each potential source.
- Evaluate the potential sources of flow by comparing measured flow rates to calculated flow rates at specific points in time.

Additionally, comparisons of the chemical constituents in liquids contained in surface impoundments or leachates from landfills with the chemical constituents in the flows from the LDCRSs often provide insight into whether a source of the flow is top liner leakage.

The interpretation methodology described above was used to evaluate the sources of flow from the 93 individually monitored cells and ponds presented in Tables 2 through 7. A review of the data on measured flow rates from the four groups of facilities and an interpretation of the data are provided in the remainder of this section of the report.

6.2 REVIEW OF DATA

6.2.1 Group I Facilities

Introduction

Group I facilities were constructed with geomembrane top liners and geonet LDCRS drainage layers. There are three landfill facilities (seven cells) and two surface impoundment facilities (six ponds) in this group. End of construction flow rate data are available for four landfill cells and all surface impoundment ponds. In addition, data are available for all cells and ponds during their active lives. No data for closed cells are available.

The only potential source of flow from the LDCRSs of the Group I facilities is top liner leakage and any small amount of construction water that drains from granular collection trenches in the LDCRS during the early active life of the facilities.

Landfills

For the four Group I cells for which end of construction data is available, average measured flow rates ranged from 3 to 470 lphd (0.3 to 47 gpad), and maximum weekly measured flow rates ranged from 10 to 560 lphd (1 to 56 gpad). These flows are primarily attributed to construction water draining from granular collection trenches and top liner leakage.

All seven cells from the three Group I landfills appear to have exhibited top liner leakage during their active lives, with average flow rates ranging from 0 to 220 lphd (0 to 22 gpad). Maximum weekly flow rates of 110 to 860 lphd (11 to 86 gpad) and maximum monthly flow rates of 20 to 160 lphd (2 to 16 gpad) were measured for these cells. These maximum flow rates are up to about seven times greater than the average values. The maximum LDCRS flows typically corresponded to high flow rates from the LCRSs, which usually occurred shortly (e.g., from a few days to a few weeks) after storm events. It should also be noted that all of the Group I landfills are located in relatively moist climatic regions. All other things being equal, smaller rates of top liner leakage would be expected at facilities located in dry climates where leachate production rates are low.

Surface Impoundments

Of the six Group 1 ponds, only two (i.e., Surface Impoundment E, Pond 2 and Surface Impoundment F) have exhibited flow since the start of operation. One pond (i.e., Surface Impoundment E, Pond 2) exhibited no flows until a 20-mm (1-in.) long defect developed along a geomembrane seam on the side slope of the pond. Flow through the defect averaged 30,000 lphd (3,000 gpad). Flow was not observed after the defect was repaired. The other pond (i.e., Surface Impoundment F) initially exhibited an average flow of 1,380 lphd (138 gpad) at 0.5 months after construction. The flow was due, in part, to top liner leakage. After a geomembrane defect was discovered and repaired and the LDCRS was flushed with water, the flow rate decreased steadily with time and was very low (i.e., about 2 lphd (0.2 gpad)) from two to eight months after the end of construction. Based on a chemical analysis of the LDCRS flow for a primary constituent in the pond liquids, the flow observed during this time can be attributed to flush water slowly draining from the LDCRS. At nine months, the geomembrane top liner was damaged and the average flow rate increased to 950 lphd (95 gpad). The geomembrane was repaired, a ponding test was performed to locate any additional geomembrane defects, and the LDCRS was again flushed with water. After this repair, the flow rates decreased with time and remained very low from 10 to 52 months after the end of construction. By several months after the repair, the flows appeared to be just flush water based on chemical analysis.

At 53 months, the maximum liquid height in Pond 2 of Impoundment E was increased to a higher level. Based on the increased flow rate and on chemical analysis of constituents in the flow, it was determined that top liner leakage was again occurring. Since the observed leakage coincided with an increase in the maximum liquid height in the pond, it is likely the pond had a geomembrane top liner defect on its side slope. The liquid height in the pond was decreased and the LDCRS was again flushed. Chemical characteristics of the LDCRS liquids went back to normal (i.e., a primary chemical constituent in the pond liquids was not detected in the LDCRS liquids) within several months. The LDCRS flow rates again decreased and remained low until 88 months after the end of construction. Prior to 88 months, beginning at 81 months, top liner leakage again began occurring based on testing of chemical constituents in the LDCRS flow. At 88 months, the average flow rate increased rapidly to 250 lphd (25 gpad), and the facility was taken out of service. An investigation of the top liner indicated that the geomembrane had a number of small holes which were located primarily on the base of the pond. It was also reported by the surface impoundment owner that the scrim of the geomembrane was exposed in a number of places and the strength properties of the geomembrane were significantly less (i.e., 50 percent or less) than the specified original properties of the geomembrane. A new geomembrane comprised of the same polymer as the old geomembrane was installed over the old geomembrane. The owner reported that the new geomembrane had a different formulation than the old geomembrane, which was installed in 1983.

One reason for the absence of top liner leakage at four of the Group I ponds and only four occurrences of top liner leakage at the other two Group I ponds is that these facilities were all subjected to ponding tests and/or leak location surveys as part of the owners' internal or third-party CQA program. It was reported that geomembrane holes identified during the leak location surveys and/or ponding tests were repaired. Additionally, geomembrane holes that developed during operation were typically repaired.

It is interesting to note that none of the geomembrane top liners at the Group I surface impoundments were protected by an overlying protective soil layer or other material.

Comparison Between Observed and Calculated Leakage Rates For Landfills and Surface Impoundments

It is useful to compare the observed top liner leakage rates at the monitored landfills and surface impoundments to the calculated top liner leakage rates. For the Group I landfills, the observed flow rates are, on average, somewhat smaller than the calculated top liner leakage rate of 600 lphd (60 gpad) given in Table 1 for h_t = 0.03 m (0.1 ft) and k_{min} > 1 cm/s. However, the calculated value appears to represent a reasonable upper bound of the observed values. In contrast, observed flow rates from the Group I ponds are typically much smaller than the calculated top leakage rate of 6,300 lphd (630 gpad) given in Table 1 for h_t = 3 m (10 ft) and k_{min} > 1 cm/s.

Giroud and Bonaparte [1989a,b] presented evidence suggesting that a geomembrane hole frequency of 3 to 5 holes per hectare (1 to 2 holes per acre) and a geomembrane hole size of 3×10^{-6} m^2 (3×10^{-5} ft^2) may be assumed for calculating "representative" flow rates due to holes in geomembranes installed using rigorous CQA programs. It is apparent from the observations of the monitored surface impoundments that the foregoing assumptions regarding the frequency and/or size of geomembrane holes may, in some cases, be too conservative for geomembrane installations that include ponding tests and/or leak location surveys as part of a CQA program and the repair of geomembrane holes that develop during operation. The use of these techniques reduced the frequency and/or size of geomembrane holes in the Group I surface impoundments in this study below the values assumed by Giroud and Bonaparte. Their assumptions were based on analyses of the performance of geomembranes that had not been subjected to ponding tests, leak location surveys, and/or geomembrane repair during operation.

6.2.2 Group II Facilities

Introduction

Group II facilities were constructed with geomembrane top liners and sand LDCRS drainage layers. There are seven landfill facilities (18 cells) and three surface impoundment facilities (five ponds) in this group, with all of the facilities located in relatively moist climatic regions. End of construction data are available for 16 of the landfill cells and two of the surface impoundments. Data are also available for 16 of the cells and all of the ponds during their active lives, and for two closed cells.

The potential sources of flow from the LDCRSs of the Group II facilities are construction water and top liner leakage.

Landfills

For the 16 Group II cells for which end of construction data are available, the hydraulic conductivity of the LDCRS drainage material is in the range of 10^{-3} to 10^{-1} cm/s. For this range of hydraulic conductivity, drainage of construction water could have occurred for about one day to one year after installation of the top liner. All 16 of the landfill cells show LDCRS flows shortly after construction. The average measured flow rates at the end of construction ranged from 60 to 17,000 lphd (6 to 1,700 gpad), with seven of the cells exhibiting average flow rates of 1,000 lphd (100 gpad) or more. The maximum end of construction flow rates for the cells ranged from 440 to 32,000 lphd (44 to 3,200 gpad), with two of the cells exhibiting maximum flow rates of more than 10,000 lphd (1,000 gpad). These maximum values were up to eight times greater than the average values.

Excluding the four cells of Landfill J (discussed subsequently), the remaining 12 Group II cells for which data are available exhibited flows during their active lives which are thought to be due to top liner leakage. The average flow rates from the 12 cells potentially attributable to top liner leakage ranged from 0 to 2,200 lphd (0 to 220 gpad), with the maximum flow rates being up to about five times larger than the average values. The maximum monthly flow rates ranged from 0.4 to 3,300 lphd (0.04 to 330 gpad), and the maximum weekly flow rates ranged from 0 to 4,300 lphd (0 to 430 gpad). It is noted that top liner leakage has clearly occurred at Cell 1 of Landfill V. A slope failure occurred at this facility shortly after construction. The failure was confined to the lining system on the 12-m (40-ft) high, 3H:1V (horizontal:vertical) side slope. The failure involved the downslope sliding of the 0.6-m (2-ft) thick sand LCRS drainage layer and underlying geotextile cushion layer on the HDPE geomembrane top liner. Flow from the cell had not been monitored prior to the failure. Shortly after the failure, however, the flow rate from the LDCRS was found to be almost 1,500 lphd (150 gpad).

The lining system was subsequently repaired, and the flow rate from the LDCRS decreased. At 22 months after the end of construction, the average measured flow rate from the cell was 200 lphd (20 gpad). Interestingly, the six cells at which CQA programs were not implemented (i.e., Landfills L and Q) had larger flow rates attributable to top liner leakage (i.e., averaging from 130 to 2,200 lphd (13 to 220 gpad)) than the cells at which CQA programs were implemented (i.e., averaging from 0.1 to 200 lphd (0.01 to 20 gpad).

As discussed by Bonaparte and Gross [1990], Landfill J is a special Group II facility because it was constructed with the compacted clay component of the bottom liner above, rather than below (as is usual), the geomembrane component. In addition, at Landfill J the LDCRS is continuous between cells, thereby allowing flow to cross from one cell to the next. A detailed analysis of LDCRS flows from the Landfill J cells was presented by Gross et al. [1990]. Their analysis indicated average construction water flow rates of 60 to 17,000 lphd (6 to 1,700 gpad) for the cells. Average consolidation water flow rates from the four Landfill J cells ranged from 6 lphd (0.6 gpad) for Cell 3, which was filled slowly over 18 months, to 1,700 lphd (170 gpad) from Cell 1, which was filled in one month. The relatively high average flow rate of 2,700 lphd (270 gpad) observed for Cell 3 at 30 months after construction was due to flooding of the LDCRS in an adjacent cell for a leak location survey. Based on an analysis of chemical constituents in flow from the LDCRSs and LCRSs, the top liners at two of the four Landfill J cells (i.e., Cell 1 and Cell 4) leaked. In the case of Cell 1, no top liner leakage was observed until several years after closure, at which time an average flow from the LDCRS of 140 lphd (14 gpad) commenced. In the case of Cell 4, no top liner leakage was observed until about 24 months after construction, when the LDCRS began experiencing an average flow of about 120 lphd (12 gpad). An evaluation of the methods used to construct Cells 1 and 4 resulted in the conclusion that the most likely cause of top liner leakage was the development of a hole at the LCRS pipe penetration of the geomembrane top liner in these cells.

Surface Impoundments

For the two Group II surface impoundments ponds for which end of construction flow data available, the hydraulic conductivity of the LDCRS drainage material is about 10^{-2} cm/s. For this value of hydraulic conductivity, drainage of construction water could have occurred for several months after installation of the top liner. The average measured flow rates at the end of construction for the two ponds were 990 and 1,020 lphd (99 and 102 gpad), and the maximum monthly flow rates were 1,230 and 1,300 lphd (123 and 130 gpad).

Three of the five ponds from the Group II surface impoundments had average flow rates during their active lives potentially attributable to top liner leakage and construction water of 20 to 250 lphd (2 to 25 gpad), and maximum monthly flow rates of 90 to 310 lphd (9 to 31 gpad). Ponding tests or leak location surveys were reportedly performed as part of the CQA program at all of these ponds. The remaining two ponds (i.e., Ponds 2 and 3 of Surface Impoundment H) had average flow rates potentially attributable to top liner leakage of 230 to 19,780 lphd (23 to 1,978 gpad), and maximum monthly flow rates of 300 to 27,440 lphd (30 to 2,744 gpad). It should be noted that leak location surveys were performed in both of the ponds before they were put into operation. The results of chemical quality testing of the LDCRS liquids indicated that top liner leakage was occurring in both of these ponds shortly after the ponds were put into operation. At 25 months, the geomembrane top liners in the two ponds were repaired. After 25 months, the average measured flow rates from these two ponds decreased significantly and ranged from 400 to 440 lphd (40 to 44 gpad).

Comparison Between Observed and Calculated Leakage Rates for Surface Impoundments

Similar to the Group I ponds, flow rates from the Group II ponds were typically much smaller than the calculated leakage rate through a geomembrane hole of 6,300 lphd (630 gpad) given in Table 1 for h = 3 m (10 ft) and $k_{min} > 1$ cm/s. The exception to this is for Ponds 2 and 3 of Surface Impoundment H, which experienced significantly higher flows than the other ponds. After the geomembrane top liners in the two ponds were repaired, however, the flow rates from these ponds became more consistent with the measured flow rates from the other ponds.

6.2.3 Group III Facilities

Introduction

Group III facilities were constructed with composite top liners and geonet LDCRS drainage layers. There are ten landfill facilities (37 cells) and two surface impoundment facilities (four ponds) in this group. End of construction data are available for seven landfill cells and two surface impoundment ponds. In addition, data are available for 31 cells and three ponds during their active lives, and for 17 closed cells.

For the Group III facilities, top liner leakage rates should be low and should not occur for some period after construction (due to the containment capabilities of composite top liners). Since geonets were used in the LDCRS drainage layers of these facilities, there should not be any construction water (except for a small amount of water that drains from granular collection trenches in the LDCRS). Therefore, flows from the LDCRSs of Group III facilities should result primarily from consolidation of the clay component of the top liner.

Landfills

For the seven Group III cells for which end of construction data is available, average measured flow rates ranged from 0 to 1,900 lphd (0 to 190 gpad), and maximum measured flow rates ranged from 0 to 6,400 lphd (0 to 640 gpad). These flows are attributed to construction water draining from granular collection trenches and consolidation water.

With one exception, all of the 31 Group III landfill cells for which data are available exhibited flows from their LDCRSs during their active lives. Average flow rates during the active lives of these cells ranged from 0 to 1,300 lphd (0 to 130 gpad), with 15 of the 31 cells exhibiting flows less than 200 lphd (20 gpad), 24 of the cells exhibiting flows less than 500 lphd (50 gpad), and 28 of the cells exhibiting flows less than 1,000 lphd (100 gpad). Based on the calculated breakthrough times for seepage through the top liner, the LDCRS flows from these cells during their active lives are primarily attributable to consolidation water. The flow rates are consistent with the calculated range of values for flows due to consolidation water of 1 to 1,500 lphd (1 to 150 gpad) reported in Section 4.5.

For the 17 Group III cells that are closed or covered with a geomembrane or soil layer (i.e., Landfill F, Cells 1 to 4, Landfill G, Cells 1 to 6, Landfill H, Cell 1, and Landfill T, Cells 1 to 6), ongoing LDCRS flows may be due to continuing consolidation or secondary compression of the clay component of the top liner. In addition, a portion of the flows from Landfills H and T, which have a geomembrane top liner on their side slopes, may be due to top liner leakage. While there is no direct evidence of leakage through the composite top liner of any of the closed cells (i.e., there is no chemical constituent data for the LDCRS), the possibility of minor top liner leakage cannot be ruled out because the LCRS at the facilities continues to produce liquid, and the calculated breakthrough time for the clay component of the composite top liner is less than the time period between the start of the active life and the recording of the LDCRS flows.

Surface Impoundments

For the two Group III ponds for which end of construction data is available, the average measured flow rates were 53 and 1,590 (5.3 to 159 gpad). These flows are attributed to construction water draining from granular collection trenches and consolidation water.

The three Group III ponds that have data from their active lives exhibited average measured LDCRS flow rates ranging from 0 to 960 lphd (0 to 96 gpad), and maximum monthly flow rates ranging from 0 to 1,380 lphd (0 to 138 gpad). The flows from these ponds are primarily attributed to consolidation water. Top liner leakage is thought to have occurred for one pond (i.e., Surface

Impoundment C, Pond 2). For this pond the average measured flow rate increased from 4 to 960 lphd (0.4 to 96 gpad) after the liquid height in the pond was increased at 38 months after the end of construction. It cannot be determined from the available information how flow entered the LDCRS in such a short time period after the liquid height in the pond was increased as the top liner was a composite on the base and side slopes. A geomembrane top liner defect was found on the side slope of the pond and repaired. Subsequently, the average flow rate decreased to 40 lphd (4 gpad).

Flow Rate Over Time

For both landfill and surface impoundment facilities it is interesting to observe how the flow rate of consolidation water from a facility decreases over time (e.g., Landfill T, Cell 9 and Surface Impoundment C, Pond 3). For example, for Landfill T, Cell 9, the average flow rate at about seven to twelve months after construction was 230 lphd (23 gpad). By 13 to 18 months, the average flow rate had decreased to 150 lphd (15 gpad). The flow decreased still further over time and was 20 lphd (2 gpad) at 26 to 30 months after construction.

6.2.4 Group IV Facilities

Introduction

Group IV facilities were constructed with composite top liners and sand LDCRS drainage layers. There are eight landfill facilities (14 cells) and one surface impoundment facility (two ponds) in this group. End of construction data are available for ten landfill cells. Data are also available for twelve cells and all surface impoundment ponds during their active lives. No data for closed cells are available.

At the end of construction, flows from the LDCRSs of the Group IV facilities should be due primarily to drainage of construction water. Subsequently, consolidation water will contribute to the flow from those facilities in which a conventional compacted clay layer was used in the composite top liner. For one of the facilities (Landfill I), a 6-mm (0.25-in.) thick GCL was placed directly under the geomembrane. This GCL is installed with the bentonite in a dry state. The bentonite in the GCL hydrates in the presence of water, thereby forming a low-permeability barrier. Due to its thinness, consolidation water from the GCL should not be a source of significant flow from the LDCRS of this facility.

Landfills

Seven of the 14 Group IV cells have a layer of compacted clay as the soil component of the composite top liner, and seven have a GCL.

At the Group IV facilities for which end of construction flow rate data is available (i.e., nine landfill cells), the hydraulic conductivity of the drainage material is on the order of 10^{-2} cm/s. For this value of hydraulic conductivity, drainage of construction water could have occurred for several months after installation of the top liner. Flow rate data at the end of construction are available for three cells with a compacted clay layer in their composite top liner. For these three cells, the average measured flow rates were 0, 15, and 23,300 lphd (0, 1.5, and 2,330 gpad). The average measured flow rates at the end of construction for the seven Group IV cells that were constructed with a GCL in their composite top liner ranged from 0 to 890 lphd (0 to 89 gpad), with five of the cells exhibiting average flow rates of less than 100 lphd (10 gpad). The maximum weekly flow rate for these seven cells ranged from 0 to 2,900 lphd (0 to 290 gpad).

Flow rate data are available for five active cells with a compacted clay layer as a component of the composite top liner. Average measured flow rates from the LDCRSs of these cells ranged from 40 to 500 lphd (4 to 50 gpad). Three of the five cells exhibited flows of less than 200 lphd (20 gpad). These flow rates are consistent with the range of flow rates attributed to consolidation water observed for the Group III cells.

Flow rate data are available for seven active cells with a GCL as a component of the composite top liner. In one of the seven cells, no LDCRS flow was observed. For five of the six cells exhibiting flow, average flow rates of 50 lphd (5 gpad) or less were observed. For the remaining cell, an average flow of 120 lphd (12 gpad) or less was observed. Maximum weekly flows for the seven cells were 430 lphd (43 gpad) or less. These flow rates could be accounted for by a combination of compression and continuing drainage of the sand LDCRS drainage layer or leakage through the geomembrane top liner on the side slopes of the cells (the GCL only extends over the base of the cells).

Surface Impoundments

Both Group IV ponds were constructed with a composite top liner on the base slope and a geomembrane top liner on the side slope. Average measured flow rates from one of the ponds (i.e., Surface Impoundment B, Pond 1) ranged from 2 to 1,120 lphd (0.2 to 112 gpad) during the active life of the pond. The maximum monthly flow rates from this pond ranged from 7 to 1,340 (0.7 to 134 gpad). These flows are primarily attributed to consolidation water and leakage through the geomembrane top liner on the side slope of the pond. It is known that top liner leakage was occurring in this pond during 35 to 37 months after the end of construction based on analysis of LDCRS flow for chemical constituents found in the pond liquid. This incidence of top liner leakage coincided with an increase in the liquid level in the pond. The LDCRS flow rate decreased when the liquid level was lowered. It therefore appears that the geomembrane top liner on the pond side slope had a defect. The flow rate from the LDCRS of the second pond (i.e., Surface Impoundment B, Pond 2) was zero from 20 to 43 months after construction; for this latter pond, consolidation water flows apparently ceased prior to flow rate measurement and quantifiable top liner leakage did not occur.

6.3 INTERPRETATION OF DATA

6.3.1 Group I and Group II Landfills

It is interesting to compare the flows attributable to top liner leakage for the Group I and II landfills (excluding Landfill J). For this comparison, the 21 landfill cells have been subdivided into those that had a CQA program (14 cells) and those that did not have a CQA program (seven cells). From Table 10, it can be seen that of the 14 cells that had a CQA program, six had average flow rates less than 50 lphd (5 gpad), and eleven had average flow rates less than 200 lphd (20 gpad). All 14 cells that had a CQA program exhibited both average and maximum flow rates less than 1,000 lphd (100 gpad), which is EPA's recommended action leakage rate value for landfills. Of the seven cells that did not have a CQA program, one cell had a average flow rate less than 200 lphd (20 gpad), and five cells exhibited average flow rates greater than 1,000 lphd (100 gpad). For the cells without a CQA program for which maximum flow rate data is available (i.e., six cells), all of the cells exhibited maximum flow rates of up to 500 lphd (50 gpad) or more, and four of the cells exhibited maximum flow rates of over 1,000 lphd (100 gpad).

On the basis of the limited available flow rate data, it appears that cells with properly constructed geomembrane top liners that have undergone CQA monitoring will consistently limit top liner leakage to a value of less than 1,000 lphd (100 gpad). From the data in Table 10, it also appears that implementation of a CQA program during construction significantly reduces top liner leakage rates in comparison to facilities that do not have a CQA program.

Table 10. Comparison of average and maximum measured flow rates at Group I and II landfills [Notes: Excludes Landfill J].

LDCRS Flow Rates for Landfills With CQA	Average	Maximum Monthly	Maximum Weekly
Less than 50 lphd	6	5	-
From 50 to 200 lphd	5	4	1
From 200 to 500 lphd	2	-	1
From 500 to 1,000 lphd	1	-	3
More than 1,000 lphd	-	-	-
LDCRS Flow Rates for Landfills Without CQA	**Average**	**Maximum Monthly**	**Maximum Weekly**
Less than 50 lphd	-	-	-
From 50 to 200 lphd	1	-	-
From 200 to 500 lphd	-	-	-
From 500 to 1,000 lphd	1	-	2
More than 1,000 lphd	5	-	4

6.3.2 Group III and Group IV Landfills

As was done with the Group I and II landfills, the flows from the LDCRSs of the Group III and IV landfills (excluding Landfill I) can also be compared (Table 11). In the case of Group I and II landfills, flows from the LDCRSs were due primarily to top liner leakage. For Group III and IV landfills, flows were primarily due to consolidation water.

From Table 11, it can be seen that 39 of the 42 Group III and IV landfill cells for which data exist have average consolidation water flow rates of less than 1,000 lphd (100 gpad), and 36 of the 42 cells have average consolidation water flow rates less than 500 lphd (50 gpad). Maximum flow rates are somewhat higher, with 26 of the 37 cells for which data is available exhibiting maximum flows less than 1,000 lphd (100 gpad), which is EPA's recommended action leakage rate for landfills. From these flow rates, it appears that landfills with composite top liners may occasionally exhibit LDCRS flow rates exceeding 1,000 lphd (100 gpad). While consolidation water is not necessarily an environmental concern, EPA intends to consider all flow from the LDCRS as top liner leakage unless it is demonstrated (in a response action plan) to be from another source. The above interpretations, however, should be interpreted cautiously because consolidation water flow rates vary with time and the reported values may not be maximums.

Table 11. Comparison of average and maximum measured flow rates at Group III and IV landfills [Notes: Excludes Landfill I].

LDCRS Flow Rates for Landfills With CQA	Average	Maximum Monthly	Maximum Weekly
Less than 50 lphd	7	2	-
From 50 to 200 lphd	14	8	1
From 200 to 500 lphd	10	5	3
From 500 to 1,000 lphd	3	-	4
More than 1,000 lphd	3	3	6
LDCRS Flow Rates for Landfills Without CQA	**Average**	**Maximum Monthly**	**Maximum Weekly**
Less than 50 lphd	-	-	-
From 50 to 200 lphd	1	-	-
From 200 to 500 lphd	2	2	-
From 500 to 1,000 lphd	2	1	-
More than 1,000 lphd	-	2	-

Bonaparte, R., Giroud, J.P., and Gross, B.A., "Rates of Leakage Through Landfill Liners", *Proceedings, Geosynthetics '89*, San Diego, Feb 1989, Vol. 1, pp. 18-29.

Bonaparte, R. and Gross, B.A., "Field Behavior of Double-Liner Systems", *Waste Containment Systems: Construction, Regulation, and Performance*, Geotechnical Special Publication No. 26, American Society of Civil Engineers, New York, 1990, pp. 52-83.

Brown, K.W., Thomas, J.C., Lytton, R.L., Jayawickrama, P., and Bahrt, S.C., "*Quantification of Leak Rates Through Holes in Landfill Liners*", EPA Report CR 810940, Cincinnati, 1987, 147 p.

EPA, "*Background Document: Proposed Liner and Leak Detection Rule*", EPA\530-SW-87-015, prepared by GeoSyntec Consultants, May 1987, 526 p.

Faure, Y.H., "*Nappes E'tanches: De'bit et Forme de l'Ecolement en Cas de Fruite*", thesis, University of Grenoble, France, Dec 1979, 263 pp. (in French)

Faure, Y.H., "Design of Drain Beneath Geomembranes: Discharge Estimation and Flow Patterns in Case of Leak", *Proceedings, International Conference on Geomembranes*, Denver, Vol. 2, June 1984, pp. 463-468.

Fukuoka, M., "*Outline of Large Scale Model Test on Waterproof Membrane*", unpublished report, May 1985, 24 pp.

Fukuoka, M., "Large Scale Permeability Tests for Geomembrane-Subgrade System", *Proceedings, Third International Conference on Geotextiles*, Vienna, Austria, Vol. 3, April 1986, pp. 917-922.

Giroud, J.P., "Geotextile Drainage Layers for Soil Consolidation", *Civil Engineering for Practicing and Design Engineers*, Vol. II, 1983, pp. 275-295.

Giroud, J.P., "Impermeability: The Myth and a Rational Approach", *Proceedings, International Conference on Geomembranes*, Denver, Vol. 1, June 1984, pp. 157-162.

Giroud, J.P. and Bonaparte, R., "Leakage Through Liners Constructed with Geomembranes - Part I. Geomembrane Liners", *Geotextiles and Geomembranes*, Vol. 8, No. 1, 1989a, pp. 27-67.

Giroud, J.P. and Bonaparte, R., "Leakage Through Liners Constructed with Geomembranes - Part II. Composite Liners", *Geotextiles and Geomembranes*, Vol. 8, No. 2, 1989b, pp. 78-111.

Giroud, J.P., Khatami, A., and Badu-Tweneboah, K., "Evaluation of the Rate of Leakage Through Composite Liners", *Geotextiles and Geomembranes*, Vol. 8, No. 4, 1989, pp. 337-340.

Giroud, J.P., Badu-Tweneboah, and Bonaparte, R., "Rate of Leakage Through a Composite Liner Due to Geomembrane Defects", *Geotextiles and Geomembranes*, Vol. 11, No. 1, 1992, pp. 1-28.

Gross, B.A., Bonaparte, R., and Giroud, J.P., "Evaluation of Flow from Landfill Leakage Detection Layers", *Proceedings, Fourth International Conference on Geotextiles*, Vol. 2, The Hague, Jun 1990, pp. 481-486.

Jayawickrama, P., Brown, K.W., Thomas, J.C., and Lytton, R.L., "Leakage Rates Through Flaws in Geomembrane Liners", *Journal of Environmental Engineering*, ASCE, Vol. 114, No. 6, Dec 1988, pp. 1401-1420.

Linsley, R.K., Jr., Kohler, M.A., and Paulhus, J.H., *"Hydrology for Engineers"*, McGraw-Hill, Inc., New York, NY, 1975, 482 p.

Schiffman, R.L., "Consolidation of Soil Under Time Dependent Loading and Varying Permeability", *Highway Research Board Proceedings No. 37*, 1958, pp. 584-617.

Sherard, J.L., "The Upstream Zone in Concrete-Face Rockfill Dams", *Proceedings of a Symposium on Concrete Faces Rockfill Dams - Design, Construction, and Performance*, sponsored by the Geotechnical Engineering Division of the American Society of Civil Engineers, ed. J. Barry Cooks and James L. Sherard, Detroit, Oct 1985, pp. 618-641.

Terzaghi, K., *Theoretical Soil Mechanics*, John Wiley and Sons, Inc., New York, 1943, 527 p.

A. REGULATORY BACKGROUND

A.1 INTRODUCTION

The purpose of this appendix to the report is to describe regulatory developments under the Resource Conservation and Recovery Act (RCRA) of 21 October 1976 that led to the design criteria for leakage detection, collection, and removal systems (LDCRSs) and the action leakage rate (ALR) concept in EPA's final rule of 29 January 1992.

A.2 EPA FINAL RULE OF 26 JULY 1982

Minimum technology requirements for lining systems at hazardous waste landfill, waste pile, and surface impoundment units were first promulgated by EPA on 26 July 1982 (47 FR 32274). (A "*unit*" was defined in the preamble to the final rule as "*the contiguous area of land on or in which waste is placed*".) These requirements (in amendments to Chapter 40 Sections 264 and 265 to the Code of Federal Regulations (CFR) (i.e., 40 CFR 265 and 266)) included: (i) a single liner "*that is designed, constructed, and installed to prevent any migration of wastes*" out of the unit during the active life (including the closure period) of the unit; and (ii) for landfills and waste piles, a leachate collection system that limited the leachate depth over the liner to 0.3 m (1 ft). In the preamble to the EPA final rule of 26 July 1982, EPA recognized that the requirement that a liner "*prevent any migration of wastes out of a unit*" would dictate the type of liner that could be used. For landfills, EPA only recognized geomembranes as being able to meet this standard. For surface impoundments and waste piles that were closed by removing or decontaminating wastes and waste residues, a compacted soil liner or geomembrane could be used. The EPA final rule of 26 July 1982 also required monitoring and inspection of liners during their construction and installation.

A.3 HSWA AMENDMENTS OF 8 NOVEMBER 1984 TO RCRA

In the 8 November 1984 Hazardous and Solid Waste Amendments (HSWA) to RCRA, Congress imposed the first double-liner requirements for hazardous waste landfills and surface impoundments. Under Sections 3004(o)(1)(A) and 3015 of HSWA, certain landfill and surface impoundment units were required to have "*two or more liners and a leachate collection system above (in the case of a landfill) and between the liners*". The leachate collection system between the top and bottom liners was referred to as the "*leak detection system*". Although waste pile units were not required to have a double-liner system, certain waste piles were required to have a leak detection system. Under Section 3004(o)(4)(B) of HSWA, the leak detection system for the units was required "*to be capable of detecting leaks of hazardous constituents at the earliest practicable time*". Section 3004(o)(5)(B) of HSWA allowed the use of a particular liner system (i.e., "*a top liner designed, operated and constructed of materials to prevent the migration of any constituents into such liner during the period such facility remains in operation (including any post-closure monitoring period)*" and a bottom liner consisting of a "*3-foot thick layer of recompacted clay or other natural material with a permeability of no more than 1×10^{-7} centimeter per second*") until EPA issued regulations or guidance to meet the requirements of HSWA. HSWA also listed deadlines for EPA to promulgate regulations or issue guidance documents for double-liner systems.

A.4 EPA DRAFT GUIDANCE OF 24 MAY 1985

In response to the requirement of HWSA that EPA to promulgate regulations or issue guidance documents for double-liner systems, EPA issued a guidance document on 24 May 1985 entitled "*Draft, Minimum Technology Guidance on Double Liner Systems for Landfills and Surface Impoundments -- Design, Construction, and Operation*" (EPA/530-SW-85-014). This draft EPA document provided guidance on liner system designs, in addition to the design in Section 3004(o)(5)(B) of RCRA as amended by HSWA (hereafter referred to as RCRA), that met the requirements of Section 3004(o)(1)(A) of RCRA. Two double-liner systems were described in the draft EPA guidance document. The first double-liner system included a geomembrane top liner and a composite bottom liner. The second double-liner system included a geomembrane top liner and a low-permeability soil bottom liner. The document also provided guidance on construction quality assurance (CQA) procedures for the various liner system components to ensure, to the degree possible, that the constructed facility met the design specifications and performance requirements.

In both double-liner systems described in the EPA draft guidance document, the thickness of the geomembrane top liner was at least 0.75 mm (30 mil) if the geomembrane was covered by a protective soil layer or waste after installation or 1.1 mm (45 mil) if the geomembrane was left exposed for an extended period or operated without a protective soil layer. The geomembrane top liner was also chemically resistant to degradation by waste and leachate and met certain other requirements.

The two double-liner systems described in the draft EPA guidance document differed only in their bottom liners. The first bottom liner was a composite liner comprising a geomembrane upper component and a compacted low-permeability soil layer lower component. The geomembrane component of the bottom liner met requirements similar to those for the geomembrane top liner. The soil component of the bottom liner was at least 0.9-m (3-ft) thick and had a saturated hydraulic conductivity of no more than 1 x 10^{-7} cm/s. The second bottom liner described in the draft EPA guidance document was a compacted soil liner that met the requirements of the bottom liner allowed by HSWA. According to EPA, this liner had a saturated hydraulic conductivity of no more than 1 x 10^{-7} cm/s, had a minimum thickness of 0.9 m (3 ft), and was of sufficient thickness to "*prevent the migration of any constituent through the liner during the facility's active life and post-closure care period*".

In both of the double-liner systems described in the draft EPA guidance document, the top liner of landfill units was overlain by a "primary" leachate collection system consisting of a 0.3-m (1-ft) thick (minimum) granular drainage layer that had a saturated hydraulic conductivity of not less than 1 x 10^{-2} cm/s, was placed with a minimum slope of two percent, and was chemically resistant to degradation by waste and leachate. A synthetic drainage layer, such as a geonet, could be used in lieu of a granular drainage layer if it was shown to be equivalent to, or more effective than, a granular drainage layer meeting the minimum requirements. In any case, the leachate collection system was designed to limit the leachate depth on the top liner to 0.3 m (1 ft) to meet the EPA final rule of 26 July 1982.

In both double-liner systems described in the EPA draft guidance document, a "secondary" leachate collection system was included between the top and bottom liners. This secondary leachate collection system was designed to rapidly detect, collect, and remove liquids that enter the system so as to "*produce little or no head of liquid on the bottom liner*". The secondary leachate collection system described by EPA was basically the same as the primary leachate collection system (i.e., a 0.3-m (1-ft) thick (minimum) granular drainage layer that had a minimum saturated hydraulic conductivity of 1 x 10^{-2} cm/s, was placed with a minimum slope of 2 percent, and was chemically resistant to degradation by waste and leachate). EPA also indicated in the document that a synthetic drainage layer, such as a geonet, could be used in lieu of a granular drainage layer if it was shown to be equivalent to a granular drainage layer meeting the minimum requirements.

A.5 EPA FINAL RULE OF 15 JULY 1985

On 15 July 1985, EPA issued a final rule (50 FR 28702) amending existing regulations to reflect those statutory provisions of HSWA that took effect immediately or shortly after its enactment. This rule incorporated into the existing regulations (i.e., into 40 CFR 264 and 265) the HSWA provisions (under Section 3004(o)(5)(B) of RCRA) requiring that, until EPA issued regulations implementing the double-liner system requirements of Sections 3004(o)(1)(A) and 3015 of RCRA, certain facilities must have a double-liner system that meets or exceeds the specific requirements of the provisions. The 15 July 1985 rule required facilities to have a top liner and a compacted soil bottom liner (i.e., the liner system allowed by Section 3004(o)(5)(B) of RCRA). For landfills, the top liner was required to be a geomembrane, but for surface impoundments the top liner could be a compacted soil layer or a geomembrane. The bottom liner was deemed to satisfy the HSWA provisions if it was "*constructed of at least a 3-foot thick layer of recompacted clay or other natural material with a permeability of no more than 1 x 10^{-7} centimeter per second*". The rule also required a leachate collection system between the top and bottom liners at surface impoundments and landfills and above the top liner at landfills.

A.6 EPA PROPOSED RULE OF 28 MARCH 1986

On 28 March 1986, EPA promulgated regulations on double-liner systems as required by HSWA. The proposed rule contained minimum technology requirements for double-liner systems and leachate collection and removal systems (51 FR 10706). This proposed rule, commonly referred to as the proposed "Double-Liner and Leachate Collection System Rule" or simply the "Double-Liner Rule", would, when finalized, amend the double-liner system requirements of 40 CFR 264 and 265.

The minimum technology requirements in the proposed Double-Liner Rule were essentially those of the draft EPA guidance document of 24 May 1985. Two double-liner system options were provided in the proposed rule (51 FR 10709). Both incorporated geomembrane top liners; however, one option allowed a compacted soil bottom liner, while the other option allowed a composite bottom liner. There was no minimum thickness requirement for the geomembrane top liner given in the regulations.

The compacted soil bottom liner option closely resembled the design standard of Section 3004(o)(5)(B) of RCRA, as codified in the EPA final rule of 15 July 1985. The compacted soil bottom liner of the proposed rule differed from that of the standard of Section 3004(o)(5)(B) in that it required the bottom liner to not only meet a minimum design requirement (i.e., be at least 0.9-m (3-ft) thick and have a hydraulic conductivity of no more than 1 x 10^{-7} cm/s), but also meet a minimum performance standard (i.e., prevent the migration of any constituent through the liner during the facility's active life and post-closure care period). This performance standard was similar to that presented in the draft EPA guidance document of 24 May 1985. The composite bottom liner option of the proposed Double-Liner Rule was also similar to that in the draft EPA guidance document, with the exception that no minimum thickness was specified in the proposed rule for the geomembrane or compacted soil component of the composite bottom liner. However, in the preamble (51 FR 10710) to the proposed rule of 28 March 1986 EPA noted that the soil component should be at least 0.9-m (3-ft) thick. The proposed rule required the compacted soil component to have a hydraulic conductivity of no more than

1 x 10^{-7} cm/s and to minimize the migration of any constituent through the geomembrane component of the liner if a defect were to develop in the geomembrane prior to the end of the post-closure care period of the facility.

The proposed rule also provided minimum requirements for the leachate collection and removal system above the top liner of landfills and between the top and bottom liners of landfills and surface impoundments. Consistent with the EPA final rule of 26 July 1982 and draft EPA guidance document of 24 May 1985, the LCRS above the top liner was required to be designed, constructed, and operated to collect and remove leachate and ensure that the leachate head on the top liner did not exceed 0.3 m (1 ft). In addition, the LCRS between the top and bottom liners was required to be "*designed, constructed, maintained, and operated to detect, collect, and remove liquids that may leak through any area of the top liner during the active life and post-closure care period*". No hydraulic conductivity requirement for the LCRSs was given in the proposed rule.

A.7 EPA NOTICE OF 17 APRIL 1987

On 17 April 1987, EPA issued "*Hazardous Waste Management System; Minimum Technology Requirements: Notice of Availability of Information*" (52 FR 12566). The notice contained data on the two bottom liner designs (i.e., compacted soil liner and composite liner) presented in the EPA proposed rule of 28 March 1986. In this notice, EPA compared the two liner systems with respect to leak detection performance characteristics, leachate collection efficiency, and leachate migration into and through the liner. Based on the data, EPA concluded that the proposed composite bottom liner contained leachate and enhanced leachate collection significantly better than the proposed compacted soil bottom liner. Based on the information in this notice, along with the minimum technology requirements of the proposed "Liner/Leak Detection System Rule", EPA decided that the final "Double-Liner Rule" would only allow the use of a composite bottom liner (i.e., a compacted soil bottom liner will not be allowed).

A.8 EPA PROPOSED RULE OF 29 MAY 1987

On 29 May 1987, EPA proposed minimum technology requirements for LDCRSs at certain land disposal units (52 FR 20218). These requirements were intended to meet the previously mentioned statutory provisions in Section 3004(o)(4)(A) of RCRA that specifically call for EPA to establish minimum standards for "*leak detection systems*". The proposed rule, commonly referred to as the "Liner/Leak Detection System Rule" or simply "Leak Detection System Rule", required all new landfills, surface impoundments, and waste piles to have an approved LDCRS that was capable of detecting leakage "*at the earliest practicable time*". The proposed rule also required waste piles to meet essentially the same double-liner system requirements as landfills. Lastly, the proposed rule codified CQA requirements for landfills, waste piles, and surface impoundments.

The proposed Liner/Leak Detection System Rule contained both minimum design specifications and minimum performance requirements for the LDCRS. The minimum design requirements consisted of: (i) a minimum bottom slope of 2 percent; (ii) for granular drainage media, a minimum thickness of 30 cm (12 in.) and a minimum hydraulic conductivity of 1 cm/s; and (iii) for synthetic drainage media, a minimum hydraulic transmissivity of 5×10^{-4} m^2/s. The performance requirements consisted of: (i) a minimum leak detection sensitivity of 10 lphd (1 gpad); and (ii) a maximum steady-state leak detection time of 1 day.

In the proposed Liner/Leak Detection System Rule of 29 May 1987, EPA introduced the concept of an action leakage rate (ALR), which was defined as (52 FR 20222) "*the rate of leakage from the top liner into the LCRS that triggers interaction between the owner or operator and the Agency to determine the appropriate response action for the leakage*". EPA proposed to establish the ALR as follows:

> "*(1) Using a standard value of (EPA is proposing to select a final value from the range of 5-20 gallons/acre/day); or*
>
> *(2) A review by the Regional Administrator of an owner or operator demonstration, and a finding by the Regional Administrator, that a site-specific top liner action leakage rate is appropriate for initiating review of the actual leakage rate to determine if a response action is necessary. The site-specific top liner action leakage rate demonstration must be based on allowing only very small isolated leakage through the top liner that does not affect the overall performance of the top liner.*"

The concepts of rapid and extremely large leakage (RLL) and response action plan (RAP) were also introduced in the proposed Liner/Leak Detection System Rule. The RLL was defined as (52 FR 20237) "*the maximum design leakage rate that the LDCRS can remove under gravity flow conditions (i.e., without the fluid head on the bottom liner exceeding one foot of water in granular leak detection systems and without the fluid head exceeding the thickness of synthetic leak detection systems)*." The RAP was defined as (52 FR 20222) a plan "*which consists of an assessment of the reason for leakage, the current conditions of the unit components..., the potential for migration out of the unit* *of hazardous waste constituents at levels exceeding health-based standards, and an assessment of the effectiveness of various responses.*"

A.9 EPA FINAL RULE OF 29 JANUARY 1992

On 29 January 1992, EPA finalized the proposed rules of 28 March 1986 and 29 May 1987 (i.e., the Double-Liner Rule and the Leak Detection System Rule). This final rule (57 FR 3462) amended the double-liner and LDCRS requirements of 40 CFR 264 and 265 for certain land disposal units, including some waste piles. The final rule also codified CQA requirements for landfills, waste piles, and surface impoundments.

The double-liner system and LCRS required in the final rule are essentially the same as those presented in the proposed 28 March 1986 rule. The double-liner system requirements can be satisfied by a geomembrane top liner and composite bottom liner consisting of a geomembrane upper component and 0.9-m (3-ft) thick compacted soil layer lower component with a hydraulic conductivity of no more than 1×10^{-7} cm/s. The LCRS requirements can be met by a drainage system that limits the depth of leachate over the top liner to 0.3 m (1 ft).

The LDCRS requirements in the final rule are somewhat different than those presented in the proposed EPA rule of 29 May 1987. In the final rule, the design requirements consist of the following: (i) a minimum bottom slope of one percent; (ii) for granular drainage media, a minimum thickness of 0.3 m (1 ft) and a minimum hydraulic conductivity of 1×10^{-2} cm/s for landfills and waste piles and 1×10^{-1} cm/s for surface impoundments; and (iii) for synthetic drainage media, a minimum hydraulic transmissivity of 3×10^{-5} m^2/s for landfills and waste piles and 3×10^{-4} m^2/s for surface impoundments. The previously-mentioned performance requirements given in the 29 May 1987 proposed rule for LDCRSs were not promulgated in the final rule.

In the final rule of 29 January 1992, EPA included the RAP concept and combined the ALR and RLL concepts of the proposed 27 May 1987 rule. In the final rule the RLL was renamed the ALR and defined as (57 FR 3474) "*the maximum design leakage rate that the leak detection system can remove without the fluid head on the bottom liner exceeding one foot*". As stated in the preamble to the final rule, "*the Agency believes that units meeting the minimum technical requirements would not require leakage rates below 100 gpad for landfills and waste piles and 1,000 gpad for surface impoundments*". However, EPA also indicated in the preamble that they recognize "*that a number of site-specific factors affect the maximum flow capacity of a leak detection system, and owners or operators may want to propose alternative action leakage rates*".

[illegible]