Report on

Controlling Groundwater Pollution from Hazardous Waste Landfills-Which System is the Best?

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ABSTRACT

Recently, the Resource Conservation and Recovery Act (RCRA) and the Hazardous and Solid Waste Amendments to the RCRA have placed limits on the emission of leachate from landfills. Engineers have created ways for satisfying these limits, and the result has been an explosion in the use of landfill liners, especially geomembrane liners. Geomembrane liners play an important role in controlling leachate emissions from landfills.

Many types of geomembrane liners are available. This paper discusses high density polyethylene (HDPE), low density polyethylene (LDPE), chlorosulphonated polyethylene (CSPE), and polyvinyl chloride (PVC) liners. Each of these liners are evaluated to determine the liner with the best combination of cost, durability, temperature resistance, strength, and seepage resistance. In addition, this paper discusses composite liners, which are a new development in the landfill liner industry. This paper then weighs the alternative liner systems, including the composite liner systems.

The most effective liner system is a composite liner composed of an HDPE or a reinforced CSPE geomembrane on top and a compacted clay liner on the bottom. This composite liner can provide up to 100 times better leachate control than a typical geomembrane or compacted clay liner alone. This composite liner can be used in a landfill leachate collection system with good leachate control being the result.

I. INTRODUCTION

When most people think of a landfill, they probably think of the city dump their dad took them to while growing up. Dad would drive his old Chevy right up to the dump site and would drop off a month's worth of garbage all at once. The whole process would cost him about $5.00 per month.

But today, landfills are areas with highly controlled access. Only vehicles with special permits are allowed to enter into a landfill area. And much thought is put into every landfill that is constructed today. It may take 10 years of debate before the construction on a landfill even begins. In fact, some landfills are never begun because of the opposition of nearby residents. It is not unusual to pay prices of $9.00 or more per *week* now to pay the local garbage collection company for garbage pickup. Today, a team of engineers is required to design and evaluate every hazardous waste landfill before, during, and after construction.

What is it that has caused such controversy, thought, and engineering to go into every landfill in existence today? One of the main reasons is because of leachate.

First, I need to explain *what* leachate is, *why* leachate can be harmful, and *what* can be done to control leachate in landfills. To explain the effects of leachate, I will first discuss the following four topics:

1. Aquifers
2. Leachate
3. How can leachate be harmful?
4. How can geomembrane liners control leachate?

Second, I will accomplish the purpose of this paper. *The main purpose of this paper will be to show you which type of geomembrane liner system best controls the flow of leachate from landfills and prevents groundwater contamination*.

To show you which type of geomembrane liner provides the best control of leachate from landfills, I will discuss four types of geomembrane liners. I have done research on the following four geomembrane liners:

- **PVC**
- **CSPE**
- **LDPE**
- **HDPE**

Finally, I will show you which type of liner *system* provides the best leachate protection in landfills. Does a *composite liner* work best, or is a geomembrane liner by itself good enough? Or, should engineers do away with geomembrane liners altogether and use the traditional *compacted clay liners*? Also, which geomembrane liner works best with a composite liner? These questions will all be answered in this paper.

II. LEACHATE AND GEOMEMBRANES

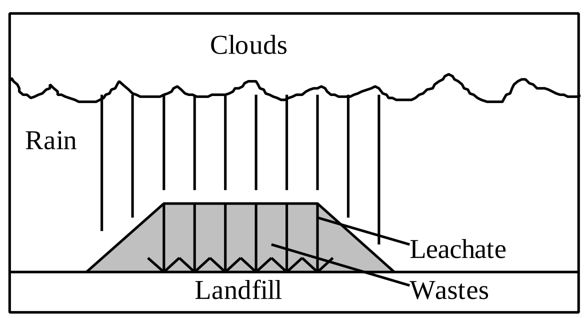
Before I begin talking about geomembrane liners and leachate in landfills, I will explain why every landfill needs a geomembrane liner.

Aquifers

We all know that an *aquifer* is an area of underground caverns, rocks, or other geologic formations capable of sustaining a water supply. An aquifer is like an underground river, except the water in an aquifer normally does not move as quickly as the water in a river. Also, the water contained in an aquifer usually is of a higher quality than surface water. Next to surface water, groundwater is the main source of water in the United States.

Leachate

Leachate is simply the off-colored ooze which flows from buried solid wastes[1]. While rain is falling or snow is melting over a landfill, water seeps into the landfill. The diagram in figure 1 shows the creation of leachate in a landfill. As the water seeps into the landfill, the water combines with material from the wastes to form leachate.



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[1]Solid wastes are defined as any wastes which are not transported by water.

How can leachate be harmful?

The leachate from a landfill, especially a landfill containing toxic materials, can be nasty stuff. When released into the environment, the leachate from a landfill can pollute water sources with organic chemicals. These organic chemicals are normally fluids which create a health hazard for human and animal life.

One of the areas of main concern is the pollution of groundwater in underground aquifers by "leachate plumes" from landfills. The drawing in figure 2 best describes how a leachate plume is formed and how a leachate plume can contaminate groundwater. Underground leachate plumes are moving areas of high concentrations of leachate which have the potential to contaminate underground aquifers.

It was not until the 1970's that people realized the danger of the "ooze" called leachate. In the late 1970's, tests revealed that the quality of groundwater below certain poorly constructed landfills was unsafe for human consumption. Environmental engineers soon realized that the contaminated groundwater came from the movement of leachate from the landfill to the groundwater below (Daniel, 1993).

These environmental engineers also realized that something must be done to keep the leachate from escaping the landfill, destroying the water supplies, and polluting the environment. The engineers found that if layers of synthetic material were placed between the landfill and the earth, the material would provide a barrier through which leachate could not escape. The leachate from the landfill could then be collected and treated. The most important part of the synthetic material used between a landfill and the earth is the *geomembrane liner*.

How can geomembrane liners control leachate?

A geomembrane liner is a synthetic material (a material produced from petroleum) which is used to control the flow of fluids in an engineering project (literally, a *geo-membrane*).

Geomembrane liners are like a baby's diapers. Just as a baby's diaper is effective in containing and isolating the wastes emitted from a baby, geomembrane liners are effective in containing and isolating the leachate flowing from a landfill. By using a geomembrane liner, the leachate from a landfill can be collected and treated before it is released into the environment. Figure 3 gives an example of how geomembrane liners and other "geosynthetics"[2] may be used in modern-day landfills.

[2]A geosynthetic is any one of a whole variety of materials used by engineers to improve the properties of soils. Examples of geosynthetics include geomembranes, geotextiles, geonets, and geogrids (see figure 3).

Geomembranes are not only used in landfill design, but are also used by highway engineers, foundation engineers, and water resource engineers to prevent water from entering the ground in undesirable places (Daniel, 1993). However, in this paper, I will concentrate on the use of geomembrane liners in landfills.

For more information on how geomembrane liners are used in landfills, you can refer to appendix B[3].

Throughout the world, three types of geomembrane liners are used:

- **Thermoset elastomers**: synthetic materials which go through a change in chemical structure when melted. The melted material cannot be changed back to its original chemical structure.

- **Bituminous materials**: materials which are soluble in carbon disulfide. Examples of bituminous materials include the tar used for roofing and the asphalt used for paving highways.

- **Thermoplastics**: synthetic materials which may be heated and cooled. Even if these materials are melted, they will continuously maintain their original chemical structure.

In the United States, thermoset elastomers and bituminous materials are rarely

[3]In appendix B, I discuss a design for an advanced *leachate collection system* suggested by Daniel and Koerner (1991).

used for geomembrane liners. Thus, *thermoplastics are the main type of geomembrane liners used in landfills today* (Daniel, 1993, p. 168).

Thermoplastic geomembranes may be grouped into many categories. The two categories considered in this paper are based on the method used in manufacturing the geomembrane. The two categories are:

1. Geomembranes manufactured by extrusion processes - Daniel (1993) lists 2 geomembranes manufactured by extrusion processes:

   - **High density polyethylene** (HDPE) - either smooth or textured
   - **Low density polyethylene** (LDPE) - either smooth or textured

2. Geomembranes manufactured using a calendering process - Daniel also lists 2 geomembranes manufactured using a calendering process:

   - **Polyvinyl Chloride** (PVC), which is a plastic also used in the production of many water pipes.
   - **Chlorosulfonated polyethylene** (CSPE) - generally reinforced with a fabric scrim (p. 168).

Geomembranes Manufactured by Extrusion Processes. High density polyethylene (HDPE) and low density polyethylene (LDPE) liners are manufactured by *extrusion* processes[4]. Figure 4 shows a typical extruder used for manufacturing geomembranes. Extrusion processes have the capability of producing a relatively thick, stable, and durable material.

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[4]An extrusion process is a process in which the geomembrane being produced is first melted, then shaped using a mold (Van Zanten, 1986).

Geomembranes Manufactured by the Calendering Process. Chlorosulfonated polyethylene (CSPE) and polyvinyl chloride (PVC) liners are all manufactured using a calendering process[5]. Figure 5 shows a typical calendering process. One advantage of the calendering process is that it may be used to introduce *reinforcing fabrics* into a geomembrane. These reinforcing fabrics would then work to improve the strength of the geomembrane liner.

When engineers design landfills, they have many types of geomembrane liners to choose from. But which type of geomembrane liner system provides the *best* leachate protection in landfills? There must be a strong, durable, and cost efficient liner which adequately protects groundwater from leachate. We will now discover which geomembrane liner system works the best.

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[5]A calendering process is a process in which a heated geomembrane is flattened between two rollers and then taken up by a third set of rollers (Van Zanten, 1986).

III. CRITERIA AND EVALUATION OF GEOMEMBRANES

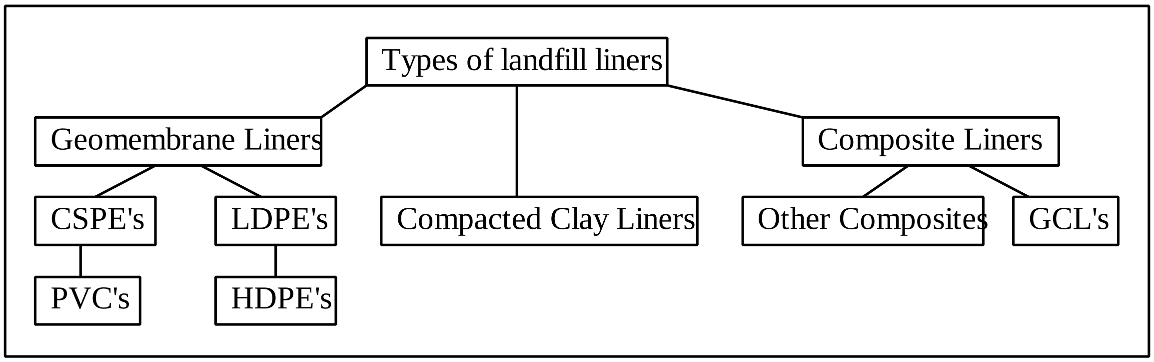
Geomembrane liners are an exciting new development in landfill design. Koerner (1986) estimated that 185 million square feet of geomembrane liners were sold in 1985. Koerner also projected that 500 million square feet of geomembrane liners would be sold in 1990 (p. 20).

One reason for the increased use of geomembranes throughout the 1980's and 1990's is government regulation. These government regulations have been aimed at controlling leachate emissions from landfills. The Resource Conservation and Recovery Act (RCRA) of 1976 and its amendments in 1980 and 1986 have established requirements for landfills containing hazardous waste. Also, on August 30, 1988, the Environmental Protection Agency (EPA) proposed that new landfills require the use of landfill liners and a *leachate collection system*[6]. If the EPA's proposition is put into law, both the "volume and quantity" of leachate produced and the quality of the groundwater below every landfill would need to be monitored and controlled (Oweis and Khera, 1990, p. 17). These landfill regulations can be met by using geomembrane liners.

Two types of geomembrane liner systems are available. The first is a *non-composite* liner, or a geomembrane liner by itself (nothing extra to make it work better). These non-composite liners are made out of plastic *only*. The second type of geomembrane liner is a *composite* liner, or a geomembrane liner attached to a layer of

[6]Appendix B contains information on a leachate collection system.

clay. A third type of liner does not contain geomembranes, and is called a *compacted*



clay liner. Figure 6 shows the different types of liners available.

To discover which type of geomembrane liner provides the best leachate control, I considered the following factors:

- ***Cost***
- ***Durability***, or resistance to weathering and chemical breakdown
- ***Temperature resistance***
- ***Strength***
- ***Seepage resistance,*** or resistance to flow of leachate through the liner.

I have examined information from several sources, including Haxo (1985), Oweis and Khera (1990), Rollin and Rigo (1991), and Koerner (1986) to find which geomembrane liner provides the best leachate protection.

Non-Composite Liners

Table I (on the next page) shows a summary of the results of my research on non-composite geomembrane liners[7]. As you can see from the table, the PVC, CSPE, and

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[7]Appendix C lists the criteria and references used in determining whether each

LDPE liners have *some* good properties, but the HDPE liner has the best properties of all the liners.

Table I: Characteristics of Non-composite Liners.

Type	***Seepage Resistance***	***Strength***	***Temperature Resistance***	***Durability***	***Cost***
HDPE	**Medium**	**High**	**High**	**High**	**Medium**
LDPE	**Low**	**Medium**	**Medium**	**High**	**Low**
CSPE	**High**	**Low***	**Medium**	**High**	**High**
PVC	**Low**	**Medium**	**Low**	**Low**	**Medium**

High strength if reinforced.

In many tests, the HDPE liner was found to have high strength, high durability, and high temperature resistance. In fact, in a study explained by Van Zanten (1986), two HDPE geomembrane liners were subjected to a 3-dimensional burst test. The HDPE geomembrane liners were found to be 2-3 times as strong as the PVC geomembrane and up to *10 times* as strong as some of the other geomembranes tested (pp. 586-588).

A *reinforced* CSPE liner also has excellent properties. If price is not a factor in selecting a landfill liner, the reinforced CSPE liner may be the best selection; but because of its high cost, many landfills are staying with the HDPE liner.

Koerner (1986), Rollin and Rigo (1991), and Oweis and Khera (1990) point out the following advantages and disadvantages for HDPE, LDPE, CSPE, and PVC

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material had "high", "medium", or "low" characteristics.

geomembrane liners (see the next page):

Table II: Advantages and Disadvantages of HDPE, LDPE, CSPE, and PVC Geomembranes.
From: Koerner 1986, p. 303, Rollin and Rigo, 1991, pp. 8-9 , and Oweis and Khera, 1990, p. 224.

Type of Geomembrane	Advantages	Disadvantages
High-Density Polyethylene (HDPE)	• Good resistance to oils, chemicals, and high temperature. • Available in thick sheets.	• Subject to cracking from applied stresses.* • Easily punctured at low thicknesses, bu normally comes in thick sheets.
Low-Density Polyethylene (LDPE)	• Good chemical resistance. • Available in thick sheets. • No cracking with applied stresses.	• LDPE is rarely use • Chemical resistance must be verified by tests.
Chlorosulphonated Polyethylene (CSPE)	• Excellent weathering properties. • Good crack resistance. • High tensile strength if reinforced with a *geotextile*.	• Poor resistance to petroleum wastes. • Low tensile strengt if unreinforced.
Polyvinyl Chloride (PVC)	• Resistant to organics. • Good strength. • Puncture resistance. • Lightweight. • Available in thick or thin sheets.	• Bad weathering properties. • May have poor cra resistance.* • May perform poorl at high temperatures.* • May have poor inorganic chemical resistance.*

**Must be verified by laboratory tests.*

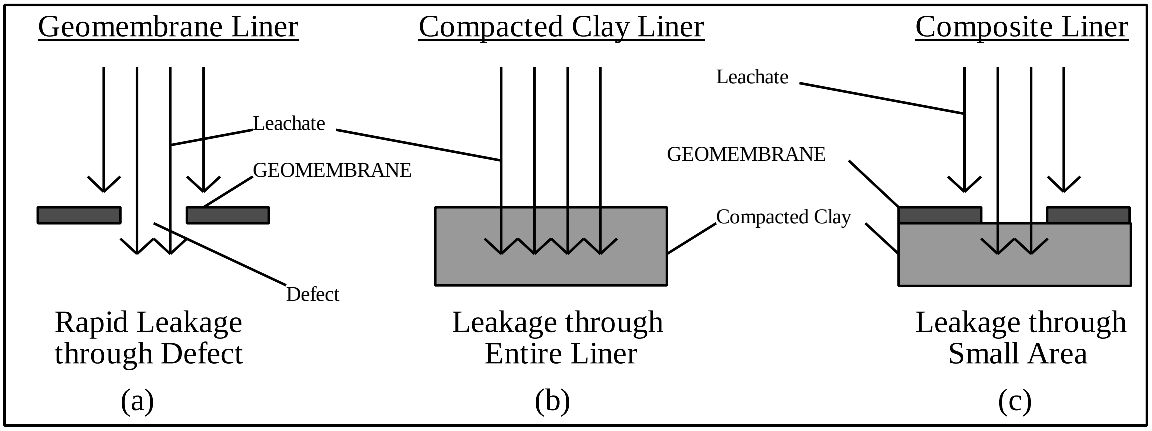
By examining tables I and II, you can see that the most effective liner for controlling leachate would be either an HDPE or a fabric-reinforced CSPE liner.

Composite Liners

Geomembranes can also be used in composite liners. *Composite liners are a combination of geomembrane liners and soil*. The soil normally used in composite liners is bentonite clay. A *compacted soil liner* is simply a barrier made of a small layer of bentonite clay.

Many new landfills today are beginning to use a new liner called a *geosynthetic clay liner* (GCL), or a compacted soil liner containing synthetic materials for greater strength.

Figure 7 on the next page shows how a composite liner works. As you can see in figure 7(a), if a hole is put in a geomembrane liner, leachate can easily seep through the hole. In a compacted clay liner such as the one in figure 7(b), you see that leachate can slowly seep through the bentonite clay; but when a geomembrane liner is put on top of bentonite clay, as in figure 7(c), a composite liner is formed. A small hole in the geomembrane on top may allow some leachate through the composite liner. However, the soil below slows or even stops the flow of leachate. *In a composite liner, the geomembrane on top and the compacted clay soil beneath work together to prevent the flow of leachate from the landfill into the ground below.*



Composite liners are a new and exciting development. Daniel (1993) gives us an idea of the quality of composite liners compared with the quality of non-composite liners. From figure 7(c), you have seen what happens when a geomembrane is placed on top of a compacted soil liner. The geomembrane liner and the compacted soil liner work *together* to control leachate, making a very effective system. In fact, Daniel has calculated and compared the flow of leachate through geomembrane liners, compacted clay liners, and composite liners. His calculations have shown that composite liners protect groundwater against leachate 100 times as well as geomembrane liners or compacted clay liners alone.

Table III (on the next page) shows the results of Daniel's calculations. He found that if you use a geomembrane with 60 holes per hectare[8] in a landfill, about 75,000 liters of fluid per hectare would leak below that geomembrane every day. With a compacted clay liner, 11,500 liters of fluid per hectare would leak below the liner every day. But in a composite liner, the geomembrane liner and the compacted soil liner would work

[8] A hectare is about 2 1/2 acres.

together--only 770 liters of fluid per hectare would leak below the composite liner every day!

Seven hundred and seventy liters per day may seem like lots of leachate. However, when you compare 770 liters to the 75,000 liters of leachate leaked from a geomembrane alone, the amount of leachate leaked from a composite liner is very little. Also, the 770 liters of leachate leaked from a liner every day is a worst-case scenario. It would only happen if one foot of leachate was waiting to penetrate the liner at all times.

Table III: Leachate flow Rates in Various Liners.
From: Daniel, 1993, p. 109

Type	Flow Rate: ***Best Case*** (Liters per Hectare per Day)	Flow Rate: ***Average Case*** (Liters per Hectare per Day)	Flow Rate ***Worst Case*** (I per Hectare per
Geomembrane *Alone*	2500	25000	75000
Compacted Soil *Alone*	115	1150	11500
Composite	0.8	47	770

Daniel backed up his calculations by discussing a study conducted by Bonaparte (1990). Bonaparte studied the performance of composite liners in 7 leachate collection systems. All of the leachate collection systems studied performed very well--in fact, *no leachate penetrated below the composite liner in any of the 7 leachate collection systems*!

Some engineers are still concerned about whether composite liners are able to hold up on steep slopes without a landslide occurring. Daniel (1990) suggests that by anchoring the liner to the earth, an earthquake will be less likely to trigger a landslide (p.

109).

III. CONCLUSIONS AND RECOMMENDATIONS

The purpose of this paper was to show which type of geomembrane liner system best controls landfill leachate. To accomplish this task, I first explained how leachate can contaminate groundwater. Then, I explained how liners, especially geomembrane liners, could be used to control leachate. Finally, I reviewed the types of geomembrane liners and showed that HDPE geomembranes and composite liners are most effective in controlling landfill leachate.

Tables I and II on pages 11 and 12 showed that the geomembrane liners with the highest quality are either the HDPE or the reinforced CSPE liners. In figure 7 on page 14, you saw that if you connect an HDPE or CSPE geomembrane to a compacted soil liner (to make an HDPE or CSPE composite liner), you can achieve a high-quality liner. An HDPE or CSPE composite liner would be resistant to weathering and seepage. It would also display high strength and durability. However, because of the high cost of CSPE liners, the HDPE liner is most cost effective.

The best type of geomembrane for leachate control in landfills is an HDPE geomembrane attached to a compacted clay liner. The HDPE liner on top is durable, strong, and temperature resistant. It is also fairly cost effective. When you combine an HDPE liner on top with a compacted clay liner on the bottom, the liner will provide good seepage resistance. Even though the HDPE liner may have holes in it (as in figure 7), the leachate from above will encounter a second layer of protection in the compacted clay liner.

APPENDIX A:
References

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APPENDIX B:
How do geomembrane liners control leachate?

In landfills, geomembranes are only a small part of a whole system called a *leachate collection system*. A leachate collection system not only contains geomembranes, but also contains *geotextiles, geocomposites, geosynthetic clay liners, and geonets*. An effective leachate collection system controls and removes leachate so the groundwater below the landfill is not contaminated. Figure A-1 shows a leachate collection and removal system recommended by David E. Daniel and Robert M. Koerner (1991), two experts in the field of landfill liner design.

A leachate collection system may contain the following components (Daniel and Koerner, 1991):

A. The primary leachate collection System:
- The filter.
- The drain.
- The protector.

B. The primary liner:
- The synthetic leachate barrier.
- The soil-based leachate barrier.
    - The separator.

C. The leak detection system:
- The drain.

D. The secondary liner:

- The second synthetic leachate barrier.
- The compacted soil barrier.
- The subgrade rock (foundation).

I now invite you to take a tour through a leachate collection system to see how it works. *As you read, think of yourself as flowing with the leachate through the collection system*. As you flow down from the solid wastes in the landfill, you will first enter the primary leachate collection system.

The Primary Leachate Collection System

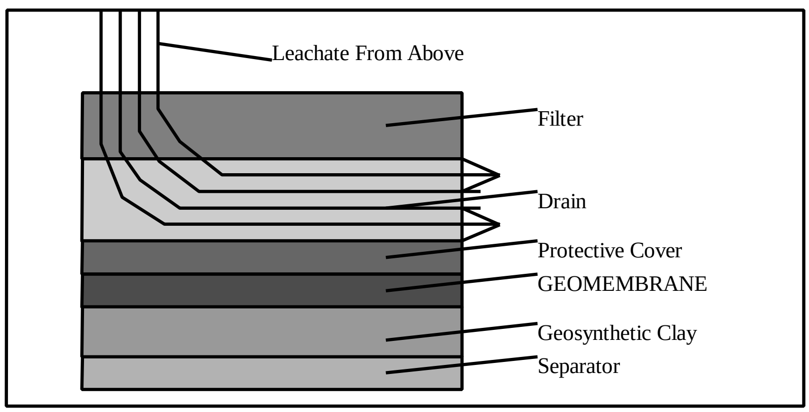


Figure A-2 shows the parts of the primary leachate collection system. The purpose of the primary leachate collection system is to collect and transport the leachate to a place where it can be treated.

The filter. As you move with the leachate into the collection system, you first encounter a filter. The filter is made of either a coarse, sandy soil *or* a *geotextile* (a synthetic fabric placed under the ground (literally, a *geo-textile*)). Most of the solids are removed from the leachate as you watch it moving through the filter. The purpose of the filter is to remove all of the large particles from the leachate. With the large particles removed, the leachate will flow out the drain below more easily. Also, the drain below will not clog from solids in the leachate.

The drain. After passing through the filter, you enter the drain. The drain is made of either coarse gravel or a *geocomposite* (a synthetic, coarse-textured material through which leachate can flow). The drain acts just a drain in the kitchen sink would. Standing in the drain, you can see that it takes most of the leachate and transports it to a leachate treatment area[9]. At the leachate treatment area, the harmful chemicals in leachate are removed and the left over water is released into the environment. As you move below the drain, very little leachate is left.

The protector. Next, you move downward into the protector. As you look around, you see that the protector is made of strong, non-woven geotextiles.

What is the purpose of the protector? Its purpose is to separate the drain above from the sensitive geomembrane below. If the drain above you is made of gravel, the gravel can put holes in the geomembrane liner below. A protector must be placed between the gravel above and the geomembrane liner below to keep these holes from happening. But if a geocomposite is used in the drain above, the geocomposite acts as

[9]Many landfills either have an on-site leachate treatment plant or they are authorized to dispose of the leachate into the municipal sewer system.

the protector, so a separate protection layer is not needed.

The Primary Liner

The primary liner is one of the keys to the whole leachate collection and removal system. The primary liner can consist of two main parts: The geomembrane liner and the geosynthetic clay liner (GCL). Below the liners, a separator holds them in place.

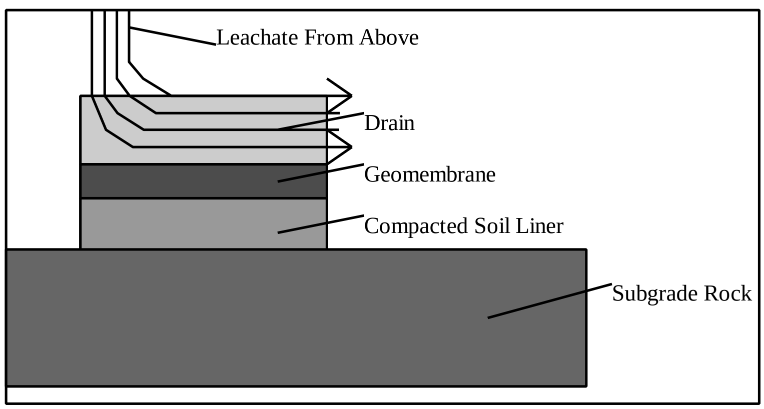
The synthetic leachate barrier. From the protector above, you move downward to the synthetic leachate barrier. *The synthetic leachate barrier is made out of the geomembrane itself*. As the leachate flows downward, you see that this geomembrane liner slows or completely stops the flow of the leachate, causing most of the leachate to flow out through the drainage material above. However, the geomembranes often have tiny holes. These tiny holes cause leachate to escape through the geomembrane liner.

The soil-based leachate barrier. As you move downward from the geomembrane to the soil-based barrier, you find yourself in a muck of fine-textured, clayey soil. Much of the leachate that escapes through the geomembrane above is stopped by this *soil-based leachate barrier*. You see that the purpose of this dense, clayey soil is to slow the flow of leachate to a mere crawl. Daniel and Koerner (1991) recommend using a *geosynthetic clay liner* (GCL) for the primary soil-based barrier. They define a GCL as "...factory-manufactured dry bentonite clay layers sandwiched between geotextiles or attached to a geomembrane." The GCL and the geomembrane liner above you work together to prevent the flow of leachate into the secondary liner system below.

The separator. As you move downward into the separator, you find yourself inside either a geotextile or a geomembrane (depending on which one the landfill uses). The clay in the GCL above you is made up of very fine, even microscopic soil particles. Because the particles of clay above you are so small, they may fall into the *leak detection system* below. The separator is here to prevent the *loss of clay* from the GCL above into the underlying leak detection system.

The Leak Detection System

You now move from the separator into the leak detection system below. The leak detection system is also known as *the secondary leachate collection system*. Figure A-3 shows the parts of the secondary leachate collection system.



Even though you have already passed through the drain and two-layered liner above you, some leachate may still get through little holes in the liners above. This leachate would slowly make its way to the leak detection system. Also, if there is a *large* leak in the primary lining system above, the leak can be detected by the leak detection system and be corrected if necessary. The leaks must be corrected if the leaks from the primary liner system of the landfill do not meet Environmental Protection Agency (EPA) specifications.

The drain. After entering the secondary leachate collection system from above, you find yourself in another drain made from a *geonet* (a net made out of synthetic materials and placed underground to promote drainage). You see that all of the leachate flowing from the landfill is monitored through the drain of the secondary leachate collection system. Far off in the distance, you see that any leachate that makes its way to the secondary collection system is drained to a leachate treatment facility.

The Secondary Liner

The purpose of the secondary liner is to prevent any remaining leachate from making its way below the landfill and into the groundwater system.

The second synthetic leachate barrier (or, the secondary geomembrane). You move from the drain above to the synthetic leachate barrier below. As you look around, you see that the secondary leachate barrier is made of a geomembrane similar to the synthetic leachate barrier used in the primary system. The secondary geomembrane acts as a barrier to prevent leachate movement into the compacted soil barrier below.

The compacted soil barrier. You move down below the geomembrane. Once again, you find yourself in a patch of dense, fine-textured, clayey soil. This compacted clay layer serves as the final barrier for the leachate before it reaches the soil, rocks, and eventually the groundwater below. The soil barrier can be very effective in slowing the flow of leachate before it leaves the landfill, and is one of the most important parts of the leachate collection system.

The subgrade rock (foundation). Below you, you can see rocks and soil. The subgrade rock is the earth itself. Common sense tells a person not to build a landfill above a cavern or sinkhole that may cave in. If the landfill caves in, all the expense put into constructing it would be for nothing. The waste would no longer be contained and a big clean-up job would be in order. So an investigation of the rocks below ground is necessary before picking a landfill site.

That is the end of your tour through the leachate collection system. Because of the complicated network of environmental controls put into every landfill built, you can see that it is important for every landfill to be designed by engineers with a sound knowledge of landfill design.

APPENDIX C:
Criteria Used for determining the properties of geomembranes

Seepage Resistance (From Haxo, 1985, p. 316)

- If the geomembrane did not allow any leachate seepage over a period of 56 months in a standard simulator, the geomembrane was classified as having **high seepage resistance**.
- If the geomembrane allowed between 1 and 10 kilograms of leachate seepage over a period of 56 months in a standard simulator, the geomembrane was classified as having **medium seepage resistance**.
- If the geomembrane allowed over 10 kilograms of leachate seepage over a period of 56 months in a standard simulator, the geomembrane was classified as having **low seepage resistance**.

Strength (From Rollin and Rigo, 1991, p. 25)

- If the tensile strength is between 0 and 15 MPa[10], the liner was classified as **low strength**.
- If the tensile strength is between 15 and 30 MPa, the liner was classified as **medium strength**.
- If the tensile strength is over 30 MPa, the liner was classified as **high strength**.

[10] A Megapascal (MPa) is equal to 145 pounds per square inch (psi).

Temperature Resistance (From Rollin and Rigo, 1991, p. 9, Oweis and Khera, 1990, p. 224, Koerner, 1986, p. 303)

- If the geomembrane exhibits very little cracking with changes in temperature, it has **high temperature resistance**.
- If the geomembrane exhibits slight cracking with changes in temperature, it has **medium temperature resistance**.
- If the geomembrane exhibits large amounts of cracking with changes in temperature, it has **low temperature resistance**.

Durability (From Haxo, 1985, p. 392)

- If the geomembrane still has the same properties after exposure to leachate, chemicals, and weathering, it has **high durability**.
- If the geomembrane has somewhat different properties after exposure to leachate, chemicals, and weathering, it has **medium durability**.
- If the geomembrane has completely different properties and low strength after exposure to leachate, chemicals, and weathering, it has **low durability**.

Cost (From Haxo, 1985, p.399)

- If the price of the geomembrane is less than $5.00 per square yard, the geomembrane is classified as **low cost**.
- If the price of the geomembrane is between $5.00 and $10.00 per square yard, the

geomembrane is classified as **medium cost**.

- If the price of the geomembrane is greater than or equal to $10.00 per square yard, the geomembrane is classified as **high cost**.