GEOTECHNICAL PRACTICE FOR WASTE DISPOSAL '87

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DESIGN OF GEOSYNTHETIC SYSTEMS FOR WASTE DISPOSAL

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Abstract

Geosynthetic materials (consisting of geotextiles, geomembranes, geogrids and geocomposites) are currently being used in large amounts to contain solid wastes in landfills, surface impoundments and waste piles. While regulations require their use in certain circumstances, considerable flexibility still remains for design variations. This paper focuses on the bottoms, sides and covers of such containment facilities in providing a design logic and a proposed methodology for the design engineer. The models and schemes proposed are felt to be rational and a logical extension of the mechanistic approach to problems typical of traditional geotechnical engineering practice.

There are, however, certain areas in need of further work. These areas have to do primarily with material selection, material properties (i.e., the data base is incomplete), and test standards. In spite of the above limitations, however, it is felt that there is enough information available to design and build waste containment systems using geosynthetics with a reasonable degree of confidence.

Overview of Solid Waste Disposal

A major problem in any industrialized society is the proper, safe and long-term handling of its residual solid waste. Such waste disposal impacts everyone; generators, workers, government agencies, adjacent neighbors and sometimes even far-distant neighbors. The obvious, but completely unrealistic, answer is to not generate any residual waste materials. To be sure, waste minimization, reduction and beneficiation are being actively pursued by every segment of industry, however, the processes are very complex and costly and the quantities of wastes are extremely large. Thus complete elimination is simply not possible. Furthermore, when coupled with other solid waste materials, the quantities become simply staggering. Recent estimates of waste production are from 400-500 M tons of municipal waste; 600-800 M tons of industrial waste, 50-100 M tons of hazardous waste and 30-60 M tons of low level radioactive waste by the year 1990 (Koerner, et al., 1986). Whatever the actual value, one can anticipate that large quantities of waste must be treated, exchanged, beneficiated, incinerated and/or landfilled. It is to this latter category of landfilling, or more appropriately secure landfilling, that this paper is directed. Furthermore, this paper is directed at

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the hazardous waste category, although for many people "waste is waste" and they feel that everything should be classified together.

In the designs to follow, the containment strategy of the waste and the leachate it generates is all important. Focus is immediately placed on the liner, for which numerous materials have been used in the past. Various systems have evolved to the present situation, a double liner with leak detection capability between the primary and secondary liners which is to be required at all surface impoundments by November 6, 1988.

The same concept of a double liner on the bottom and sides of a landfill should be applied to the cap or closure system. When the facility is full and has seen its full service life, the closure becomes the focus for long term considerations. All surface water must be captured and/or diverted from the encapsulated waste and done so for time periods of 30 to 100 years. Redundancy is certainly called for, and the design and construction of a double closure consisting of primary and secondary systems is again a logical philosophy to pursue.

As will be seen in the next section, synthetic materials (mainly polymeric) are involved throughout the recommended cross sections. These below-ground synthetic materials are collectively called "geosynthetics" and encompass the following specific materials (Koerner, 1986). All will be used in various parts of the designs to follow.

- Geotextile (GT) - Any permeable textile used with foundation, soil, rock, earth, or any other geotechnical engineering-related material as an integral part of a human-made project, structure, or system. (Also called filter fabric, construction fabric, filter cloth, etc.)
- Geogrid (GG) - A deformed or nondeformed netlike polymeric material used with foundation, soil, rock, earth, or any other geotechnical engineering-related material as an integral part of the human-made project structure or system. (Also called grid, drainage grid, net, drainage net, etc.)
- Geomembrane (GM) - An essentially impermeable membrane used with foundation, soil, rock, earth, or any other geotechnical engineering-related material as an integral part of the human-made project, structure, or system. (Also called flexible membrane liner, synthetic membrane liner, pond liner, etc.)
- Geocomposite (GC) - A manufactured material using geotextiles, geogrids, and/or geomembranes in laminated or composite form. (Also called drainage composite, prefabricated drainage composite, etc.)

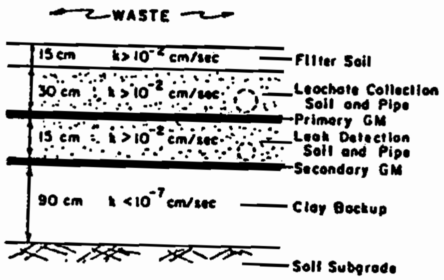
Design Concepts and Recommended Cross Sections

In order to safely contain waste materials, and more importantly the liquid leachate which they generate, a completely encapsulating liner is necessary. Liners made from traditional construction materials (e.g., concrete and asphalt) and from naturally occurring soils (primarily in the montmorillonite clay family) are well known to the geotechnical engineer. While such materials are still used and being actively researched as other papers in these Proceedings attest, it is the synthetic liner materials that form the first line of defense for current containment strategies. This is due in large part to Federal regulations (U.S. EPA, 1985; U.S. EPA, 1982) which have appeared over the past five years resulting in a series of cross sections shown schematically in Figure 1. Each shows barrier redundancy via a double system for the bottom, side slopes and closure of a waste management facility. An explanation of each system follows:

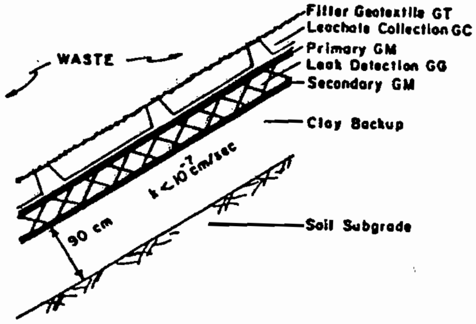
(a) <u>The Bottom Liner</u> - The bottom liner system is of paramount importance for the protection of the subsurface groundwater from leachate generated within the landfill. The cross section shown in Figure 1(a) is the genesis of a series of liners, first with clay alone, then with geomembranes and clay and currently to the double liner composite system shown. Some important features follow:

- The primary geomembrane must be of synthetic material a at least 0.75 mm thick. It is the focal point of the system and must be designed with chemical, mechanical and environmental considerations in mind.
- The secondary geomembrane must be of the same synthetic material and thickness as the primary geomembrane.
- This secondary geomembrane is actually a part of a composite secondary liner since a minimum 90 cm thick clay layer of hydraulic conductivity 10^{-7} cm/sec or lower must be immediately beneath it.
- The primary leachate collection and removal system is placed above the primary geomembrane and is in intimate contact with the landfill itself. It currently consists of 30 cm of drainage stone (hydraulic conductivity of 10^{-2} cm/sec or greater) with a perforated pipe underdrain system within it. Also required is a 15 cm soil filter above it and a requirement that the hydraulic head of the leachate be 30 cm or less.
- The secondary leachate collection and removal, or leak detection, system lies between the two geomembranes. Its function is to collect any amount of leakage which escapes through the primary geomembrane. It is also included to alert personnel for leachate quantities greater than a nominal amount called "de minimus" (9.35 l/ha-day = 1.0 gal/acre-day), thereby indicating problems with the primary geomembrane. The collection system that is currently recommended is a 30 cm thick drainage stone layer with a perforated collector pipe network within it. It, too, must be gravitationally drained to a low point where a questioning system between the two liners (often a small diameter collection pump) is used to measure and remove any liquid contained therein.

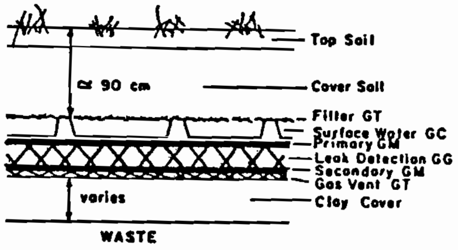
(b) <u>The Side Slope Liner</u> - To place drainage sand and an internal pipe underdrain network within it under congested



(a) Bottom Liner System



(b) Side Slope Liner System



(c) Cover or Closure Liner System

Figure 1. Recommended Cross Sections for Landfills and Related Waste Containment Systems

conditions at carefully held line and grade presents difficult construction conditions, even under ideal circumstances. On side slopes it becomes impossible to maintain line and grade and to place subsequent layers of geosynthetics. Thus, drainage geocomposites(Koerner and Lawrence, 1986) have become a possible solution and are included in the sketch of Figure 1(b). The double liner concept is still maintained except now:

- The secondary leachate collection system between the two geomembranes is shown as a geogrid or geonet. Such grids are quite constructable on side slopes and, when properly designed, should be capable of transmitting to the collection system whatever leachate escapes through the primary liner.
- The primary leachate collection system above the primary liner is shown as a drainage geocomposite. These systems consist of a drainage core (made in the shape of waffles, columns, ribs, etc.) covered by a geotextile filter. Constructability is straightforward and, when properly designed, can be adequate to handle relatively large amounts of leachate. The use of drainage geocomposites is currently limited by the use of volatile organics in the adhesives used to bond the geotextile to the drainage core.
- As currently proposed, the primary and secondary geosynthetic leachate collection systems run down the side slopes and empty directly into the complimentary systems at the bottom made from granular soils.

(c) The Cap or Closure - This last part of a landfill is constructed after the waste has been placed and the site, or a portion of it, is closed from accepting additional material. The essential details as shown in Figure 1(c) are as follows:

- Primary (top) and secondary (bottom) geomembranes provide the same redundancy as with other parts of the enclosure. If the drainage medium between the geomembranes shows water, it signifies a leaking upper geomembrane which must be excavated and repaired.
- The upper geocomposite functions as a drain which must handle whatever rainfall and snowmelt that has penetrated through the topsoil and clay cap. It must have a properly designed geotextile filter at the interface.
- The lower geotextile functions as a venting system for any gases generated in the landfill which escape through the lower clay seal.
- Geotextiles providing a cushioning effect are sometimes necessary adjacent to the geomembranes. These are largely dependent upon the gradation and shape characteristics of the drainage stone placed adjacent to the geomembranes.

It should be noted that these same concepts apply to above ground facilities such as waste piles and surface landfills. In such cases, the bottom liner is identical to that shown in Figure 1(a) and the cap or closure of Figure 1(c) comes down over the exposed sides of the waste and ties into the bottom liner at ground level.

Chemical Considerations

Potential chemical degradation of a liner system by the leachate it is meant to contain is a critical factor in its selection. This is particularly the case for geomembranes since even a nominal attack challenges their thinness, which is relatively small to begin with. Thus, the first step in geomembrane design must be an assessment of chemical compatibility.

(a) Overview -The fundamental level at which chemicals might degrade geomembranes is at the molecular bond level. This is known as bond "scission." The main mechanisms involved insofar as thermoplastic materials like polyethylene are concerned are as follows:

- metathesis - breaking of carbon-to-carbon bonds
- solvolysis - breaking of carbon-to-noncarbon bonds in the amorphous phase
- oxidation - liquid reaction with molecular oxygen
- dissolution - separation into component molecules by solution

Obviously, when taken either separately or collectively, the above mechanisms will have a negative effect on the geomembrane's ability to contain leachate.

The test methods one could select in monitoring geomembrane degradation by various chemicals fall into macroscopic and microscopic categories. They are as follows:

- Macroscopic measurement methods:
  - physical tests (thickness, mass per unit area)
  - mechanical tests (tension, compression, tear, puncture, impact, creep, stress relaxation)
  - transmission tests (water vapor, radioactive tracer)
- Microscopic measurement methods:
  - molecular weight determination (to quantify scission and crosslinking reactions)
  - differential scanning calorimetry (to reveal changes in crystallinity)
  - infrared spectroscopy (to quantify end groups in analyzing oxidation reactions and scission products)
  - differential infrared spectroscopy (to analyze for carbonyl formation in liners)

These and/or other methods are used to track chemical degradation in geomembranes. As one might suspect the macroscopic tests are generally favored by civil/geotechnical engineers, while the microscopic tests are generally favored by chemical/environmental engineers and chemists. It is generally thought that the microscopic tests are the most accurate and form the basis of "accelerated aging tests." This process will be discussed first, followed by the macroscopic procedure embodied in the EPA 9090 (U.S. EPA, 1984) and the NSF Standard 54 (NSF, 1983) test methods.

(b) Accelerated Aging Tests - Accelerated aging tests utilize a laboratory column wherein the geomembrane with soil on each side of it is exposed to a chemical leachate for extended time periods and at different temperatures. The selection of the leachate is an important and difficult task since synergism of mixed chemicals is hard to assess. In general, a worst case scenario should be used to select the leachate. Columns similar to that shown in Figure 2 are then used (Mitchell and Spanner, 1985) where in-situ conditions are simulated as closely as possible (i.e., pressure, soil type, hydraulic head, leachate quality and consistency). Generally, multiple columns are set up identically except for temperature. These temperatures are held constant for the duration of the test. At selected time intervals, rates of reaction of the geomembrane to the various temperatures are measured. One, or more, of the microscopic test methods previously discussed are generally used for this purpose. Using the resulting value of activation energy (i.e., a rate of reaction), one assumes an Arrhenius model to estimate the equivalent time that would be required to obtain the same field behavior as did the elevated temperature.

$$K = A\,e^{-E/RT}$$

where

K = rate constant
A = constant
E = reaction activation energy (cal/g-mole)
R = gas constant (1.986 cal/g-mole-°K)
T = temperature (°K = 273° + °C)

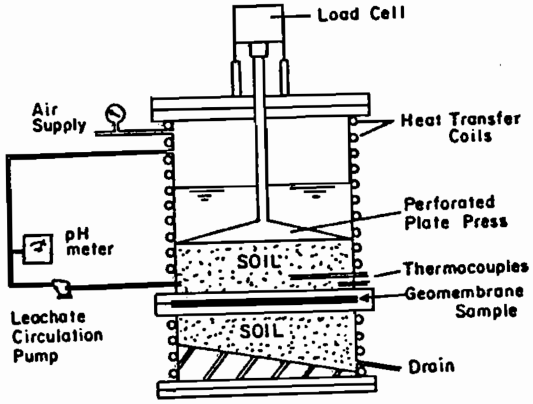


Figure 2. Schematic Diagram of Accelerated Aging Test Setup, after Mitchell and Spanner, 1985

An example problem for polyethylene in air was presented by Myers (Myers, 1952). He found the activation energy equal to 16,000 cal/g-mole over an 18 week period using two test chambers at 18°C and 78°C respectively. Using this information in the Arrhenius equation yields the following:

$$\frac{rate_1}{rate_2} = \frac{A\,e^{-E/R[1/T_1]}}{A\,e^{-E/R[1/T_2]}}$$

$$\frac{rate_{78}}{rate_{18}} = e^{-E/R[1/T_1 - 1/T_2]}$$

$$= e^{-\frac{16,000}{1.986}[1/351 - 1/291]}$$

$$= e^{(-8056)(-0.587 \times 10-3)}$$

$$= e^{+4.73}$$

$$= 113$$

Thus the temperature induced rate change between 78°C and 18°C was equivalent to 113 times the actual exposure period of 18 weeks. Had the temperature remained at 18°C, the same reaction would have taken

$$113 \times 18 = 2034 \text{ weeks}$$
$$= 39.1 \text{ years}$$

Some major assumptions must be made when interpreting the results of the accelerated aging test previously described. They are listed below but it should recognized that these tests actually represent the current state-of-the-art; e.g.,

- leachate is representative of actual situation
- experimental setup is realistic, e.g., scale effects are not prohibitive
- elevated temperature does not alter the geomembrane's chemical structure by itself.
- the proper measurement parameter(s) was selected
- Arrhenius extrapolation of time equivalency is valid

Coupling these limitations with the pragmatic realization that such accelerated aging tests are not very practical, are very time consuming and are extremely costly has led to an abbreviated version of the tests. Such a version is embodied in the EPA 9090 (U.S. EPA, 1984) and the NSF 54 (NSF, 1983) test procedures.

(c) EPA 9090 Test Method -As with the test procedure just described, the EPA 9090 test method has several distinct and parallel steps. The following process is generally followed (note that there is some variation permitted);

- the chemical leachate is selected.
- the candidate liner(s) is incubated in the leachate by one of two methods: immersion or tub at a temperature of 27°C or at an elevated temperature.
- they are periodically exhumed after different time periods, from 120 days up to one year.
- they are tested by one, or more, of the macroscopic tests listed previously, compared to the as-received liner (which was not incubated), and plotted as percent change versus time of exposure.
- a decision is made as to whether the change was indicative of chemical degradation or was due to typical test method variation, e.g., the guide of Table 1 has been suggested.

Table 1 - Limits of Acceptability for Chemical Effects in High Density Polyethylene (HDPE) Liners (ref. Agranoff, 1983)

Effect of Chemical	Percent Change		
	Weight	Dimensions	Tensile Strength
usually not significant	<0.5	<0.2	<10
significant but not conclusive	0.5 to 1.0	0.2 to 0.6	10 to 20
usually significant	>1.0	>0.6	>20

This test procedure is the current one by which candidate geomembranes are judged suitable or not for the lining of hazardous waste landfills, surface impoundments and waste piles.

As a result of this test procedure, polyethylene has clearly emerged as the liner of choice for containment of hazardous materials. Furthermore, the higher the density (hence crystallinity), the more chemical resistant the material appears to be; thus, high density polyethylene (HDPE) is often selected. It should be recognized, however, that with such high density comes some decided drawbacks, and most seem to involve workability during liner placement. With increasing density of polyethylene, comes increased hardness, stiffness, lack of comformability, decreased friction coefficient and greater difficulty in seaming. This last point, in itself, can be devastating in making field seams under varying ambient conditions. The construction quality assurance problems associated with this situation are apparent. Nevertheless, HDPE is the liner material of choice and it will be emphasized in the specific design sections to follow.

Mechanical and Hydraulic Considerations

(a) Geomembranes on Bottoms and Sides of Landfill

There are a large number of conceptual scenarios that one can develop in the design of geomembranes. They are based in large part on the mechanical properties of the polymeric material used in the geomembrane's manufacture. For HDPE the short term stress vs. strain curves are typical of that shown in Figure 3(a). In all cases, a well defined yield, the targeted value for design purpose, is seen. Thus, a design ratio can be calculated (whereby DR = σ_y/σ_{act}) and the resulting number can then be assessed. This same concept can also be used for polymer materials which do not show a pronounced yield, e.g., nonreinforced PVC, CPE, EPDM, as seen in Figure 3(b). Here, one would use an allowable stress based on some limiting strain, (e.g., σ_{allow} at $\varepsilon = 100\%$) and form a design ratio in a similar manner as before. In both cases, the design philosophy is that an enormous amount of deformation of the geomembrane still remains even if the stress level σ_y or σ_{allow} is reached. Values of DR greater than unity can be required for additional safety.

Table 2 presents eight illustrative problems all of which can be quantified on the basis of force (or stress) summations using the free body diagrams indicated. As with any type of rational design method, a number of required properties (both geomembrane and landfill related) are necessary. Some of those listed in Table 2 are obtained via standardized test methods while others must be tuned directly to the site specific conditions, e.g., friction between a specific geomembrane and the particular material adjacent to it. While very dangerous to do, an attempt at giving a range of design ratios is also included in the Table. A few comments regarding these values and their significance are in order:

- The frictional downdrag force of waste being placed against the liner can be very high for large lift thicknesses within the interior cells. DR values for problem #2 can easily fall below unity if lift heights (h) exceed 3 m.
- Impact of any object against an unprotected geomembrane can be disastrous. Problem #3 illustrates that construction survivability is critical under all situations.
- Puncture of hard objects mobilized by the weight of the landfill can be very serious as illustrated by Problem #5. Drainage soil and clay backup must be free of sharp objects.
- Anchorage at the end of the geomembrane is an important detail which requires a minimum runout length and depth of anchor trench, see Problem #6.
- Weak zones under the landfill which create differential settlement, called subsidence in Problem #8, can result in high stresses and low DR values. The key here is good construction quality control during subgrade preparation at the site.

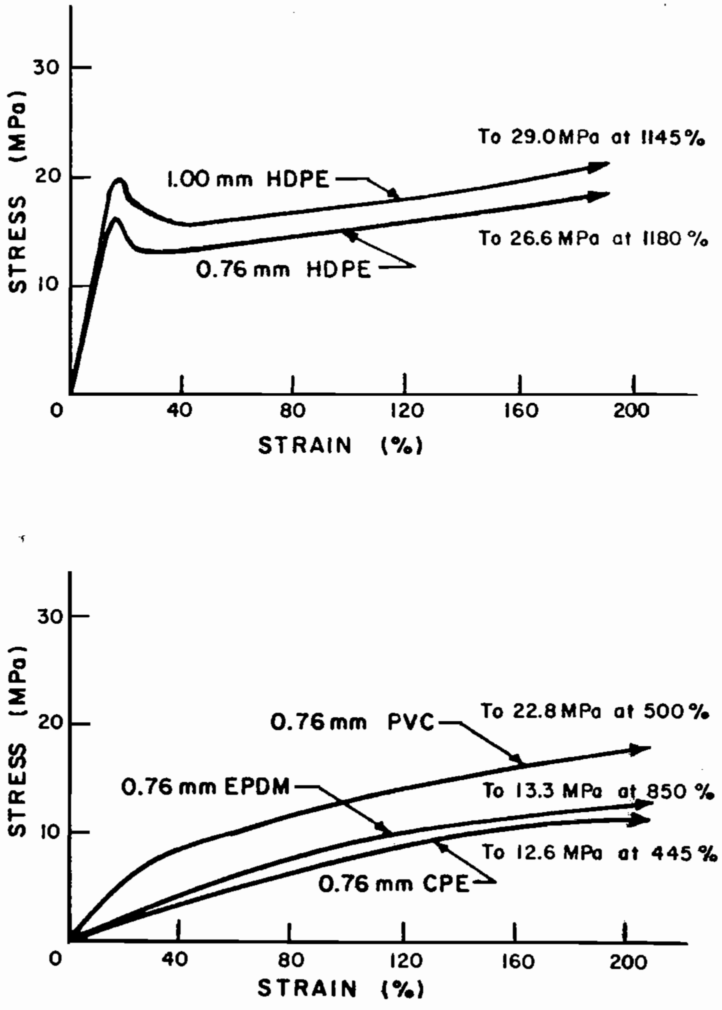
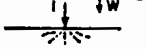
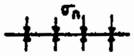
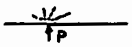
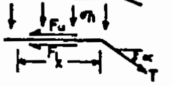


Figure 3. Stress vs. Strain Response Curves of Various Geomembranes Used in Waste Containment Systems

Table 2 - Various Design Models for Geomembranes in Waste Disposal Situations

Problem	Liner Stress	Free Body Diagram	Required Properties		Typical Design Ratio
			Geomembrane	Liner	
1. liner self weight	tensile		G,t,σ_y,δ_L	β,H	10 to 100
2. weight of filling	tensile		$t,\sigma_y,\delta_U,\delta_L$	β,h,γ,H	0.5 to 10
3. impact during construction	impact		I	d,w	0.1 to 5
4. weight of landfill	compression		σ_y	γ,H	10 to 50
5. puncture	puncture		σ_p	γ,H,P,A_p	0.5 to 10
6. anchorage	tensile		$t,\sigma_y,\delta_U,\delta_L$	β,γ,ϕ	0.7 to 5
7. settlement of landfill	shear		τ,δ_U	β,γ,H	10 to 100
8. subsidence under landfill	tensile		$t,\sigma_y,\delta_U,\delta_L,X$	α,γ,H	0.3 to 10

Notes:

- Geomembrane Properties

G = specific gravity
t = thickness
σ_y = yield stress (or allowable stress)
τ = shear stress
I = impact resistance
σ_p = puncture stress
δ_U = friction with material above
δ_L = friction with material below
X = mobilization distance

- Landfill Properties

β = slope angle
H = height
γ = unit height
h = lift height
α = subsidence angle
ϕ = friction angle
d = drop height
W = weight
p = puncture force
A_p = puncture area

(b) Drainage Systems in Bottom and Sides of Landfill

The geosynthetic drainage cores play an essential role in the system in that they must convey leachate from any part of the landfill to a low point where it is collected and removed. The driving criteria in the selection of a drainage core is the transmissivity required to (a) satisfy the minimum statute requirements, i.e., 30 cm thick drainage soil at 10^{-2} cm/sec, or (b) that required to maintain 30 cm maximum head under the assumed inflow flow rate. It is generally preferred to use the required transmissivity since it is readily calculated and compared to the allowable transmissivity of the candidate geocomposite. It is important to recognize that the allowable transmissivity must include the elastic and plastic deformation of materials adjacent to the drainage core. These intruding materials are either the adjacent geotextile (for the primary leachate collection system) or the two geomembranes (for the secondary leachate collection system). While such problem solutions are not simple, they are "doable" as suggested by Table 3. Here the problems are arranged in the order of their suggested solution having a particular, or candidate, drainage geocomposite in mind.

- The strength of the core must be capable of supporting the maximum load of the landfill and its closure. This is a straightforward calculation and test method (see problem #1). Most manufacturers know the mechanical capacity of their products. Note that this applies mainly to the built-up rib or column type products and not to grids which can sustain extremely high loads and essentially have no crush potential.
- The transmissivity or flow rate capability of the core is of major importance, for when compared to the actual (anticipated or by statute) transmissivity or flow rate it will result in a flow design ratio. Note in problem #2 that this value must be measured at the maximum applied normal pressure and minimum hydraulic gradient of the landfill. Here again most manufacturers of drainage geocomposites have this information available.
- Numeric solutions involving drainage core flow become difficult when time dependent deformation (creep) of the core is considered. The creep sensitivity of drainage curves vary from nil to enormous, see problem #3. Manufacturers' literature on this subject is weak. Furthermore, extrapolation of creep data to between 30 and 100 years is very risky. Models based on rate process theory, rheology or three-element concepts are the best available and even these require experimentally obtained constants.
- The elastic deformation of the material adjacent to the core (geomembranes for secondary leachate collection, see problem 4a, and geotextiles for primary leachate collection, see problem 4b) will cause intrusion thereby reducing flow. Analytically the problem can be approached using elastic plate theory for which a wealth of information is available (Szilard, 1974). The reduced flow can then be calculated on a volumetric basis and a modified flow DR can be obtained. For high stresses and low modulus materials, this reduction can be severe, e.g., up to 50%!

Table 3 - Various Design Considerations for Drainage Geocomposites in Waste Disposal Situations

Problem	Reason	Approach	Required Properties		Severity of Problem
			Geocomposite	Landfill	
1. strength of core	avoid crushing of core	$DR = \sigma_{ult}/\sigma_{max}$	σ_{ult}	γ,H	minor
2. flow in core	first approximation	$DR = \theta_{allow}/\theta_{act}$	θ_{allow}	$\gamma,H,i,q_{act},\theta_{act}$	minor
3. creep of core	first reduction	$DR = \theta'_{allow}/\theta_{act}$	θ'_{allow}	$\gamma,H,q_{act},\theta_{act}$	nil to major
4(a). elastic intrusion of geomembrane	second reduction	elastic plate theory	E,μ,x,y	$\gamma,H,q_{act},\theta_{act}$	major
4(b). elastic intrusion of geotextile	second reduction	elastic plate theory	E,μ,x,y	$\gamma,H,q_{act},\theta_{act}$	major
5(a). creep intrusion of geomembrane	third reduction	creep theory	$\varepsilon(\sigma,t),x,y$	γ,H,t	unknown
5(b). creep intrusion of geotextile	third reduction	creep theory	$\varepsilon(\sigma,t),x,y$	γ,H,t	unknown

Notes:

- Geocomposite Properties
  - σ_{ult} = ultimate (compression) strength
  - σ_{max} = maximum stress
  - σ = applied stress
  - θ_{allow} = transmissivity
  - t = time
  - E = modulus of elasticity
  - μ = Poisson's ratio
  - x,y = core dimensions
  - $\varepsilon(\sigma,t)$ = strain rate
- Landfill Properties
  - γ = unit weight
  - H = height
  - i = hydraulic gradient
  - q_{act} = actual (design) flowrate
  - θ_{act} = actual (design) transmissivity
  - t = time

- The creep deformation of these adjacent geosynthetics must also be addressed. Shown as problems 5a and 5b in Table 3, they are very difficult to quantify. Not only is creep design difficult as noted earlier, the orientation is now aligned perpendicular to the usual testing direction, i.e. this is a problem of out-of-plane creep deformation. Once assessed, the deformation can be related to a decreased flow volume and a correspondingly reduced flow DR.

(c) The Cover System

As shown in Figure 1(c), the cover system has elements similar to the liner in that it has two geomembranes with two collection systems. There are basic differences, however, and these are listed below:

- Hydrological models must be used to obtain the values of q_{act} in the upper drainage systems.
- Chemical compatibility should not be a problem since rainwater and snowmelt should be the only liquids involved. This allows for a wide variety of geomembrane materials to be used, e.g., HDPE, LLDPE, LDPE, PVC, CPE, EPDM, etc.
- If large quantities of water appear in the drainage layer between the two geomembranes, leakage through the upper geomembrane must be investigated, located and repaired.
- While a drainage geocomposite might be used between the two liners, it is not compulsory since 1.2 m of total cover is usually required. Thus a sand drainage layer is generally recommended. However, holding line and grade might be a constructability feature which favors use of a drainage geocomposite.
- The lower gas collection system (geotextile) and lower geomembrane should be evaluated for methane gas compatibility.

Additional Details

While preparation of plans and specifications is the primary mission of the design consultant, miscellaneous details are usually controlled by the contractor and the inspection team. Even the best of designs will be completely ineffective without meticulous attention to details. Sometimes these details are capable of being quantified, other times only extreme care and highest quality workmanship will result in proper functioning of the system.

(a) Seams - The preferred type of geomembrane seam is primarily dependent on the polymer it is made from (Frobel, 1984). For HDPE the methods are hot air, hot wedge or extrusion welding. Hot air uses a machine consisting of a resistance heater, temperature controls, and a blower to blow hot air between the two sheets and to actually melt the surfaces. Usually, temperatures greater than 250°C (≅ 500°F) are required. Immediately following the melting of the surfaces, pressure by rollers is applied. The hot wedge or hot knife method consists of an electrically heated resistance element in the shape of a blade that is passed between the two sheets to be sealed. As it melts the surfaces, roller pressure is applied. An interesting variation is the dual-hot-wedge method, which forms two parallel seams with an unbonded space between them. This space is subsequently pressurized with air and any lowering of pressure signifies a leak somewhere in the seam. Extrusion welding is used exclusively on HDPE. It is a direct parallel of metallurgical welding in that a ribbon of molten polymer (instead of metal) is extruded between the two surfaces to be joined. The electrode causes some of the sheet material to be liquified and the entire mass then fuses together. One patented system has a mixer in the molten zone which aids in homogenizing the extrudate and the molten surfaces. The technique is called "flat welding" when the two sheets to be joined are on top of one another, and "fillet welding" when joining the edge of the upper sheet to the lower sheet. For other types of geomembranes, different seaming methods are used, e.g., solvent, bodied solvent, solvent adhesive, contact adhesives or tapes.

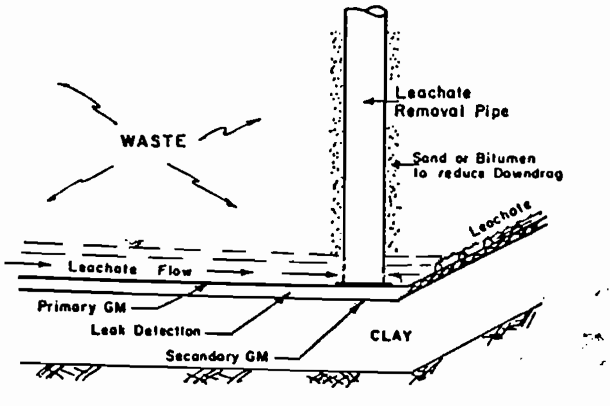
(b) Difficult Seaming Areas - Proper joining of long, straight, uniform seams of geomembranes is greatly aided by the use of mechanized equipment. Seams around penetrations, connections and appurtenances, however, are very difficult. Two necessary penetrations in every cell of a landfill are the primary and secondary leachate collection and removal systems. These systems are a manhole and a pipe and are shown schematically in Figure 4. They generally require prefabricated boots at penetration locations along with a clamped O-ring seal. The designer must anticipate high localized stresses under and around such rigid objects which must be accomodated by high geomembrane deformation (S & ME, 1987).

(c) Seam Testing - Seam testing takes one of two forms: destructive or nondestructive. The destructive tests of shear and peel require direct sampling (thus subsequent patching) and are essentially indicators of the adequacy of the seaming method itself, e.g., proper temperature, pressure and travel time versus quality of seam. They tell nothing of the continuity of the seam between sampling locations. One hundred percent coverage by a nondestructive test is needed for this task. Table 4 lists the different methods of nondestructive testing available. While much has been written about each method (Frobel, 1984, and Lord, et al., 1986), the authors current strategy is to use the ultrasonic shadow method (Koerner, et al., 1987) over all seams including penetrations, corners and other details. If the energy received is less then 50% of that of a known competent seam, then vacuum chamber tests are used. When vacuum boxes cannot be used an extrusion welded cap strip must be placed over the questionable area.

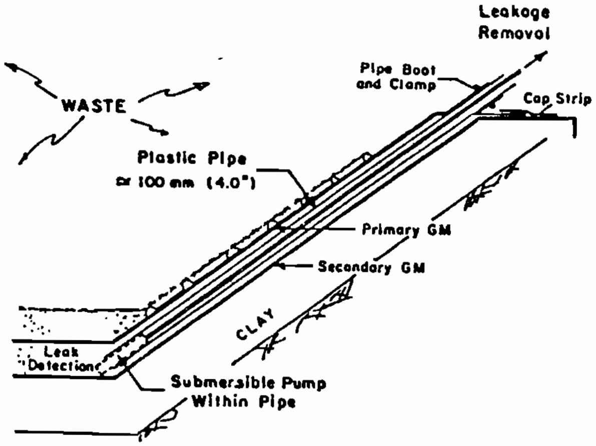
(d) Access Ramps - Access ramps are a necessity during construction and while filling the landfill area. With heavy loads and high tire inflation pressures, the stresses on various geosynthetic materials can be enormous. Generally, the construction ramps into the site are made during excavation and the entire liner system is placed above them. This requires careful planning and grading and should be included in the design. Conversely, filling of the landfill with waste requires travelling above the liner system. Thus, crushing of leachate collection systems and puncture of geomembranes is very possible. Furthermore, the system is now covered and not accessible for inspection. The problem is so formidable that consideration has

Table 4 - Overview and Critique of Nondestructive Geomembrane Seam Tests

Nondestructive Test Method	Primary User			General Comments					
	Contractor	Design Engr. Insp.	Third Party Inspector	Cost of Equipment	Speed of Tests	Cost of Tests	Type of Result	Recording Method	Operator Dependency
1. air lance	yes	-	-	$200	fast	nil	yes-no	manual	v. high
2. mechanical point (pick) stress	yes	-	-	nil	fast	nil	yes-no	manual	v. high
3. vacuum chamber (negative pressure)	yes	yes	-	$1000	slow	v. high	yes no	manual	high
4. dual seam (positive pressure)	yes	yes	-	$200	fast	mod.	yes-no	manual	low
5. ultrasonic pulse echo	-	yes	yes	$5000	mod.	high	yes-no	automatic	moderate
6. ultrasonic impedance	-	yes	yes	$7000	mod.	high	qualitative	automatic	unknown
7. ultrasonic shadow	-	yes	yes	$5000	mod.	high	qualitative	automatic	low



(a) Leachate Collection and Removal System



(b) Leak Detection and Removal System

Figure 4. Leachate Collection and Leak Detection Removal Systems

been given to forbidding vehicles from entering into the site and filling it by using cranes or conveyor systems, see S & M, 1987 for additional details. If, however, dumping proceeds using heavy trucks entering the site, then thick cushioning layers of soil must be used. Stress dissipation calculations using elastic theory as is conventionally done in geotechnical engineering must be used in this design.

(e) Leak Location - A properly functioning leak detection system, i.e., the secondary leachate collection and removal system, will indicate the presence of a leak at its downstream collection point. By continuous sampling from a pipe such as shown in Figure 4(b), a time history of the leakage can be developed. If excessive, e.g., greater than "de minimus" leakage of 9.35 l/ha-day (1.0 gal/acre-day), one immediately suspects a leak and wonders where it is located. Of the various leak location methods available none have been overly successful although some are still in the research stage (Koerner, et al., 1984). These include the following:

- soil borings with groundwater sampling - this only tells if the contaminant has left the landfill site, not the specific leak location in the landfill.
- geophysical resistivity - the background conductivity at landfill sites is usually too high to locate the leak.
- electric field (voltage gradient) survey - the method is only useful for liquid storage impoundments, not solid waste sites.
- time-domain reflectometry - the technique needs wires beneath the liner and is still in the research stage.
- acoustic emission monitoring - the technique also needs wires beneath the liner and is still in the research stage.

In short, there is no method available today to locate the actual position of leaks in a landfill. The only way of solving such a problem is to zone the landfill into discrete sections or not to let it occur to begin with.

(f) Construction Quality Assurance (CQA) - To even a casual observer, the cross sections shown in Figure 1 represent extremely difficult sections to construct. When further considering the strict adherence to line and grade, the necessity of clean and dry surfaces to seam the geomembranes and the high temperatures generated during warm weather, meeting the de minimus leakage requirement becomes a challenge of the first order. A strictly written and rigidly enforced CQA program is needed. Furthermore, the use of third party consultants as CQA officers is highly recommended. As recommended by EPA, the following elements should be included in a CQA agreement (U.S. EPA, 1985) They are indeed necessary and demanded in the construction of hazardous waste facilities.

- Responsibility and Authority; (i.e., organization and meetings)
- Personnel Qualifications (i.e., CQA officer, inspection staff and consultants)
- Inspection Activities (i.e., foundation, dikes, clay liners, geomembranes, leachate collection systems, final cover systems

and general activities)
- Sampling Requirements (i.e., strategies, sample size, outliers, corrective measures, control charts)
- Documentation (i.e., daily records, photographs, evaluation reports, designer's acceptance components, final documentation, storage of records)

Conclusions and Recommendations

Hazardous waste containment represents one of the greatest challenges known to modern society. Proper treatment, storage and disposal are of highest priority for a large number of known and identified hazardous substances. While zero discharge of waste should be a target for all generators, there appears always to be some residue. When this residue is totaled, and further augmented by nonhazardous wastes, the quantities become extremely large. Thus there is an unfortunate necessity for landfills and/or waste piles. Generated by all types of solid waste is a leachate which must be collected and properly treated. If allowed to escape the site, leachate has been known to be extremely damaging to persons and to the adjacent environment. If allowed to contaminate the subsurface groundwater the consequences can be disastrous.

As a design strategy for containment of the waste and its leachate a double liner system for bottom; sides and cap has been legislated by the U.S. Environmental Protection Agency. This paper elaborated upon these design elements with the entire focus on the geosynthetic materials involved. Geotextiles, geogrids, geomembranes (FML's) and drainage geocomposites are all involved. Numerous details such as seams, penetrations, seam testing, access ramps, leak location and CQA programs were also addressed. While designs such as described here might seem to be excessive to some, they are the price we must pay to safeguard ourselves and the environment.

Projects of the type described in this paper are being constructed presently. While too soon to decide on their ultimate performance, a rational design methodology appears to be available for us to "build with some degree of confidence." It would be presumptuous to state that the designs included here are the limits to which this technology will, or should , be taken. Much more remains. The following list presents some of our ideas on areas needing further development.

- Better assessment of chemical compatibility of all geosynthetics to the liquids and/or gases they must contain.
- Designs based on viscoelasticity or rheology which relate to the noncrystalline phase of geomembranes.
- Better assessment of creep test methods and design techniques to project behavior up to 100 years.
- Deterministic insight toward predicting long term aging or durability of geosynthetics.
- Methods to assess bacteriological effects on geosynthetic systems considering the long lifetimes that are required.
- Further quantification of seam integrity by NDT methods.
- An accurate method for leak detection.

- Methods to better unitize or compartmentalize different zones in a landfill.
- Innovative methods for waste placement while remaining outside of the site itself.
- Methods and/or designs to safeguard cap and closures against erosion, burrowing animals, deep root growth and other time dependent phenomenona.

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