# Appendix K – Leachate Collection System

# K.1 – Leachate Design Compatibility

TECHNICAL NOTE

# Chemical Resistance for Geomembrane Products

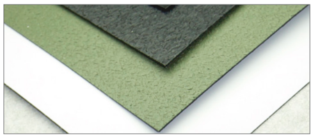
GSE geomembranes are made of high quality, virgin polyethylene which demonstrates excellent chemical resistance. GSE polyethylene geomembranes are resistant to a great number and combinations of chemicals. It is this property of (HDPE) high density polyethylene geomembranes that makes it the lining material of choice.

In order to gauge the durability of a material in contact with a chemical mixture, testing per ASTM D5747 is required in which the material is exposed to the chemical environment in question. Chemical resistance testing is a very large and complex topic because of two factors. First, the number of specific media is virtually endless and second, there are many criteria such as tensile strength, hardness, etc. that may be used to assess a material's resistance to degradation.

The chemical resistance of polyethylene has been investigated by many people over the past few decades. We are able to draw from that work when making statements about the chemical resistance of today's polyethylene geomembranes. In addition to that, many tests have been performed that specifically use geomembranes and certain chemical mixtures. Naturally, however, every mixture of chemicals cannot be tested for. As a result of these factors, GSE published a chemical resistance chart, demonstrating general guidelines.

Polyethylene is, for practical purposes, considered impermeable. Be aware, however, that all materials are permeable to some extent. Permeability varies with concentration, temperature, pressure and type of permeant. The rates of permeation are usually so low, however, that they are insignificant. As a point of reference, polyethylene is commonly used for packaging of several types of materials. These include gasoline, motor oil, household cleaners (i.e. bleach), muratic acid, pesticides, insecticides, fungicides, and other highly concentrated chemicals. Also, you should be aware that there are some chemicals which may be absorbed by the material but only when present at very high concentrations. These include halogenated and/or aromatic hydrocarbons at greater than 50%; their absorption results in swelling and slight changes in physical properties such as increased tensile elongations. This includes many types of fuels and oils. Recognize that this action, however, does not affect the liner's ability to act as a barrier for the material it is containing.

Since polyethylene is a petroleum product, it can absorb other petroleum products. Like a sponge, the material becomes slightly thicker and more flexible but does not produce a hole or void. However, unlike a sponge, this absorption is not immediate. It takes a much longer time for a polyethylene liner to swell than it does for a sponge. The exact time it takes for swelling to occur depends on the particular constituents and concentrations of the contained media. However, a hole would not be produced.  Also, this absorption is reversible and the material will essentially return to it's original state when the chemical is no longer in contact with the liner.



**GSE Geomembranes**

**GSE Textured HPDE**

**GSE GEOMEMBRANES**

**An HDPE geomembrane used in applications that require excellent chemical resistance and endurance properties**

With regard to typical municipal landfills in the United States, legally allowable levels of chemicals have been demonstrated to have no adverse affect on polyethylene geomembrane performance. The very low levels of salts, metals and organic compounds do not damage polyethylene. A double-lined containment with a leachate (leak detection) removal system effectively prevents any significant, continuous exposure of the secondary membrane to these materials and for practical purposes makes the total liner system even more impermeable.

## Other Reference Materials

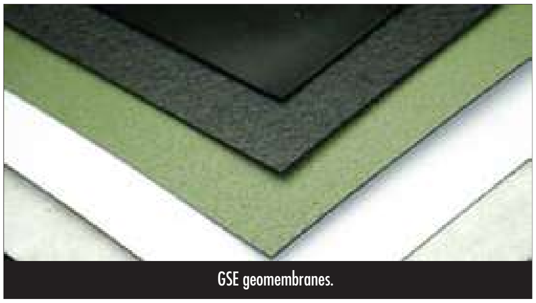
### GSE Geomembranes

For more information regarding GSE Geomembrane products, refer to these items:

-GSE HDPE Geomembrane Application Sheet

The Pioneer Of Geosynthetics
SINCE 1972

# Ultraviolet (UV) Resistance for Geomembrane Products



GSE geomembranes.

Weathering of geomembrane lining materials continues to be a major interest to those seeking long term protection against ultraviolet exposure. In general, weathering and other environmental effects which cause lasting material changes are classified as aging. Changes in a material can be determined by studying the changes in material's mechanical properties. Under certain conditions, a change in mechanical characteristics can permit an estimation of the material's life span.

GSE polyethylene geomembranes are manufactured from first quality polyethylene resins[1]. To combat causes of aging, such as ultraviolet exposure, properly selected and dispersed carbon black is added to GSE geomembranes at a rate of 2 - 3%. Carbon black is universally accepted as being resistant to significant deterioration caused by weathering for 50 years or more. In fact, AT&T Bell Laboratories (Polyolefin Longevity for Telephone Service, H.M. Gilroy, AT&T Bell Laboratories, ANTEC, '85) set out many years ago to demonstrate that the resistance to ultraviolet exposure and weathering for polyethylene is in excess of 45 years[2].

In addition to a high quality carbon black, GSE utilizes highly effective chemical UV stabilizers which further extend the life of the material to which it is added. These additives absorb incident radiation and/or terminate free radical production, thus protecting the polyethylene against thermal degradation and possible chemical reactions with surrounding materials. Polyethylene resins, chemical stabilization components and carbon black dispersions have all been improved as a result of research and testing. As a result, properly formulated and compounded polyethylenes have an estimated projected life in excess of 100 years for resistance to weathering.

Not only is the quality of additive packages important, but the integrity of the polyethylene resin itself plays a vital roll in UV resistance. There are various properties of the resin package which can be adjusted to improve the UV resistance of a material. It has been determined that reducing the density of the polyethylene base resin reduces both the weathering and chemical resistance of the resin and the effectiveness of chemical stabilizers and carbon black. It is GSE's current opinion that polyethylene resins below a density of about 0.915 g/cc are undesirable for use where dependable long-term weathering or chemical resistance is required.

There are, however, other factors which effect the potential UV resistance of a material and thus any lifetime predictions determined in a laboratory. Some items which effect or cause variation in the resistance of a material to UV degradation are:

- Average Density
- Carbon Black Type, Content and Dispersion
- Density Range or Distribution
- Chemical Stabilizer System
- Catalyst Type and Amount of Residue
- Copolymer Type
- Combined Chemical Exposures
- Failure Criteria

Essentially all liquid containment applications leave some portion of the slope liner exposed to weathering. Therefore proper resin and additive formulations are very important to enhance the material's resistance to UV degradation.

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References:

[1] GSE Technical Note TN010, GSE Lining Technology, Houston, Texas.

[2] Gilroy, H.M., "Polyolefin Longevity for Telephone service", AT&T Bell Laboratories, ANTEC, 1985.

TN3 UVResistance R01/15/10

POLY-FLEX®
GEOMEMBRANE

# REFERENCE MANUAL

# CHEMICAL RESISTANCE INFORMATION

## CHEMICAL COMPATIBILITY OF POLY-FLEX® LINERS

Chemical compatibility or resistance, as applied to geomembranes, is a relative term. Actual compatibility would mean that one material dissolves in the other, such as alcohol in water or grease in gasoline. An example of incompatibility would be oil and water. In liners it is undesirable to have the chemicals dissolve in the liner, hence the term compatibility is the reverse of what is normally meant in the chemical industry. In the strictest sense and from a laboratory perspective, chemical compatibility, as the term applies to this industry, would imply that the chemical has no effect on the liner. From an engineering perspective, chemical compatibility means that a liner survives the exposure to a given chemical even though the chemical could have some effect on the performance of the liner, but not enough to cause failure. One must understand and define chemical compatibility for a specific project.

Generally polyethylene is affected by chemicals in one of three ways:

1. No effect—This means that the chemical in question and the polyethylene do not interact. The polyethylene does not gain (lose) weight or swell, and the physical properties are not significantly altered.
2. Oxidizes (cross linking)—Chemicals classed as oxidizing agents cause the polyethylene molecules to cross link and cause irreversible changes to the physical properties of the liner, i.e., they make the liner brittle.
3. Plasticizes—Chemicals in this classification are soluble in the polyethylene structure. They do not change the structure of the polyethylene itself but act as a plasticizer. In doing so, the liner experiences weight gain of 3-15%, may swell by up to 10%, and has measurable changes in physical properties (e.g. the tensile strength at yield may decrease by up to 20%). Even under these conditions the liner maintains its integrity and is not breached by liquids, provided the liner has not been subjected to any stress. These effects are reversible once the chemicals are removed and the liner has time to dry.

Aside from the effect that chemicals have on a liner is the issue of vapor permeation through the liner. Vapor permeation is molecular diffusion of chemicals through the liner. Vapor transmission for a given chemical is dependent primarily on liner type, contact time, chemical solubility, temperature, thickness, and concentration gradient, but not on hydraulic head or pressure. Transmission through the liner can occur in as little as 1-2 days. Normally, a small amount of chemical is transmitted.

As stated above, chemical compatibility is a relative term. For example, the use of HDPE as a primary containment of chlorinated hydrocarbons at a concentration of 100% may not be recommended, but it may be acceptable at 0.1% concentration for a limited time period or may be acceptable for secondary containment. Factors that go into assessment of chemical compatibility are type of chemical(s), concentration, temperature, and the type of application. No hard and fast rules are available to make decisions on chemical compatibility. Even the EPA 9090 test is just a method to generate data so that an opinion on chemical compatibility can be more reliably reached.

A simplified table on chemical resistance is provided to act as a screening process for chemical containment applications.

# CHEMICAL RESISTANCE INFORMATION

| CHEMICAL CLASS | CHEMICAL EFFECT | PRIMARY CONTAINMENT (LONG TERM CONTACT) | | SECONDARY CONTAINMENT (SHORT TERM CONTACT) | |
|---|---|---|---|---|---|
| | | HDPE | LLDPE | HDPE | LLDPE |
| CARBOXYLIC ACID | 1 | | | | |
| - Unsubstituted (e.g. Acetic acid) | | B | C | A | C |
| - Substituted (e.g. Lactic acid) | | A | B | A | A |
| - Aromatic (e.g. Benzoic Acid) | | A | B | A | A |
| ALDEHYDES | 3 | | | | |
| - Aliphatic (e.g. Acetaldehyde) | | B | C | B | C |
| - Hetrocyclic (e.g. Furfural) | | C | C | B | C |
| AMINE | 3 | | | | |
| - Primary (e.g. Ethylamine) | | B | C | B | C |
| - Secondary (e.g. Diethylamine) | | C | C | B | C |
| - Aromatic (e.g. Aniline) | | B | C | B | C |
| CYANIDES (e.g. Sodium Cyanide) | 1 | A | A | A | A |
| ESTER (e.g. Ethyl acetate) | 3 | B | C | B | C |
| ETHER (e.g. Ethyl ether) | | C | C | B | C |
| HYDROCARBONS | 3 | | | | |
| - Aliphatic (e.g. Hexane) | | C | C | B | C |
| - Aromatic (e.g. Benzene) | | C | C | B | C |
| - Mixed (e.g. Crude oil) | | C | C | B | C |
| HALOGENATED HYDROCARBONS | 3 | | | | |
| - Aliphatic (e.g. Dichloroethane) +A4 | | C | C | B | C |
| - Aromatic (e.g. Chlorobenzene) | | C | C | B | C |
| ALCOHOLS | 1 | | | | |
| - Aliphatic (e.g. Ethyl alcohol) | | A | A | A | A |
| - Aromatic (e.g. Phenol) | | A | C | A | B |
| INORGANIC ACID | | | | | |
| - Non-oxidizers (e.g. Hydrochloric acid) | 1 | A | A | A | A |
| - Oxidizers (e.g. Nitric Acid) | 2 | C | C | B | C |
| INORGANIC BASES (e.g. Sodium hydroxide) | 1 | A | A | A | A |
| SALTS (e.g. Calcium chloride) | 1 | A | A | A | A |
| METALS (e.g. Cadmium) | 1 | A | A | A | A |
| KETONES (e.g. Methyl ethyl ketone) | 3 | C | C | B | C |
| OXIDIZERS (e.g. Hydrogen peroxide) | 2 | C | C | C | C |

Chemical Effect (see discussion on Chemical Resistance)

1. No Effect—Most chemicals of this class have no or minor effect.
2. Oxidizer—Chemicals of this class will cause irreversible degradation.
3. Plasticizer—Chemicals of this class will cause a reversible change in physical properties.

Chart Rating

A. Most chemicals of this class have little or no effect on the liner.
Recommended regardless of concentration or temperature (below 150° F).

B. Chemicals of this class will affect the liner to various degrees.
Recommendations are based on the specific chemical, concentration, and temperature.
Consult the design engineer.

C. Chemicals of this class at high concentrations will have a significant effect on the physical properties of the liner.
Generally not recommended but may be acceptable at low concentrations and with special design considerations.
Consult the design engineer.

The data in this table are provided for informational purposes only and are not intended as a warranty or guarantee. Poly-America, L.P. assumes no responsibility in connection with the use of these data. Consult with the design engineer for specific chemical resistance information and liner selection.

# Designing for Durability

# Designing for Durability

## Initial consideration

Geotextiles used in civil engineering applications are expected to carry out one or more functions over a given design life. There are five defined functions[1], these are; drainage, separation, filtration, protection and reinforcement. The functional requirements of the geotextile in a given application will determine the performance properties required, and any assessment of the products durability will be based on the degradation of these properties over a given time.

There are a number of factors that will help to determine the durability of a geotextile; the physical structure of the fabric, the nature of the polymer used, the quality and consistency of the manufacturing process, the physical and chemical environment in which the product is placed, the condition in which the product is stored and installed and the different loads that are supported by the geotextile.

It is essential that a geotextile performs effectively for the required duration of the design (many being in excess of 100 years), and not just in initial conformance testing.

This report is intended to provide guidance on selecting the appropriate geotextile for a given application in relation to long term product durability and 'lifetime prediction'. It will explain the steps taken by GEOfabrics to ensure that its product range meets the highest possible standards.

## Raw material selection

Geotextiles are normally manufactured by either woven or nonwoven techniques, the polymers used are generally thermoplastic materials which contain variations of both amorphous and semi-crystalline regions.

The GEOfabrics product range is manufactured from needle-punching polypropylene staple fibre[2]. The fibre that is used by GEOfabrics is sourced from a limited number of suppliers, all of which have been through a lengthy approval process and ongoing auditing to an ISO 9001 framework to ensure that the material consistently meets very stringent specification criteria.

There are several factors relating to fibre selection that must be considered in relation to end product durability; the basic polymer from which the product is made, any additives compounded with it, and the fibre morphology. Fibre morphology in materials science relates to the science of form and is linked to all physical aspects of the polymers structure.

GEOfabrics HPS range is manufactured from high tenacity virgin polypropylene fibre which is mechanically drawn to form fibres with higher tensile properties and improved durability. The increased drawing within the fibre manufacturing process re-orientates the molecules within the fibre making it stronger. The increased molecular orientation and associated higher density leads to increased environmental resistance. This is because the level of crystallinity within the fibre has a large effect on the properties relating to durability[3]. The tightly packed molecules result in dense regions with higher intermolecular cohesion and resistance to penetration by chemicals. An increase in the degree of crystallinity leads directly to an increase in rigidity and yield or tensile strength, hardness and softening point, and decrease in chemical permeability.

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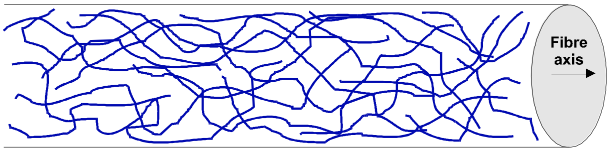
1. ISO 10318 – Geosynthetics: Terms and definitions.
2. Staple fibre means that the individual fibres within the product have been cut to a specified length prior to the manufacturing
3. Where molecular chains are kinked, randomly orientated and often entangled, the configuration of the polymer region is said to be amorphous. Where molecular chains are more closely packed, taking a more regular form, the polymer region is said to be crystalline. Most polymers contain both amorphous and crystalline regions.
4. ISO 13434:1998 – Guidelines on durability of geotextiles and geotextile related products.

Fibre A: Standard fibre - random molecular chains (amorphous structure)



Fibre B: High-tenacity fibre - oriented molecular chains (crystalline regions)

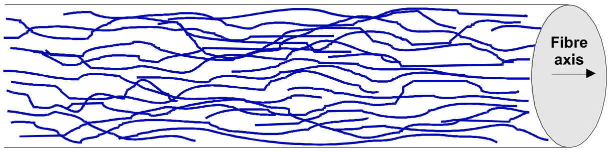


*Figure 1: Improved molecular orientation of high-tenacity fibres.*

Low-cost fibre is also available within the market, usually as a by-product of another manufacturing process such as carpet making; designed for aesthetics rather than performance. These fibres will be of mixed origin and can therefore have inconsistent properties, moreover the performance consistency and hence the quality of the resultant geotextile will be inferior to those produced from prime quality virgin fibre made to a controlled specification.

The fibre morphology in such products will be inconsistent from batch to batch as the fibres may be sourced from multiple types and colours. The ratio of amorphous and crystalline regions can vary from batch to batch as the fibres are not of one type. The variation in pigmentation will also have an effect on the level of crystallinity within the polymer and thus the level of attack that the fibre can be susceptible to[5].

Fabrics can be produced from both industrial and post-consumer recycled fibres. Such fibre types can be of different thicknesses, and volume to surface ratios. Some types of degradation, such as oxidation and UV-exposure, are dependent on surface area, whilst others such as diffusion and absorption are inversely related to thickness.

The selection of the right polymer type for the manufacture of textiles for use in civil engineering applications is essential. GEOfabrics HPS range is manufactured from virgin polypropylene fibres which have a high resistance to acids, alkalis and most solvents. Polypropylene can be considered as inert to acid and alkali attack and is suitable for most geotextile applications. Polypropylene can be susceptible to oxidation, however oxygen levels are normally low below soil level and GEOfabrics perform ongoing oxidation tests to ensure accurate assessment of oxidation rates in relation to long term durability (reviewed later in report).

Another polymer fibre that is used within Geotextile manufacturing is polyester, of which the most common type is polyethylene-terephthalate (PET) which is produced using condensation polymerisation. Polyethylene terephthalate is made by condensing ethylene glycol with either terephthalic acid itself or with dimethyl terephthalate (see Figure 2).

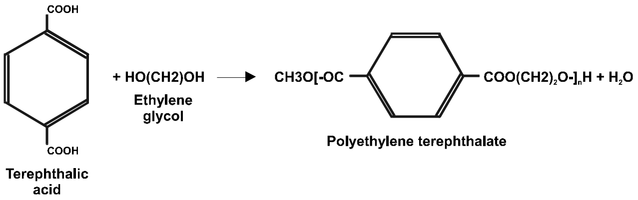


*Figure 2: Production of PET*

PET can offer good mechanical properties and is suitable for some applications; however the ester group can be hydrolysed in the presence of water[6], which is accelerated by alkaline conditions. Polyester can also be susceptible to heightened degradation where there is lime treated soil, concrete or cement present[7].

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5. Morphology of the noncoloured and coloured polypropylene fibres – Institute of Textile Engineering and Polymer Materials, University of Bielsko-Bia a, ul. Willowa 2, Bielsko-Bia a 43-309, Poland
6. Hydrolysis is a reverse reaction of the initial condensation polymerisation used to produce PET.
7. Broken concrete is generally between pH 11-13, lime marl between pH 10-11 (CEN-Bericht 13434-2000, Table 2 & Kuntze et al)

Hydrolysis in polyester takes two forms. The first form of hydrolysis is alkaline or external hydrolysis which occurs more rapidly in soils above pH 10, and particularly in the presence of calcium, and takes place in the form of surface attack, or etching. Increased caution should be taken with polyester in soils with pH 9 or above[8]. The second type is internal hydrolysis which takes place across the entire cross section of the fibre, this occurs in aqueous solutions or humid soil at all pH levels. This process is slow in mean soil temperatures of <15°C or neutral soils, however this is accelerated in acids and increased soil temperatures.

Although polyester can have advantages over other polymers the alkaline sensitivity of this polymer under long-term loadings should be a major concern in many geotextile applications, polyester can be susceptible to damage in high pH applications. An independent study conducted by the University of Leeds showed that 'I*f the conditions are slightly alkaline, the combined action of load and alkali could be catastrophic and the use of polyester would have to be restricted*'[9].

## Standards for durability testing – CE marking

Since the late 1980's the CEN TC 189 committee has standardised testing methods and procedures to encourage continuity and consistency across the industry. Since the early part of 2002 it has become a mandatory requirement to CE mark geotextile and geotextile related products to demonstrate compliance with the European construction products directive.

The main aim of the construction products directive is to break down technical barriers to trade in construction products between Member States in the European Economic Area. To achieve this it provides for four main elements:

- A system of harmonised technical specifications
- A framework of notified bodies
- The CE marking of products
- An agreed system of attestation of conformity for each product family

The construction product directive does not aim to harmonise regulations, what it aims to do is harmonise the methods of testing and the way in which manufacturers of products report on their performance values, and the method of conformity assessment.

The CE marking is a 'passport' that enables a product to be legally placed on the market within any member state. *CE marking does not mean that the product is suitable for an end use*, it simply means that the manufacturer has complied with the regulations set out within the CPD and that it must report on the harmonised declared values set out within the standards.

For geosynthetics, there are several standards published by CEN TC 189 for CE marking based on product applications, these are:

| | |
|---|---|
| **EN 13249:** | **Geotextiles for roads and other trafficked areas** |
| **EN 13250:** | **Geotextiles for railways** |
| **EN 13251:** | **Geotextiles for earthworks, foundations and retaining structures** |
| **EN 13252:** | **Geotextiles for drainage systems** |
| **EN 13253:** | **Geotextiles for erosion control works** |
| **EN 13254:** | **Geotextiles for reservoirs and dams** |
| **EN 13255:** | **Geotextiles for canals - Intended uses** |
| **EN 13256:** | **Geotextiles for tunnels and underground structures** |
| **EN 13257:** | **Geotextiles for solid waste disposal** |
| **EN 13265:** | **Geotextiles for liquid waste disposal** |

The testing that needs to be performed on a product depends on the function that the product is required to perform within the application. The functions are based on the five functions that are set out within ISO 10318 as described earlier

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8. ISO 13434:1998 – Guidelines on durability of geotextiles and geotextile related products.
9. The alkaline degradation of polyester geotextiles- Dr. Mashiur Rahman; Univ. of Leeds Department of Textile Industries 1997 – Also published within GEOQuebeq 2004.

The levels of control within the manufacturing process are audited by the accrediting body – GEOfabrics use BTTG certification for this. The manufacturer is then issued with a certificate of factory production control under the guidelines identified within the EN application standards.

Within Annex B of the standards, there is guidance on the testing that is required in order to make an assessment of the long-term durability of the product. For Polypropylene geotextiles the tests that are required are:

| | |
|---|---|
| **Determination of resistance to weathering (UV)** | **EN 12224 (2000)** |
| **Determining the resistance to liquids (acids & alkalis)** | **ISO 12960 (2000)** |
| **Determination of resistance to oxidation** | **EN 13438 (2000)** |
| **Resistance to microbiological attack by soil burial** | **EN 12225 (2000)** |
| **Procedure for simulating damage during installation**[10] | **EN 10722 (1998)** |

Following a factory inspection to verify procedures and a further inspection of records and equipment calibration – GEOfabrics have obtained a CE mark for all of its HPS geotextile range.

## Resistance to weathering

Geosynthetic products can be exposed to weathering and the resulting effect on the performance of products is of importance. The ageing of geotextiles in predominately set in motion by the climate effects through the presence of solar radiation, heat, wetting and moisture.

Geosynthetics are normally exposed to weathering for a relatively short but somewhat varying time during construction work. The properties of unprotected polymers with are such that just one week of outdoor exposure can seriously damage the geotextile[11]. The mechanism of degradation in most polymers is photochemical in nature, the absorption of ultraviolet light by the polymer provides the energy to break key molecular bonds near the surface of the exposed plastic. The resultant free radicals then react with oxygen to form peroxy radicals which will attack other polymer molecules, or even other points within the same polymer chain. More free radicals are then formed resulting in a chain reaction along the duration of the polymer chain. Consequently, polymers used in geosynthetics must be protected by appropriate additives to minimise the detrimental effects of exposure to ultraviolet light energy.

GEOfabrics HPS range contains fine grade carbon black additive for ultraviolet light stabilisation. This is mixed in the polymer prior to the point of extrusion to allow for homogenous dispersion within the product. Carbon black acts as a strong UV absorber.

Natural weathering processes require testing over very lengthy durations and test replication is impractical, it is therefore desirable for practicality to use an accelerated method of testing to simulate the effects of natural weathering in a controlled environment using an artificial light source. This type of testing produced comparable data which can be used to accurately compare products. The principle of testing is to expose the product to simulated solar ultraviolet light for different radiant exposures with controlled cycles of temperature and moisture.

The guidance within the standards for CE marking dictates that unless products are to be covered on the day of installation, they should be tested in accordance with EN 12224 - Determination of resistance to weathering. This European test is an index test for determining the resistance of geosynthetics to weathering conditions more intense than those of natural weathering and allows differentiation between products which have little or no resistance to those which do have such resistance.

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[10] Not part of harmonised testing (H); considered relevant to conditions of use (A)

[11] Prediction of the weathering resistance of Geotextiles: Hufenus, Trubiroha and Schröder, BAM Berlin.

# Designing for Durability

The method of the test is such that specimens of material to be tested are exposed to a light source for a defined radiant exposure and at recommended temperature and moisture conditions. After this exposure the change in performance is determined. In order to eliminate (as much as practically possible) the potential variation from one machine to another weathering processes must be represented as a function of the radiant exposure in MJ/m$^2$ (energy per surface). European standard EN 12224 exposes specimens to a continuous UV radiant exposure of 50 MJ/m$^2$; this is combined with a wet dry cycle of one hour spraying at a black standard temperature of 25±3 ˚C and five hours drying at a black standard temperature of 50±3 ˚C. 50MJ/m$^2$ is between 1.5 – 5 months of natural weathering in central Europe. The variation is due to the changing weather conditions from year to year. Research conducted by the BAM laboratory in Berlin was conducted during the 1990's to validate the EN 12224. Table one shows the significant level of variation of radiant exposure in Berlin and Bandol (Southern France). It is for this reason that it is extremely difficult to place product guarantees on products that do refer to natural conditions rather than MJ/m$^2$ of radiant exposure.

| Natural weathering station | Radiant exposure λ (wavelength) < 400nm | Duration (days) | Season |
|---|---|---|---|
| Berlin | 28 MJ/m$^2$ | 134 | Winter 94/95 |
| | 44 MJ/m$^2$ | 59 | Spring 95 |
| | 72 MJ/m$^2$ | 76 | Summer 95 |
| | 147 MJ/m$^2$ | 182 | Spring/Summer 95 |
| | 176 MJ/m$^2$ | 317 | Autumn 94 to Autumn 95 |
| Bandol | 154 MJ/m$^2$ | 147 | Spring/Summer 95 |

Table 1: Specification of the natural weathering tests in Berlin and Bandol[12]

In 2002 GEOfabrics performed comparative UV testing to EN 12224[13]. Figure 3 shows a significant difference in the reduction in performance between the HPS and MPS range of products. The MPS range loses up to 70% strength while the HPS range loses a maximum of 16% with most of the range limited to only a 10% strength. This is explained by the presence of carbon black (added for UV protection) in the HPS range, which is not added to the MPS range of products. The percentage loss in mechanical performance is reduced with increasing thickness, and hence the percentage of the product influenced by UV reduces.

GEOfabrics HPS products are manufactured using a needle-punching process; they are mechanically entangled and receive no thermal finishing. This gives them excellent thickness to weight ratios, as the degradation process due to weathering starts at the surface[14]; they will generally perform better than similar products with low thickness values.

As part of the ongoing product assessment for CE marking a weathering test was performed by BTTG laboratories on GEOfabrics HPS 3 in Feb 2009[15]. The test was conducted in accordance with EN 12224:2000.

A Q-panel accelerated weathering tester was used which applied a total radiant exposure of 50 MJ/m$^2$ over a total exposure time of 350 hours. The test cycles over 6 hours with 5 hours dry light exposure at a black standard temperature of 50± 3˚C and 1 hour water spray at a black standard temperature of 25± 3˚C. The equipment incorporates a solar eye which maintains the correct irradiance automatically with UV intensity being monitored via four sensors at the sample plane. On completion of the test tensile tests were conducted on the material and assessed against control samples.

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12. Trubiroha, P., Schröder, H. (1997) Klassifizierung von Geotextilien hinsichtlict der Wetterbeständig-keit. – 5 Informations – und Vortragsveranstaltung űber Kunstoffe in der Geotechnik, Műnchen. Natural weathering was performed to ISO 877: 994 Method A on the roof of a 40mtr building in Berlin and a natural weathering test station in Bandol, Southern France. The angle of exposure was 45˚.
13. Ref: GEOfabrics durability test data D1/D2 – Report No. R-020823-06
14. Prediction of the weathering resistance of Geotextiles: Hufenus, Trubiroha and Schröder, BAM Berlin
15. Test report dated 02nd Feb 2009 – BTTG Ref: 10/13356/CA

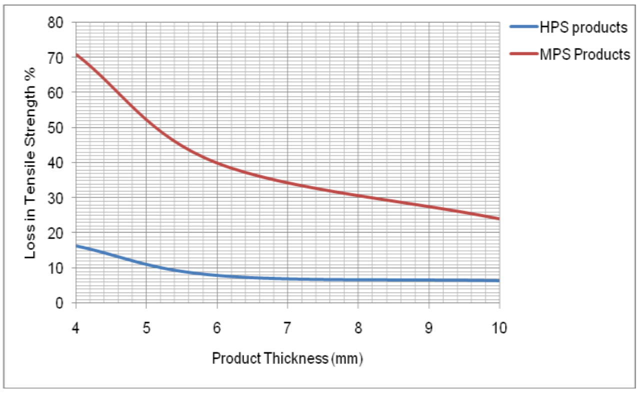

*Figure 3: Loss in strength of protected and unprotected PP fibres after weathering*

The results shown in table 2 highlight that HPS 3, one of the lowest grades in the HPS product range has excellent resistance to weathering. HPS products that are thicker than this will inevitably have improved performance.

| | Control | | Exposed | | | |
|---|---|---|---|---|---|---|
| | Tensile strength (N) | Extension % @ max. load | Tensile Strength (N) | Extention % @ max. load | % retained strength | % retained extension |
| **MD** | | | | | | |
| **Mean** | 699.20 | 92.6 | 688.90 | 79.9 | 98.53 | 86.26 |
| **SD** | 70.82 | 4.20 | 36.47 | 2.51 | | |
| **CV** | 10.13 | 4.53 | 5.29 | 3.14 | | |
| **CMD** | | | | | | |
| **Mean** | 1230.06 | 88.3 | 1143.56 | 75.1 | 92.97 | 85.05 |
| **SD** | 32.70 | 1.59 | 54.07 | 1.87 | | |
| **CV** | 2.66 | 1.80 | 4.73 | 2.49 | | |

*Table 2: EN 12224:2000 - GEOfabrics HPS 3 test results. Feb 2009*

As a guideline for assessing the weathering resistance of a product outside Europe and in relation to EN 12224 it is possible to use a global radiation map. Figure 4 shows a generalised guideline view of the isolines of global radiation expressed in kilolangleys of exposure per annum (Kcal/cm$^2$/yr).

1 kilolangley equates to 41.84 MJ/m$^2$ of the complete spectrum, however we are specifically concerned with the ultraviolet part of the spectrum. The ultraviolet part of the spectrum (<400nm) is approximately 7% of total solar radiation.

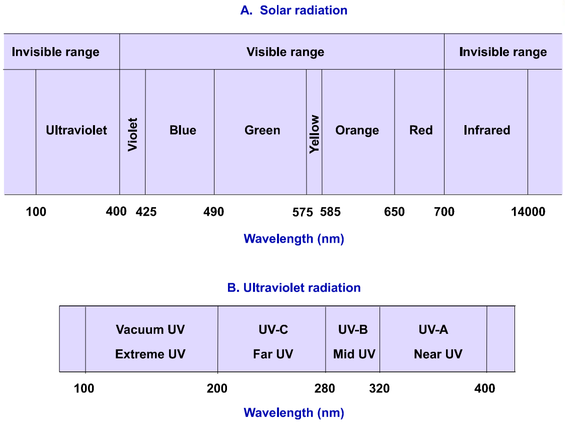

*Figure 3: Solar radiation spectrum*

If we use the map in Figure 5 we can make some basic assumptions about the products ability to withstand natural weathering in global locations.

**Northern Spain** = 120 kilolangleys of global radiation per annum
120 kilolangleys = 5020.8 MJ/m$^2$ total exposure.
(5020.8/100) x 7 = 351.456
*= 351.456 MJ/m$^2$ radiant exposure (UV) per annum*
*= 29.288 MJ/m$^2$ average radiant exposure (UV) per month*

*And:*

**Central Australia** = 180 kilolangleys of global radiation per annum
180 kilolangleys = 7531.2 MJ/m$^2$ total exposure
(7531.2/100) x 7 = 527.184
*= 527.184 MJ/m$^2$ radiant exposure (UV) per annum*
*= 43.932 MJ/m$^2$ average radiant exposure (UV) per month*

and

**Middle East** = 220 kilolangleys of global radiation per annum
220 kilolangleys = 9204.8 MJ/m$^2$ total exposure
(9204.8/100) x 7 = 644.336
= 644.336 *MJ/m$^2$ radiant exposure (UV) per annum*
= *53.694 MJ/ m$^2$ average radiant exposure (UV) per month*

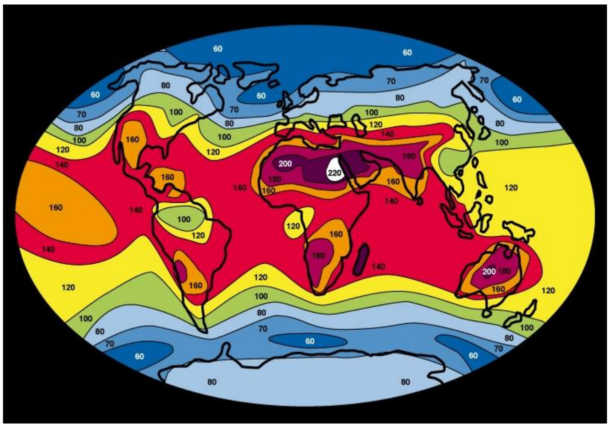

*Figure 5: Generalised Isolines of global radiation expressed in Kilolangleys per annum (Kcal/cm2/yr)*

It is important to remember that this calculation does not account for seasonal variation, which can be significant. However, it does highlight the need for a geotextile that has been designed to withstand UV attack. If we look at the performance of a geotextile without UV protection, we can clearly see that in some parts of the world, it could be a matter of weeks or even days before a catastrophic failure in mechanical performance occurs.

It must also be remembered that the MPS products are manufactured with fibres produced to a tightly controlled specification, with control of fibre diameter, draw ratio and polymer formulation. This is therefore the best case scenario for fabrics manufactured without UV protection; products manufactured from fibres that are not to a specification could potentially have a much poorer performance.

Before selecting an appropriate geotextile for an application, the level of weathering that the product may be subjected to pre, during and post installation must be considered. The location and duration of exposure can drastically affect the physical and mechanical performance of the polymer. Geotextiles with appropriate additives must be selected to match the application conditions.

## Resistance to liquids (acids & alkalis)

In nearly all civil engineering applications geotextiles can be in contact with aqueous solutions of acids, bases or dissolved oxygen. The resistance of geotextiles to these chemicals is a product of polymer formulation, manufacturing parameters, and fabric structure. External influences may also affect product performance, such as existing damage, liquid composition and in situ conditions such as temperature, pressure and mechanical stress.

Below the ground the main factors influencing durability are[16]:

- Particle size distribution and angularity of the soil
- Acidity/alkalinity (pH) – humates, sodium or lime soils, lime hydration, concrete, metal ions present
- The presence of oxygen
- Moisture content
- Organic content
- Temperature

ISO 13434 – Guidelines on durability identifies typical pH values of minerals and fills, it also notes *that the use of bentonite and other clays in civil engineering construction, such as diaphragm wall construction, grouting processes, sealing layers in landfill and tunnelling causes local areas of high alkalinity between pH values of 8,5 to 10*

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16. ISO 13434

Also, soils treated with lime (calcium hydroxide) can have pH values as high as 11. Concrete substrates also have high alkalinity (pH 11).

| Minerals & fills | Formula | Maximum pH |
|---|---|---|
| **Felspar** | | |
| **Albite** | **$NaAlSi_3O_8$** | **9 – 10** |
| **Anorthite** | **$CaAl_2Si2O_8$** | **8** |
| **Orthoclase** | **$KAlSi_3O_8$** | **8 – 9** |
| **Sand** | | |
| **Quartz** | **$SiO_2$** | **7** |
| **Muscovite** | **$KAl2(OH,F)_2AlSi_3O_{10}$** | **7 – 8** |
| **Clay:** | | |
| **Kaolinite** | **Al4(OH)8Si4O** | **5 – 7** |
| **Carbonate:** | | |
| **Dolomite** | **$CaMg(CO_{3})_2$** | **9 – 10** |
| **Calcite** | **$CaCO_3$** | **8 – 9** |

*Table 3: Typical Minerals & Fills*

GEOfabrics HPS and MPS product ranges are manufactured from virgin polypropylene fibres. Polypropylene fibres have a high resistance to acids and alkalis in all concentrations, and up to comparatively high temperatures. Polypropylene fibre is inherently inert but can be susceptible to oxidising agents; however the rate of attack is extremely slow on fibres that have been manufactured to appropriate specifications (see Oxidation).

EN 14030:2001 is an index test used as a method of screening geotextiles for resistance to liquids with specific pH values. As part of the ongoing product assessment for CE marking this test was performed by BTTG laboratories on GEOfabrics HPS 3 in Feb 2009[17]. Five specimens in each direction were immersed in the test liquids at a temperature of 60± 1˚C for a period of three days. The test liquids used were:

- An inorganic acid: 0.025 M sulphuric acid with 1mMol ferric sulphate and 1 mMol ferrous sulphate added.(Approximate pH 1.5)
- An inorganic base: calcium hydroxide (Ca(OH)2), used as a saturated suspension. (Approximate pH 12.1)

Post exposure the specimens were rinsed thoroughly in accordance with the standard. The control specimens were immersed in water at 60± 1˚C for one hour. The specimens were then dried before tensile tests were conducted to assess performance.

Table 4 shows the results of testing performed in early 2009 on GEOfabrics HPS 3. As we can see from the results, the product experienced virtually no loss in tensile strength. The increase in tensile strength, and subsequent CMD decrease on the acid test, can be attributed to primarily to low sample variation. This highlights the high level of performance of polypropylene fibres in liquids with extreme pH levels (note that earlier testing on the MPS products showed similar results).

| Acid | Control | | Exposed | | | |
|---|---|---|---|---|---|---|
| | Tensile strength (N) | Extension % @ max load | Tensile strength (N) | Extension % @ max load | % Retained strength | % Retained extension |
| MD | | | | | | |
| Mean | 1020.86 | 87.8 | 1067.88 | 91.2 | 108.73 | 97.41 |
| SD | 143.53 | 7.39 | 45.85 | 9.68 | | |
| CV (%) | 14.06 | 8.42 | 4.29 | 10.62 | | |
| CMD | | | | | | |
| Mean | 1137.52 | 107.6 | 1142.34 | 102.0 | 96.98 | 92.24 |
| SD | 52.67 | 5.81 | 97.97 | 3.23 | | |
| CV (%) | 4.63 | 5.40 | 8.58 | 3.16 | | |

| Alkali | Control | | Exposed | | | |
|---|---|---|---|---|---|---|
| | Tensile strength (N) | Extension % @ max load | Tensile strength (N) | Extension % @ max load | % Retained strength | % Retained extension |
| MD | | | | | | |
| Mean | 1020.86 | 87.8 | 1055.96 | 92.4 | 107.19 | 99.11 |
| SD | 143.53 | 7.39 | 91.93 | 3.38 | | |
| CV (%) | 14.06 | 8.42 | 8.71 | 3.66 | | |
| CMD | | | | | | |
| Mean | 1137.52 | 107.6 | 1065.58 | 97.6 | 104.96 | 105.61 |
| SD | 52.67 | 5.81 | 88.90 | 5.81 | | |
| CV (%) | 4.63 | 5.40 | 8.34 | 5.96 | | |

*Table 3: Resistance to Liquids - EN 14030 - Alkali (pH 12.1& Acid (pH 1.5)[18]*

[17] Test report dated 02nd Feb 2009 – BTTG Ref: 10/13356/CA

[18] The apparent increase in tensile strength should be attributed to low level variation in sampling rather than a resultant property change due to the test

## Resistance to Oxidation

Oxidation is the reaction of the polymer, specifically polypropylene and polyethylene, with oxygen that can lead to the degradation of performance properties. The resultant outcome of the process of oxidation can be embrittlement, surface cracking, discolouration and most importantly reduction in molecular weight leading to a consequential loss in mechanical strength. Oxidation is a chain reaction started by free radicals normally produced by energising radiation (photo-oxidation) or heat; *this takes place in the amorphous regions of the fibre*.

Effectively designed antioxidant packages can be added to the fibre to significantly reduce the rate of oxidation. These will prevent the chain reaction in a number of ways and increase the lifetime of the product to an extent where it will outlive the duration of the design life. The degradation of polymers has been sub-divided into three stages: i) the reaction with surplus antioxidant within the polymer, ii) the consumption of the antioxidant and iii) the degradation of the unprotected polymer.

Polypropylene geotextiles are supplied in a wide variety of structures, the structure of the polymer and the additives within the fibre play a key role in the rate at which the material will oxidise. Antioxidants can be lost prematurely by migration, evaporation, leaching and may be deactivated by other additives or by incompatibilities arising in the polymer compound[19]. For long-term durability with a known rate of oxidation it is essential that a geotextile is manufactured from fibres produced to a controlled specification under consistent manufacturing conditions. Fabrics manufactured from fibres with inconsistent diameters, different pigmentations and additive packages cannot guarantee a level of durability. This is because even if a product is tested, the level of variation within the material is too great to ensure that the rate of oxidation is consistent.

As discussed earlier, GEOfabrics HPS range is manufactured from high tenacity virgin polypropylene. The fibre is manufactured to controlled diameters, with a draw ratio giving a high level of molecular crystallinity.

For CE marking of Geotextiles there is an accelerated test for the evaluation of the rate of oxidation of polyolefin materials. EN ISO 13438 is a screening test whereby test specimens are exposed to an elevated temperature in air over a fixed time period, using a regulated laboratory oven without forced air circulation. For polypropylene in non-reinforcement applications the temperature of the oven is 110 ± 1 ˚C and is maintained for a period of 14 days (i.e. 25 years equivalent) or 28 days for reinforcement, the tensile strength retained after completion of the test must exceed 50%. After the fixed period of oven aging the exposed specimen is subjected to a tensile test and measured against a control specimen taken from the same production sample. The resultant loss in tensile strength is measured.

Oxidation testing on GEOfabrics HPS 3 was undertaken at BTTG laboratories. The results can be seen in Table 5.

| 28 days | Control | | Exposed | | | |
|---|---|---|---|---|---|---|
| | Tensile strength (N) | Ext. % @ max load | Tensile strength (N) | Ext. % @ max load | % Retained strength | % Retained extension |
| MD | | | | | | |
| Mean | 832.92 | 83.1 | 892.82 | 82.4 | 107.19 | 99.11 |
| SD | 63.45 | 3.42 | 122.50 | 6.68 | | |
| CV (%) | 7.62 | 4.12 | 13.72 | 8.11 | | |
| CMD | | | | | | |
| Mean | 1063.58 | 94.1 | 1116.36 | 99.3 | 104.96 | 105.61 |
| SD | 60.68 | 11.25 | 61.96 | 3.30 | | |
| CV (%) | 5.71 | 11.96 | 5.55 | 3.32 | | |

| 56 days | Control | | Exposed | | | |
|---|---|---|---|---|---|---|
| | Tensile strength (N) | Ext. % @ max load | Tensile strength (N) | Ext. % @ max load | % Retained strength | % Retained extension |
| MD | | | | | | |
| Mean | 832.92 | 83.1 | 1006.70 | 86.0 | 120.86 | 103.44 |
| SD | 63.45 | 3.42 | 65.50 | 5.17 | | |
| CV (%) | 7.62 | 4.12 | 6.51 | 6.02 | | |
| CMD | | | | | | |
| Mean | 1063.58 | 94.1 | 1201.96 | 94.9 | 113.01 | 100.91 |
| SD | 60.68 | 11.25 | 105.50 | 4.60 | | |
| CV (%) | 5.71 | 11.96 | 8.78 | 4.84 | | |

| 84 days | Control | | Exposed | | | |
|---|---|---|---|---|---|---|
| | Tensile strength (N) | Ext. % @ max load | Tensile strength (N) | Ext. % @ max load | % Retained strength | % Retained extension |
| MD | | | | | | |
| Mean | 832.92 | 83.1 | 935.12 | 91.8 | 112.27 | 110.51 |
| SD | 63.45 | 3.42 | 45.80 | 1.46 | | |
| CV (%) | 7.62 | 4.12 | 4.90 | 1.59 | | |
| CMD | | | | | | |
| Mean | 1063.58 | 94.1 | 1124.24 | 100.0 | 105.71 | 106.32 |
| SD | 60.68 | 11.25 | 44.75 | 3.23 | | |
| CV (%) | 5.71 | 11.96 | 3.98 | 3.23 | | |

*Table 4: EN ISO 13438 - Resistance to Oxidation - 28, 56 & 84 days*

Tensile testing of HPS3 revealed no loss in tensile strength after 84 days of oven accelerated oxidation testing (or 150 years in non-reinforcing applications).

## Resistance to microbiological attack

The purpose of this test is to assess the resistance of geotextile products to attack by micro-organisms, bacteria and fungi by a soil burial test. Experience and exhumations of geotextiles manufactured from synthetic polymeric materials, in some cases for more than two decades show that most are generally resistant to this type of decay. However, it was deemed prudent to perform this test in order eliminate any doubt.

Samples of GEO*fabrics* products were tested to EN 12225; the loss in tensile strength recorded is of little significance and can be attributed to experimental error/ variation in sampling.

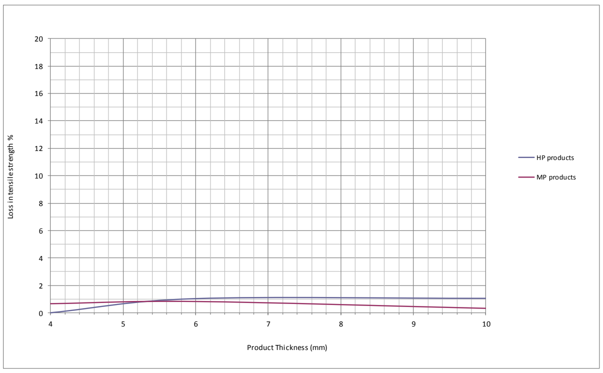


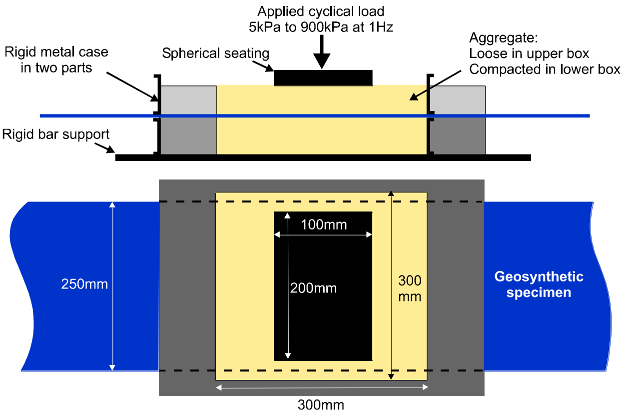
*Figure 4: Microbiological Resistance: EN 12225*

## Damage during installation

Damage during installation in this instance relates to mechanical damage normally as a result of direct contact between the soil fill and the geosynthetic under load, the effect of accidental damage caused by site plant are not accounted for. Damage can range from relatively light damage such as scuffing and abrasion of the fibres from the surface to more severe damage such as holes. The severity of the damage increases with the coarseness and angularity of the fill and applied compaction, and decreases with the thickness of the geotextile, such damage can affect the mechanical and hydraulic properties of a geotextile.

In 2002 GEOfabrics performed installation damage testing to ENV ISO 10722. The principle of the test is that a Geotextile specimen is placed between two layers of synthetic aggregate and subjected to a period of dynamic loading using a sinusoidal pressure between 5kPa and 900kPa at a frequency of 1Hz. The synthetic aggregate used is a sintered aluminium oxide with a grading of 5-10mm and a hardness of not less than1, 9.

Once this is complete the sample is removed from the apparatus, examined for any visual damage and then subjected to a mechanical or hydraulic test. The results of the test are expressed as the change as a percentage of the properties measured. The layout of the test is shown in Fig 7



The resultant loss in tensile strength after the test has been completed is shown in Fig8. It can be seen that there is an improvement in performance as thickness increases

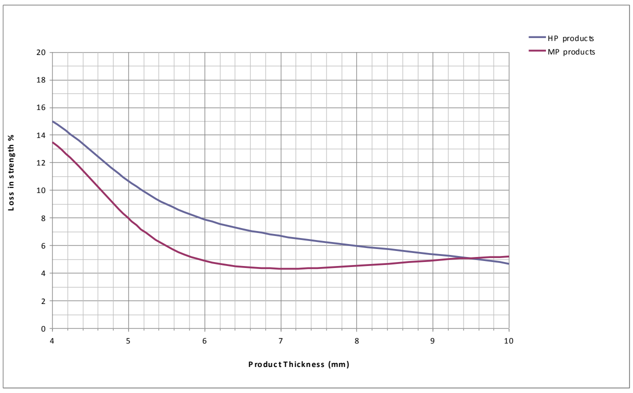


*Figure 8: ENV ISO 10722 - Resultant loss in tensile strength after completion of test*

## Testing using site specific leachate

In 1997 GEOfabrics set out a program to investigate and compare the performance of geotextiles manufactured from both polypropylene (PP) and polyethylene (PE) in a chemically aggressive leachate environment. The investigation was founded as a result of a claim that PE was more chemically resistant than PP, this claim was based on tests which immersed base polymers in its pure material state in pure acids or alkalis.

In order to test this theory in aggressive site leachate, a decision was made to perform a laboratory controlled test using leachate collected from site. The initial test was performed on a leachate collected from the Orgreave contaminated land containment cell.

The principle of the test was that five samples of geotextile were taken from both GEOfabrics Protector GP90 polypropylene and GEOfabrics Protector GP151 polyethylene fabrics. The samples were then fastened using polythene yarn to glass rods and hung in on racks inside the tank. The temperature chosen was a compromise between a number of factors, similar tests are commonly carried out at 55˚C as accelerated tests (e.g. 90 days in the American EPA 90/90 tests). For this test it was decided that longer periods were preferable to simulate site conditions as much as possible.

The site temperature was around 20˚C, although the possibility that some exothermic reactions could take place in isolated pockets was recognised. In order to achieve a long term anaerobic test it was deemed necessary to minimise evaporation and exposing the samples to air a lower temperature was desirable. Also at a higher temperature it was felt that there was a danger that biological growth would be halted or even killed off. Therefore in order to accelerate the test as much as possible without any negative results a test temperature of 35˚C was deemed to be most appropriate.

Fig. 9 shows the layout of the test. The samples in this first test were immersed for 437 days, samples were removed at appropriate intervals and CBR tests were performed and compared against a control sample. The resultant change in strength is shown in Fig 8.

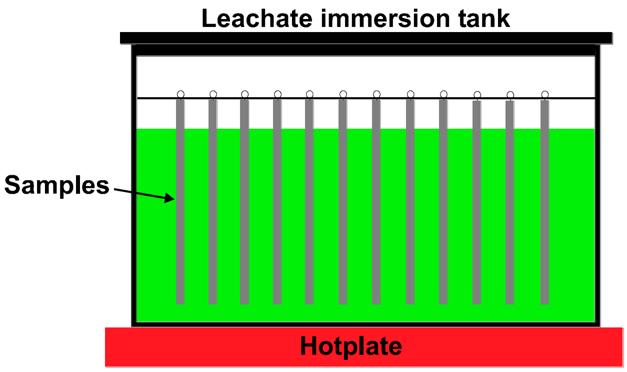


*Figure 5: Long-term leachate immersion test*

The results of the Orgreave’s test show that the there was a marked increase in puncture strength on both the PP and the PE geotextiles, with elongations generally decreasing on both of the materials. The increase in strength was seen as a combination of the stiffening of the fibres due to the increased temperature and free floating particles lodging themselves within the matrix of the fibres reinforcing the material. The test needed to be stopped after 437 days as the acidic leachate corroded the stainless steel tank at the welded seams causing the leachate to leak out.

The results showed that the PP and PE fibres behaved in a very similar way, and there was no indication that either polymer had superior performance. However, with Polypropylene being the stronger and cheaper choice, it was felt to be the appropriate way forward.

Tests have also been carried out using an evolving leachate supplied periodically from Breighton Landfill Site over the decade. During the test the level of leachate has been maintained by recharging it with samples supplied from the site providing a continuously evolving leachate to create as authentic a test as possible. This test has now been running for over a decade and is the longest running leachate immersion test in the world.

## Conclusion

The majority of applications that call for the use of geosynthetics require the products to perform for a minimum expected time, commonly referred to as the design life. The rate degradation of geosynthetics used must be such that the required properties time to failure exceeds the requirements of the design. The available properties must exceed the required properties for the duration of the design.

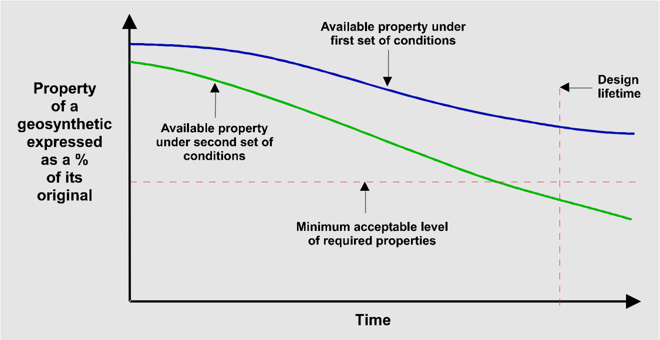


*Figure 6: Available and required properties as a function of time under two different sets of conditions.*

From the guidelines published by CEN and the established research on Geosynthetic durability it is possible to design a geotextile to fulfil its function for the duration of the design life. However it is imperative that the product selected uses an appropriate polymer formulation, is manufactured from fibres produced to a controlled specification and with fabric properties designed for long term use.

When selecting a geotextile a designer must take into account not only the mechanical and hydraulic properties of the geotextile at the point of manufacture, but the proven longevity of the properties in the site environment, both prior to installation and for the duration of the design. The consistency of the material provided is imperative if the tests performed in a laboratory are to be trusted.

The use of geotextiles manufactured from the bi-products of other manufacturing processes must be undertaken with extreme caution as the long term performance can never be fully known.

GEOfabrics HPS range has been engineered for long term durability, both index and performance testing has proven time and time again that the product is suitable for the most demanding civil engineering applications. Model specifications are available for specific applications, which include parameter for durability; these are available on request and can be downloaded from the GEOfabrics' web site –

*www.geofabrics.com*.

## Appendix

### Test Report – Orgreave Site Leachate Cocktail

| **Sample I.D. W/EX/94. Reference**<br>**Sample Data** | **6344**<br>**Sample 1** |
|---|---|
| pH Units | 3.1 |
| Suspended Solids | 85 |
| Total Alkalinity as $CaCO_3$ | Nil |
| Chloride as Cl | 275 |
| Total Sulphur as $SO_2$ | 42600 |
| Nickel as Ni | 4.19 |
| Chromium as Cr | 5.17 |
| Cadmium as Cd | < 0.01 |
| Copper as Cu | 0.62 |
| Lead as Pb | 1.78 |
| Zinc as Zn | 10 |
| Arsenic as As | <0.04 |
| Mercury as Hg | <0.05 |
| Total Nitrogen as N | 153 |
| Ammoniacal Nitrogen as N | 271 |
| Total Cyanide as CN | 0.27 |
| Thiocyanate as SCN | 27 |
| Sulphide as S | 1.68 |
| Phosphate as P | 72 |
| Chemical Oxygen demand | >1500 |
| Biochemical oxygen demand | 1030 |
| Total organic carbon | 3510 |
| Oil | 72 |
| Phenol index as $C_3H_5OH$ | 161 |

(Results expressed as mg/l except where stated)

### Test Report – Breighton Site Leachate Cocktail

| Sample Ref: E504240<br>Data | Sample after 1 month<br>Units |
|---|---|
| Conductivity 20C (uS/cm) | 12060 |
| pH Units | 10.0 |
| Nitrate | 0.50 |
| Nitrite | 0.10 |
| Nitrogen Ammoniacal | 482 |
| Nitrogen Total Oxidised | 0.6 |
| BOD Total +ATU | 250 |
| COD Total | 2620 |
| Chloride | 2660 |

(Results expressed as mg/l except where stated)

ENGINEERING
BULLETIN

Propex®
GEOSOLUTIONS

# EB405 - THE DURABILITY OF POLYPROPYLENE GEOTEXTILES

## Summary of Benefits

Polypropylene is a very durable polymer commonly used in aggressive environments including automotive battery casings, fuel containers and the like. Because of its excellent resistance to harmful chemical environments, the use of polypropylene to manufacture nonwoven geotextiles for waste containment systems is a beneficial use of this versatile polyolefin. Presently, nonwoven polypropylene geotextiles are used in more than 80% of all waste containment applications.

This Engineering Bulletin addresses the suitability of nonwoven polypropylene geotextiles for waste containment applications. Although primarily used in other civil engineering applications, woven polypropylene geotextiles are just as durable and, for some exposures, even more durable since the individual yarns used to manufacture the woven geotextiles have a much larger cross-sectional area than the fibers used to make nonwovens.

### Moisture Resistance

Unlike nonwoven polyester geotextiles, polypropylene does not absorb water nor does the presence of water have any effect whatsoever on tensile strength or other mechanical properties.

### Chemical Resistance (pH)

Extensive research has shown polypropylene is very resistant to certain concentrations of aggressive chemicals such as nitric acid, hydrochloric acid, sulfuric acid, sodium hydroxide and potassium hydroxide. Therefore, polypropylene geotextiles have been found acceptable in most solid and hazardous waste landfills.

### Leachate Compatibility

Many independent landfill leachate immersion tests conducted in accordance with EPA Method 9090 have shown no significant reduction in mechanical properties of our nonwoven polypropylene geotextiles.

### Biological Resistance

Since polypropylene does not support, attract, or deteriorate from fungal growths, Propex GEOTEX® nonwoven geotextiles are rot and mildew resistant.

### Temperature Stability

Polypropylene can withstand temperatures of at least 160 degrees Celsius (320 degrees Fahrenheit) without melting.

### Ultraviolet Resistance

Because polypropylene degrades during extended exposure to sunlight, Propex GEOTEX® nonwoven polypropylene geotextiles are produced with carbon black and other UV inhibitors. These additives allow our nonwoven polypropylene geotextiles to be exposed for up to 14 days between laydown and cover.

### Installation Survivability

Nonwoven polypropylene geotextiles made from staple (3 to 5 inch long) fibers in the needle punched manufacturing process have superior puncture and Mullen burst strength, which increase their installation survivability.

### Lifetime Prediction

When properly stabilized and buried, nonwoven polypropylene geotextiles have been expected to last for up to 200 years.

## Introduction

By virtue of its chemical composition, molecular structure, and thermodynamic properties, polypropylene is one of the most resistant organic raw materials known today. This is one of the reasons that over 80 percent of all geosynthetics are made from the polypropylene (Schneider 1989).

## Methods of Degradation

Chemical degradation of geotextiles is a result of environmental and polymer compositional factors. Regarding environmental factors, one can expect the greatest amount of degradation to occur, in general; (1) at relatively high temperatures (i.e.

>100” C), (2) in soils which are chemically active; (3) and when the geosynthetic is under stress. Key chemical degradation mechanisms that can be found in some soil and waste environments include oxidation, hydrolysis, and environmental stress cracking.

An oxidation reaction can either be initiated by ultraviolet radiation or thermal energy, but must have sufficient oxygen present. Since the geosynthetic will be buried in most applications, thermally activated oxidation is of most interest. Polypropylene oxidation is the reaction of free radicals within the polymer with oxygen, resulting in breakdown and/or degradation of the molecular chains and embrittlement of the polymer.

*(continued)*

Antioxidants are typically added to the polymer to prevent oxidation during processing and use. Broad classes of antioxidants often used in geosynthetics include phenolic and hindered amine light stabilizers (HALS). As the antioxidants are consumed, resistance of the polymer to oxidation will decrease. The rate of polymer oxidation is dependent on how much and what type of antioxidant is present initially, at what rate it is used, how well it is distributed within the polymer, and how fast it can be leached out by the flow of fluids, such as water, into and around the polymer. Environmental factors which affect the rate of oxidation include temperature and oxygen concentration. In soil, oxygen concentrations can vary from 21% in gravels at shallow depth to 1% in fine-grained soils at deeper depths. The presence of transition metal ions such as iron or copper may act as catalysts to accelerate the oxidation reaction. Thermal oxidation at typical in-soil temperatures appear to be quite slow. (Allen and Elias, 1996.)

The stabilizers and potentially the resin carriers for the stabilizer additive package represent the only small fraction of the geotextile which is not 100% polypropylene.

## Toxicology

Polypropylene is biologically inert and used for packaging food intended for human consumption (i.e., yogurt containers, Tupperware® , etc.). To ensure that the processing performed does not alter these characteristics, skin and mucous laboratory tests have shown that polypropylene does not cause irritating effects. An extensive series of repeat insult patch testing in humans and many years of extensive use in diverse products such as infant diapers, feminine hygiene products, and surgical fabrics have confirmed that adverse effects on the skin should not be expected. Furthermore, polypropylene is considered to be without significant oral toxicity. When tested by the Food and Drug Administration's specific methods, polypropylene is well below the specified limits of extractables. In addition, the United States Pharmacopoeia (U.S.P.) specifies oral toxicity testing on plastics intended for medical uses. Polypropylene materials have never caused toxicity when tested according to the U.S.P. method (MATAFAXX, 1992).

## Moisture

Polypropylene is a paraffinic hydrocarbon and does not adsorb water like the polyamides polyester (PET) or nylon. The moisture gain of polypropylene fibers is insignificant and water has no effect on tensile strength and other mechanical properties.

Therefore, water alone does not cause any noticeable degradation in polypropylene fibers. Fibers subjected to boiling water or steam for long periods show no loss of strength (Cook, 1984).

## Ultraviolet (UV) Resistance

Like polyethylene, polypropylene is attacked by atmospheric oxygen and the reaction is stimulated by sunlight. Polypropylene fibers will deteriorate on exposure to light, but may be effectively protected by stabilizers (Cook, 1984). Without site-specific environmental conditions, Propex recommends a maximum exposure period of 14 days between laydown and cover of all of our nonwoven geotextiles. This is in compliance with guidelines issued by the US Environmental Protection Agency (EPA 1993). If the maximum exposure period will exceed these guidelines, we recommend that the installer either (1) utilize an economical, lightweight woven geotextile, such as Propex GEOTEX® 135ST as a temporary cover; or (2) install a test roll on the most southward facing slope and remove samples every 30 days of actual exposure to evaluate possible strength loss. Site personnel should carefully cut a representative roll-width by 5-foot sample (1.5m); label with contact name, address and telephone number; period of exposure; a roll number, style and project name; place in a strong black wrap and send to a laboratory. It is the responsibility of the Construction Quality Assurance (CQA) engineer to identify the index tests required to determine the actual strength retention.

Three different Propex nonwoven geotextiles were exposed in accordance with ASTM D 5970-96, Deterioration of Geotextiles From Outdoor Exposure, starting June 15, through July 15, 1996 in Northwest Georgia, USA. Machine direction (MD) and cross- machine direction (CMD) coupons for each style were attached to a test frame oriented to 45 from horizontal and facing due south. Unexposed coupons were retained for control testing. After 30 days exposure, five specimens from each coupon were tested for tensile strength and elongation in accordance with ASTM D 4632. The exposed results were then compared to the unexposed test results and the percent strength retained was calculated. The results are shown in Table 1 below:

| Product | Percent Strength Retained | | |
|---|---|---|---|
| Style | MD | CMD | Average |
| GEOTEX® 801 | 96 | 85 | 91 |
| GEOTEX® 1601 | 90 | 89 | 90 |

Table 1 - Results of 30-Day Outdoor Exposure Tests

## Temperature Stability

### High Temperatures

The mechanical properties of the fibers deteriorate as temperature increases, but polypropylene performs better than polyethylene in this respect. The softening point of polypropylene fibers is approximately 150 C (300 F), and the fibers "melt" at 165 C (330 F). The softening and melting points of polypropylene are determined in the way which crystallinity has been influenced during and after spinning. Shrinkage of polypropylene fibers depends greatly

*(continued)*

upon the treatment the fiber receives during processing. In boiling water, monofilament yarns may shrink as much as 15 percent after 20 minutes; multifilament and staple fibers only shrink between 0 and 10 percent (Cook, 1984). However, polypropylene exhibits a moisture regain of only 0.01 to 0.1 weight percent (Cox, 1994).

### Flammability

Polypropylene is a hydrocarbon and will burn. On being exposed to a flame, however, the fiber melts and draws away from the flame, extinguishing itself. When tested in accordance with BS2963, polypropylene fabrics are self-extinguishing and therefore of low flammability, (as defined in BS3121). Construction, additives, finishes, and the presence of other fibers have a considerable influence on the burning characteristics of any particular fabric or structure. For the purpose of fire insurance, polypropylene fabric is included in the same class as wool (Cook, 1984).

### Low Temperature

The low temperature flexibility of polypropylene is excellent for most applications. Propex polypropylene geotextiles retain normal flexibility from -40C to 150C (-40F to 302F). Below -40F, polypropylene can become less flexible and not suitable for all applications.

## Biological Resistance

### Insects

Polypropylene cannot be digested by insect and related pests, such as white ants, dermestid beetles, silverfish, and moth larvae. Polypropylene fiber is not liable to attack unless it becomes a barrier beyond which the insect much pass to reach an objective. In this case, the insect may cut through the fiber without ingesting it. Furthermore, polypropylene does not attract nor is it a food source for insects or rodents. As stated earlier, much like humans, it is believed that rodents would not be adversely affected by ingesting small quantities of polypropylene.

### Micro-Organisms

Polypropylene fibers will not support the growth of mildew or fungi. Some micro-organisms, however, may even grow on the very small amount of contaminants which may develop on the surface of fibers or yarns in use. Such growth has no effect on the strength of any materials made from polypropylene fiber. Similarly, polypropylene is an inert resin which does not support or attract fungal growths and does not deteriorate due to fungal presence (Cox, 1994).

## Chemical Resistance

Polypropylene is inert to a wide range of chemicals. Its resistance and susceptibilities are similar to those of polyethylene, but its higher crystallinity tends to make it more resistant that polyethylene to those chemicals which degrade polyolefin fibers. There is no known solvent for polypropylene at room temperature (Cook, 1994). Extensive information on the chemical resistance of polypropylene shows that it is very resistant to acids and alkalis at room temperatures (Ahmed, 1994). For example, polypropylene is acceptable at room temperature for use with the following, which covers the entire measurable pH range (Cox, 1994):

| CHEMICAL (CONCENTRATION) | PH LEVEL |
|---|---|
| NITRIC ACID - UP TO 39% | 1 |
| HYDROCHLORIC ACID - UP TO 37% | 1 |
| SULFURIC ACID - UP TO 96% | 1 |
| SODIUM HYDROXIDE - UP TO 70% | 14 |
| POTASSIUM HYDROXIDE - 10%, 25% | 14 |

Table 2 - Chemical Resistance of Polypropylene at Various pH Levels

However, polypropylene is vulnerable to the following substances: highly oxidizing substances (peroxide), concentrated nitric acid (>40%), concentrated sulfuric acid, chlorosulphonate acid, pure halogen, certain chlorinated hydrocarbons (halogenated hydrocarbons), and certain aromatic hydrocarbons (Schneider, 1989).

Polypropylene does not show any tendency to develop surface cracks when subjected to stresses in the presence of detergents or other substances (Cook, 1994). Polypropylene is extremely stable chemically due to its structural properties as a hydrocarbon construction. Extensive studies testing the chemical stability of polypropylene when exposed to hundreds of organic and inorganic chemicals have shown it to be highly stable against: acids, alkalis, aqueous solutions of inorganic salts, detergents, oils and greases, and gasoline and lubricants. Actual test results are shown on the next page:

| CHEMICAL | % CHANGE IN MASS PER UNIT AREA* | |
|---|---|---|
| | 23°C | 60°C |
| SULFURIC ACID (98%) | -0.2 | -0.2 |
| NITRIC ACID, FUMING | -0.1 | - |
| SODIUM HYPOCHLORITE (20%) | 0.1 | -2.1 |
| GASOLINE | 4.8 | 6.6 |
| BENZENE | 3.4 | 0.6 |
| XYLENE | 7.0 | 0.3 |
| MENTHYLENE CHLORIDE | 5.5 | 1.6 |
| CARBON TETRACHLORIDE | 13.5 | 0.9 |
| TURPENTINE | 9.5 | 10.5 |
| TRANSFORMER OIL | 0.4 | 14.9 |

Table 3 - Physical Effecst of Chemicals on Polypropylene (Schneider)

*The weight change as listed is due to the sum of the effects of swelling and dissolution

Propex, in accordance with ASTM D 543, has evaluated the chemical compatibility of our nonwoven geotextiles with JP4 jet fuel. A sample of Propex GEOTEX® 451 (4.5 oz/yd2 or 150 g/m2) nonwoven geotextile was exposed to the fuel for 7 days at room temperature. It was then evaluated for retention of grab tensile properties in accordance with ASTM D 4632. The results are as follows:

| Product | Percent Strength Retained | | |
|---|---|---|---|
| Style | MD | CMD | Average |
| GEOTEX® 451 | 91.5 | 87% | 89 |

Table 4 - Results of JP4 Jet Fuel Tests

## Landfill Leachate

Propex has performed several studies on the compatibility of our polypropylene nonwoven geotextiles with leachates and in various pH solutions commonly encountered in soil or solid waste applications. Since the evaluation of long-term chemical aging of nonwoven geotextiles is nearly impossible due to the inherent stability of the polymer, laboratory immersion tests were conducted at elevated temperatures (50C) to accelerate behavior. Variables such as temperature, moisture, and oxygen content were controlled in the lab and samples were removed at 30-, 60-, 90-, and 120-day intervals. The results of these tests are shown in Table 5 (Boschuk, 1993 and Narejo, 1995).

| PROPERTY | TEST METHOD | % CHANGE AFTER 120 DAYS @ 50°C | |
|---|---|---|---|
| | | GEOTEX®451* | GEOTEX®1601* |
| GRAB TENSILE | ASTM D-4632 | 0.88 | -1.14 |
| TRAPEZOIDAL TEAR MD | ASTM D-4533 | -23.79 | 54.82 |
| TRAPEZOIDAL TEAR CMD | ASTM D-4533 | -16.28 | -7.48 |
| PUNCTURE | ASTM D-3786 | -8.42 | -6.6 |
| PERMITTIVITY | ASTM D-4491 | -15.61 | -7.46 |

Table 5 - Results of Chemical Compatibility Testing

## Lifetime Prediction

Using the assumption that kinetics double with every 10°C rise in temperature, polypropylene embrittlement would not take place for 45 years in a 30°C landfill under anaerobic conditions (Wheat, 1992). Since the first geotextile installation occurred in North America in 1958, it is not possible to demonstrate 100-year durability with ‘real-time’ success stories. As a result, the Geosynthetic Research Institute (GRI) designed a series of four accelerated laboratory incubation protocols to demonstrate aging progression in polyethylene geomembranes. The ‘durability’ (e.g. the prevention of aging) of polyethylene and polypropylene is typically extended by manufactures by adding antioxidants to the resin during processing. This prevents oxygen from attacking the polymer itself. Since it is well established that the engineering properties are not reduced until the antioxidants are completely depleted, tests were conducted at GRI to measure the amount of time to initiate polymer degradation.

Series III samples were exposed to water on top and air below with a compressive stress of 260 kPa (37.7 psi). This test series is intended to model leachate or surface water collection systems in a waste containment facility. Since polyethylene and polypropylene geotextiles behave similarly to the materials in this study, the predicted antioxidant lifetime at 25°C for the specimens evaluated is approximately 120 years, (Hsuan and Koerner, 1985).

In a separate study, properly stabilized polypropylene geotextiles have been estimated to have a functional longevity of nearly 200 years in an oceanic or marine application (Wisse & Birkenfeld, 1982).

## Installation Survivability

Nonwoven polypropylene geotextiles have higher puncture and Mullen burst strength than polyester nonwoven geotextiles which make them very resistant to installation stresses and enhance their construction/installation survivability success.

| PROPERTIES | TEST METHOD | MARV | |
|---|---|---|---|
| | | PET | PP |
| MASS/UNIT AREA | ASTM D 5261 | 8.0 | 8.0 |
| PUNCTURE STRENGTH | ASTM D 4833 | 100 LBS | 140 LBS |
| MULLEN BURST | ASTM D 3786 | 380 PSI | 440 PSI |

Table 6 - Selected Strengths of Typical Needle-Punched Nonwoven Geotextile

The structure of the needle-punched, staple fiber nonwoven has also proven to be more resistant to installation damage testing, such as puncture and Mullen burst than continuous filament spunbond nonwovens geotextiles. This is especially true for heat bonded spunbond geotextiles which are rarely used in waste containment applications due to their thin structure, limited permittivity, and limited resistance to damage.

## Conclusions

As previously stated, polypropylene is a very durable polymer commonly used in aggressive environments including automotive battery casings, fuel containers and the like. Because of its excellent resistance to harmful chemical environments, the use of polypropylene to manufacture nonwoven geotextiles for waste containment systems is a beneficial use of this versatile polyolefin. Presently, needle-punched nonwoven polypropylene geotextiles are used in more than 90% of all waste containment applications. Current knowledge on available polymers points to polypropylene being the geotextile polymer of choice for the longevity of waste containment systems.

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Material Behaviour

# Chemical resistance and transmissivity of nonwoven geotextiles in waste leachate solutions

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**Abstract**

Eight types of polyester (recycled or new) and polypropylene (PP) nonwoven geotextiles to be generally used in Korean waste landfills were adopted as test materials. The modified EPA 9090 test method was applied to compare the chemical resistance in pH 3, 8 and 12 solutions and waste leachate solution. The immersion conditions were 30–180 days at 25, 50, 80 °C, respectively. Chemical resistance of these nonwoven geotextiles was estimated by the average retention of tensile properties after exposure in the above chemical solutions. Finally, transmissivity of the geotextiles for drainage were slightly decreased in pH 3 and pH 8 solutions but clearly decreased in the strong alkaline solution, pH 12.

*Keywords:* Nonwoven geotextiles; Waste landfills; Modified EPA 9090 test method; Chemical resistance; Waste leachate solution; Retentions of tensile properties; Transmissivities

## 1. Introduction

Nonwoven geotextiles are widely used in waste landfills as materials having the functions of protection, separation, filtration and drainage etc. [1–3].

In general, polyester or polypropylene nonwoven geotextiles are the most important geosynthetic materials that are installed above the geomembranes for protection and drainage [4,5]. These geotextiles are exposed to chemicals such as acidic or alkaline solutions, especially leachate solutions, until the reclamation of waste is completed [6,7].

In Korea, most of the waste in sanitary landfills is wet food waste and the waste solutions would have acidic or alkaline properties during the landfill periods. Because of these properties of waste solutions, it is very important to assess the chemical resistance of nonwoven geotextiles and other geosynthetics to the leachate solutions from different waste landfills [8–10].

In this study, eight types of polypropylene and polyester nonwoven geotextiles/geotextile composites to be generally used in Korean waste landfills were adopted as test materials.

The modified EPA 9090 test method was applied to the geotextiles to compare the chemical resistance in the leachate solutions and in solutions of pH 3, 8 and 12. The exposure conditions were 30, 60, 90, 120, 150, 180 days at 25, 50, 80 °C, respectively.

Chemical resistance of these nonwoven geotextiles was estimated by the average retention of tensile properties after exposure in the above chemical solutions.

## 2. Experimental

### 2.1. Preparation of geotextiles

Table 1 shows the specification of all the geotextiles to be used in this study. For the purpose of enhancing

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Table 1
Specifications of geotextiles

| Specifications | | |
|---|---|---|
| Geotextiles | Weight (g/m$^2$) | Composition |
| GT-1 | 600 | PP staple fiber (no carbon black): needle punched |
| GT-2 | 1000 | |
| GT-3 | 600 | Recycled polyester staple fiber(contains carbon black): needle punched |
| GT-4 | 1000 | |
| GT-5 | 600 | Polyester filament fiber (no carbon black): spunbonded |
| GT-6 | 600/400 | Duplicated GT—PP/Recycled polyester GT[a]: needle punched |
| GT-7 | 400/600 | 3-layer structure GT[b]: needle punched |

[a] PP nonwovens that do not contain carbon black and polyester nonwovens that contain carbon black were used to manufacture the duplicated GT.

[b] [GT/Drainage layer/GT] structure, which recycled polyester fibers were used in drainage layer as filled fibers in this study.

the stability of PP geotextiles to ultraviolet light, geotextile composites were produced by combining polyester geotextile from recycled fibers and PP geotextile. Fig. 1 and 2 show a schematic diagram and photographs of duplicated geotextile and its manufacturing method, respectively. Fig. 3 shows a photograph of the 3-layer structure geotextile.

### 2.2. Estimation of resistance to chemical degradation

Due to the lack of widely accepted experimental procedures to assess the resistance of geotextiles to chemical degradation, EPA 9090 Test Method for Chemical Resistance of FML (Flexible Membrane Liner) that was proposed by American Environment Protection Agency was applied.

In this study, a modified EPA 9090 test method was performed by immersing the materials in solutions at 25, 50, 80 deg;C and taking a sample of each material every 30 days for 180 days, for measurement of tensile strength test in the machine direction (MD) in accordance with ASTM D 4632.

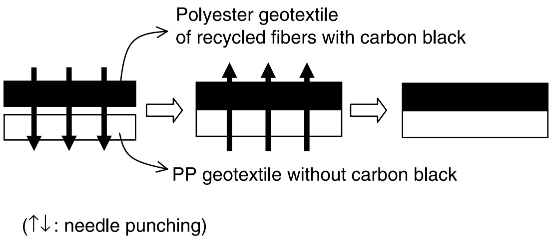

Fig. 1. Schematic diagram of manufacturing process duplicated geotextile by needle punching.

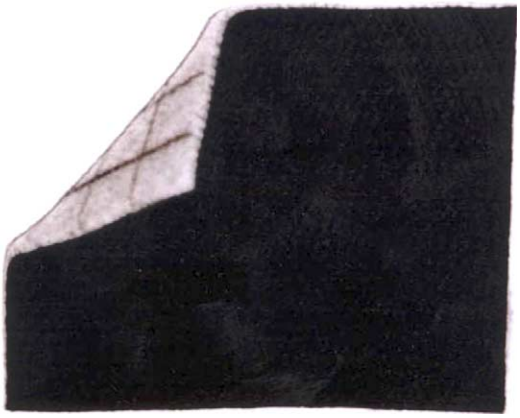

Fig. 2. Photograph of duplicated geotextile.

The general refuse in a landfill site disintegrates during filling of the site and produces a strong acid leachate solution, while other solid refuse becomes oxidized and when broken down can produce a strong alkaline leachate solution. This experiment used buffer solutions of pH 3, 8 and 12 and the final waste leachate solution of pH 8 from the real waste landfill. In real conditions, the pH value of waste leachate solution changes from pH 3→pH 12→pH 8. The period of this change is almost 3 months and the pH value of the final waste leachate solution is 8. To consider this situation, we chose the above pH solutions for test.

## 3. Results and discussion

### 3.1. Tensile property

Table 2 shows the tensile strength of geotextiles that are generally used in Korean waste landfills. For PP staple fiber geotextiles, GT-2 has higher tensile strength than GT-1, but for recycled polyester staple fiber geotextiles, both GT-3 and GT-4 have lower tensile strength than GT-1 and GT-2.

GT-5 has higher tensile strength than GT-2 and this is a typical characteristic of the spunbonded nonwoven

Fig. 3. Photograph of 3-layer structure geotextile.

Table 2
Tensile properties of geotextiles

| Tensile property | | |
|---|---|---|
| Tensile property geotextiles | Strength (kg) | Strain (%) |
| GT-1 | 248.4 | 78.5 |
| GT-2 | 283.2 | 74.3 |
| GT-3 | 166.8 | 38.3 |
| GT-4 | 242.5 | 32.1 |
| GT-5 | 326.3 | 28.6 |
| GT-6 | 321.5 | 58.4 |
| GT-7 | 285.7 | 47.2 |

material. These materials have higher tensile strength than the needle punched nonwovens for the same weight because of the strong filament entanglement effects.

The composite geotextiles, GT-6 and GT-7, show higher tensile strength than GT-2 and GT-4 for the same weight.

Tensile strengths of geotextile composites were higher than for PP staple fiber geotextile at the same weight and this is due to the combined effect with different fiber densities, duplicated structure and double needle punching effects etc.

GT-8 is used only for drainage and shows the lowest tensile strength of the 8 geotextiles, which is due to its structure.

### *3.2. Resistance to chemical degradation and transmissivity*

Figs. 4–7 show the average retention of tensile properties of geotextiles in pH 3, 8 and 12 and waste leachate solutions.

In Fig. 4, GT-1–2 and GT-5–8 show an increase of tensile strength at 25 and 50 °C but show a decrease of tensile strength at 80 °. It is seen that tensile strength is increased by the reinforcement effect due to the physically absorbed water among fibers of geotextiles. This reinforcement effect decreased due to the evaporation of this water at high temperature and the tensile strength decreased.

GT-3–4 show a decrease of tensile strength for all the temperatures and it is thought that this was due to

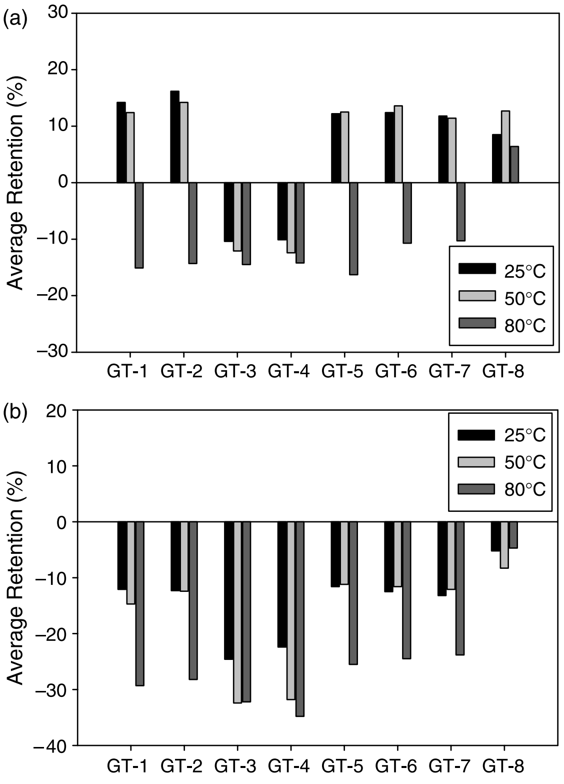

Fig. 4. Average retention of tensile properties of geotextiles in pH 3 solution, 180 days; (a) tensile strength, (b) tensile strain.

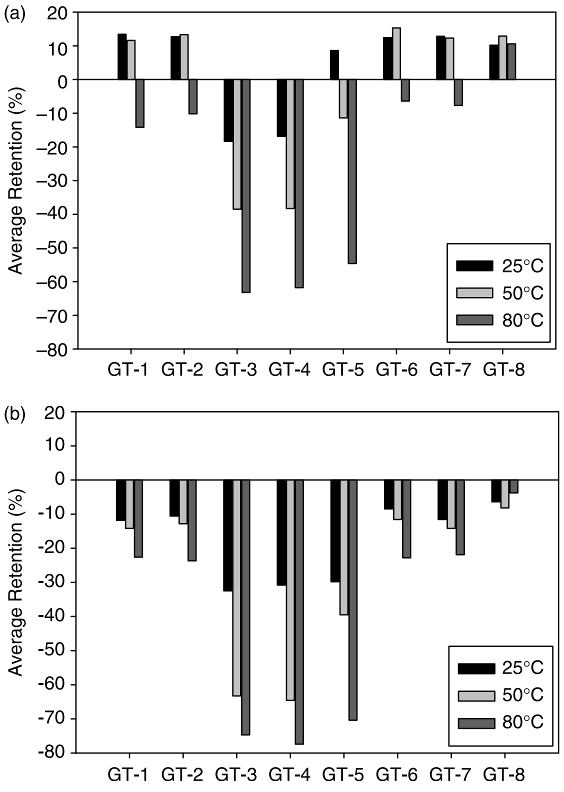

Fig. 5. Average retention of tensile properties of geotextiles in pH 8 solution, 180 days; (a) tensile strength, (b) tensile strain.

the thermal degradation of recycled polyester and weak tensile properties of recycled polyester fiber itself.

Tensile strain of all geotextiles decreased for all the temperatures.

In Fig. 5, GT-1–2 and GT-6–8 show the same tendency as shown in Fig. 2 but all polyester fiber geotextiles, GT-3–5, show a decrease of tensile strength at all temperatures and this was due to the hydrolysis effects in weak alkaline solution, pH 8, on polyester fibers. However, PP geotextiles were not influenced by hydrolysis. The decrease of strength for polyester geotextiles was clearly observed with temperature increase.

Tensile strain of all geotextiles decreased at all temperatures the same as in Fig. 4.

In Fig. 6, GT-1–2 and GT-8 show the same tendency as shown in Figs. 4–5 but all polyester fiber geotextiles, GT-3–5, and geotextile composites for which the exposure layer was composed of recycled polyester fiber show a decrease of tensile strength at all temperatures. This was due to the severe hydrolysis effects of strong alkaline solution, pH 12, on polyester fibers. Recycled polyester fiber geotextiles, GT-3–4, show a significant decrease of tensile strength by this hydrolysis effect under all temperature ranges.

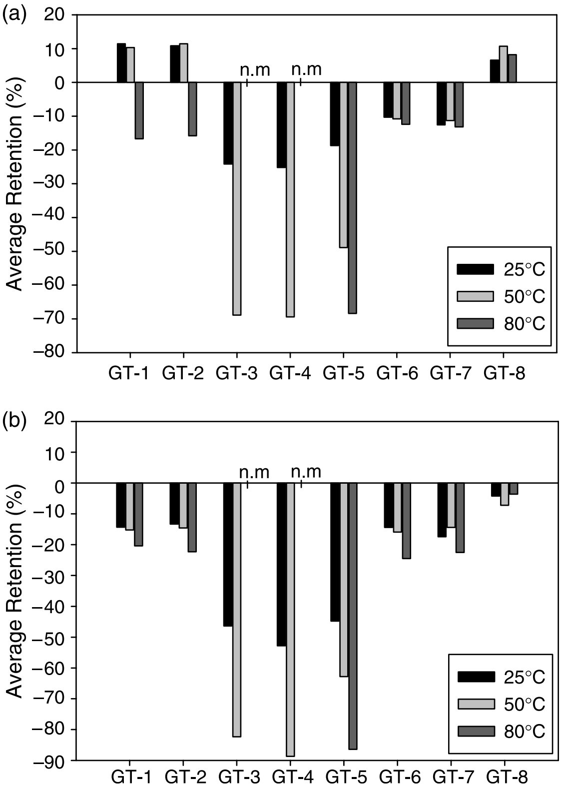

Fig. 6. Average retention of tensile properties of geotextiles in pH 12 solution, 180 days; (a) tensile strength, (b) tensile strain (where n.m. means the state which cannot measure the tensile property).

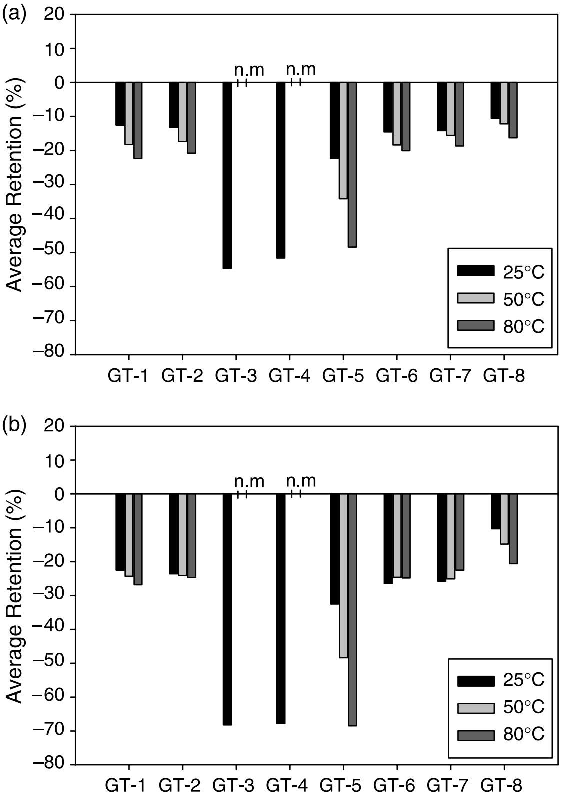

Fig. 7. Average retention of tensile properties of geotextiles in waste leachate solution, 180 days; (a) tensile strength, (b) tensile strain (where n.m. means the state which cannot measure the tensile property).

The tensile strain of all geotextiles decreased for all temperatures, the same as in Fig. 5.

In Fig. 7, all geotextiles show a decrease of tensile properties in waste leachate solution but the degree of damage for PP geotextiles, GT-1–2 and GT-6–8 was less than for polyester geotextiles.

Tensile properties of GT-3–4 at 50 and 80 °C were not measured because of severe damage of the specimens, as shown in Fig. 8. From this, it was seen that polyester geotextiles in alkaline waste leachate solution could be damaged seriously and this may be an important cause of reduction in performance for waste landfills.

Table 3 shows the transmissivity of GT-8, which was newly manufactured to apply as a drainage material to the slope and liner system of waste landfills. Transmissivity of GT-8 was only clearly decreased in the strong alkaline solution, pH 12, at high temperature.

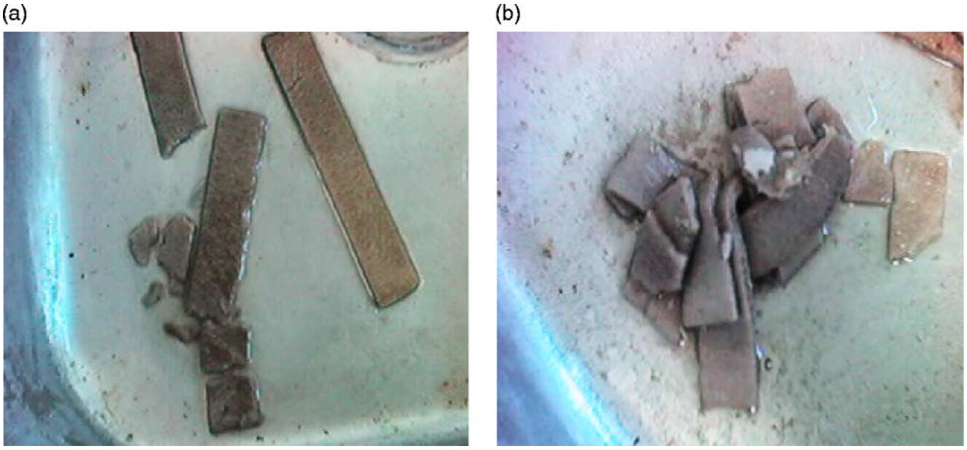

Fig. 8. Photographs of GT-4 after 180 days immersion in waste leachate solution; (a) 50, (b) 80 °C.

It is thought that recycled polyester fibers were used as filled fibers in GT-8 and these fibers would be decomposed in high alkaline solution. This may not occur if we use a fiber more stable to high alkaline solution instead of recycled polyester fibers.

## 4. Conclusion

Geotextiles and geotextile composites, which are used in the slope and liner system of waste landfills, were subjected to various chemical conditions and the following conclusions were made after assessing the experimental results.

- GT-2 has higher tensile strength than GT-1 but both recycled polyester staple fiber geotextiles, GT-3 and GT-4, have lower tensile strength than GT-1 and GT-2. Tensile strength of geotextile composites, GT-6 and GT-7, were higher than PP staple fiber geotextile, GT-2, and recycled polyester staple fiber geotextile, GT-4, for the same weight.
- GT-1–2 and GT-5–8 show increase of tensile strength at 25 and 50 °C but show decrease of tensile strength at 80 °C in pH 5. GT-3–4 show decrease of tensile strength at all temperatures.
- GT-3–4 show significant decay of tensile properties over the temperature range in pH 12. All geotextiles show decrease of tensile properties in waste leachate solution and, especially, tensile properties of GT-3–4 at 50 and 80 °C were not measured because of severe damage to the specimens.
- Transmissivity of GT-8 was slightly decreased in pH 5 and pH 8 solutions but clearly decreased in the strong alkaline solution, pH 12.

Table 3
Average retention of transmissivity of GT-8 after 180 days in immersion solution

| Immersion Solution | Average retention of transmissivity ($m^3$/s-m) | | |
|---|---|---|---|
| | 25 °C | 50 °C | 80 °C |
| PH3 | 100 | 98.4 | 97.6 |
| PH8 | 100 | 96.4 | 96.2 |
| pH12 | 92.2 | 86.7 | 82.9 |
| Leachate | 98.4 | 94.6 | 92.7 |

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A Final Report:

# Laboratory Testing of
# Ten Cate Nicolon S600 Nonwoven Geotextile
# EPA Method 9090A

May 2003

Submitted to:

**Ten Cate Nicolon**
365 South Holland Drive
Pendergrass, GA 30567

Attn: **Ms. Melissa Medlin**

Submitted by:

**TRI/Environmental, Inc.**
9063 Bee Caves Rd.
Austin, Texas  78733

TRI/ENVIRONMENTAL, INC.
A Texas Research International Company

May 5, 2003

**Ms. Melissa Medlin**
**Ten Cate Nicolon**
365 South Holland Drive
Pendergrass, GA 30567

Dear Ms. Medlin

TRI/Environmental, Inc. (TRI) is pleased to present this Final Report for a geotextile chemical compatibility study performed in general accordance with EPA Method 9090A.

TRI is very pleased to be of service to Ten Cate Nicolon. Please call me if you have any questions or require any additional information.

Respectfully submitted,

Jarrett A. Nelson

Jarrett A. Nelson
Special Projects Manager
Geosynthetic Services Division

# FOREWORD

The testing reported herein is based upon accepted industry practice as well as the test method listed. TRI/Environmental Inc. (TRI) neither accepts responsibility for nor makes claim as to the final use and purpose of the materials tested.

Tests were performed under laboratory conditions and not under actual usage conditions. TRI can give no conclusions as to the serviceability, life expectancy or general durability of the products tested when used in a lining and/or leachate collection system.

## 1.0 INTRODUCTION

This report describes the work performed by TRI/Environmental, Inc. (TRI) to determine the chemical compatibility of one geotextile product with one waste leachate. The objective was to determine the resistance of the geotextile to changes caused by exposure to leachate. Changes in physical, mechanical and hydraulic properties were measured after exposure to the leachate at 23°C and 50°C for 30, 60, 90 and 120 days. Exposures were performed in accordance with the exposure regimen specified in United States Environmental Protection Agency (EPA) Method 9090A.

All samples were logged in and all testing performed under TRI log number E2176-87-10. Methods, results and discussion are provided in the sections which follow. Test results are provided in the Tables of Results which accompany this report.

## 2.0 METHODS

### 2.1 Materials

The material selected for evaluation in this chemical compatibility study was Ten Cate Nicolon. S600 polypropylene staple fiber nonwoven needlepunched geotextile.

### 2.2 Leachate

The waste leachate used was supplied by TRI and was a synthetic MSW leachate approximating the PaDER leachate recipe.

### 2.3 Exposure Conditions

Geotextile specimens were exposed to the waste leachate following the specifications of EPA Method 9090A as they relate to exposure to waste fluids. The tanks used for these exposures were maintained at 23 ± 2°C and 50 ± 2°C throughout the 120-day exposure period. Tanks were constructed from chemically resistant glass fitted with stirrers. The 50°C tanks were heated with a circulating hot water heat exchanger system. They were also sealed with a lid, and a reflux condenser was installed to minimize loss of volatile leachate components.

### 2.4 Testing Procedures

Table 1 lists tests performed on the geotextile. The number of test replicates was doubled for baseline determinations on unexposed material.

**Table 1. Tests performed on TNS - Nevown, Inc. nonwoven geotextile**

| Test or Physical Property | Method | Number of replicate specimens |
|---|---|---|
| Dimensions and weight | EPA 9090 | 2 readings |
| Grab Tensile Strength | ASTM D 4632 | 3 MD & TD readings |
| Grab Tensile Elongation | ASTM D 4632 | 3 MD & TD readings |
| Trapezoidal Tear Strength | ASTM D 4533 | 3 MD & TD readings |
| Puncture Resistance | ASTM D 4833 | 3 readings |
| Mullen Burst | ASTM D 3786 | 3 readings |
| Permittivity | ASTM D 4491 | 3 readings |

## 3.0 RESULTS AND DISCUSSION

Test results are presented in the Test Results section which is included with this report. Test results are presented in tabular form as well as graphical form.

In considering these results, it must be determined through engineering judgment whether observed differences in the value of test results measured before and after immersion are due to product variability, unidentified factors relating to the test procedure, or leachate interaction with the product. Any significant chemical interaction with leachate would be expected to result in degradation trends which are consistent across the various properties being evaluated, and not isolated to one set of test results only. However, with each type of material there may be specific properties which are highly sensitive to leachate-induced effects. These factors must be considered in evaluating the various test results for a given product.

Also of critical importance is the issue of product variability. With nonwoven geotextiles, a range of physical and mechanical index test values covering 20% or more of the average is not uncommon. This can be traced to variability inherent in the product, and the randomness associated with the onset of failure under the specified testing conditions. However, in chemical compatibility testing the statistical sampling of a broad range of manufactured product is not possible. Therefore, the small size of the sample population tested at each time point must be taken into consideration. The criteria to be applied in evaluating data measured before and after leachate immersion should be that property changes, if observed, are consistent and so great that product variability and experimental factors can be ruled out.

In this report, standard deviations (STD) are reported for measurements involving three or more replicate specimens. In statistics, the standard deviation is defined as root of the mean squared deviations of individual test results about the mean value. The standard deviation is a quantitative measure of variability within a group of measurements.

One related measure of variability observed within a sample set, relative to the magnitude of the mean value itself, is the *coefficient of variation or variance* (COV). The coefficient of variance is defined as the standard deviation divided by the mean associated with a group of specimens, and may be expressed as a percentage. The COV provides an indication of what proportion of the mean value may be attributable to random experimental factors or product variability. It is useful to consider apparent changes in property values against the criterion of COV since observed changes which fall below the COV may not be significant. This approach was used in preparing the tables in the next section.

The term *range* refers to the difference between the extreme highest and lowest points within a group of measured values. Considering range as a percentage of the mean values provides another measure of variability within a dataset.

In the tables, the high and low extremes for percentage change in mean values are listed for comparison against COV and range as a percentage of mean from the baseline sample group. The high and low percentage changes are the extremes from data measured at 30, 60, 90 and 120 days.

## Ten Cate Nicolon S600 nonwoven polypropylene geotextile

Table 2 illustrates the range of variability in baseline data compared with some of the observed changes in average test values measured after immersion for the geotextile.

**Table 2. Baseline coefficients of variation and range of percentage change results for Nicolon geotextile**

| Test | Baseline COV (%)* | Baseline Range as % of Mean* | High Observed % Change | Low Observed % Change |
|---|---|---|---|---|
| Grab Tensile Strength (MD) | 15 | 48 | 20 | -3 |
| Grab Tensile Elongation @ Maximum Load (MD) | 9 | 29 | -12 | -24 |
| Trapezoidal Tear Strength (MD) | 17 | 52 | -1 | -10 |
| Puncture Strength | 19 | 61 | 22 | -9 |
| Mullen Burst Strength | 9 | 26 | 13 | 1 |

**Table 2. Baseline coefficients of variation and range of percentage change results for Nicolon geotextile**

| Test | Baseline COV (%)* | Baseline Range as % of Mean* | High Observed % Change | Low Observed % Change |
|---|---|---|---|---|
| **Permittivity** | **10.01** | **34.2** | **12.59** | **-2.52** |

## 4.0 CONCLUSION

Grab tensile strength was observed to increase slightly with a corresponding loss in strain. This may have been related to hydration and relaxation of the "oriented" geotextile fibers when placed in the exposure baths. In addition, the observed changes were observed to fall within the baseline population ranges (see Table 2).

While other changes in certain measured physical and mechanical properties were noted for the geotextile, the observed variances were random and are believed to be the effects of product variability and experimental factors.

TRI/Environmental, Inc. is pleased to have been selected to participate in this project. We trust that the information provided in this report meets your requirements for technical documentation of this chemical compatibility study. Please do not hesitate to call if you have any questions or require any additional information.

Respectfully submitted,

Jarrett A. Nelson

Jarrett A. Nelson
Special Projects Manager
Geosynthetic Services Division

TRI/Environmental, Inc.

# APPENDIX:

# EPA METHOD 9090A TEST RESULTS

## Ten Cate Nicolon S600 Nonwoven Geotextile TEST RESULTS

**Dimensions**

**TRI LOG NUMBER: E2176-87-10**

## TABLE OF CHEMICAL COMPATIBILITY TEST RESULTS
## Client: Ten Cate Nicolon

Report Date: May 2003
TRI Log Number: E2176-87-10

Exposure Time and Temperature

### GEOTEXTILE: S600 POLYPROPYLENE NONWOVEN EXPOSED TO PADER MSW SYNTHETIC LEACHATE

| | | 30 Day | | | 60 Day | | | 90 Day | | | 120 Day | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Test Parameters | Temp. | Baseline | Exposed | % Change | Baseline | Exposed | % Change | Baseline | Exposed | % Change | Baseline | Exposed | % Change |
| Thickness (mils) | 23C | 92 | 95 | 3.3 | 99 | 103 | 4.0 | 88 | 94 | 6.8 | 95 | 102 | 7.4 |
| | 50C | 105 | 117 | 11.4 | 92 | 97 | 5.4 | 106 | 126 | 18.9 | 100 | 108 | 8.0 |
| Length (inches) | 23C | 8.01 | 7.95 | -0.7 | 8.03 | 7.98 | -0.6 | 8.03 | 8.02 | -0.1 | 8.03 | 7.99 | -0.5 |
| | 50C | 8.03 | 7.94 | -1.1 | 8.03 | 7.92 | -1.4 | 7.99 | 7.82 | -2.1 | 8.04 | 7.93 | -1.4 |
| Width (inches) | 23C | 4.04 | 4.05 | 0.2 | 4.04 | 4.04 | 0.0 | 4.02 | 3.99 | -0.7 | 3.99 | 4.00 | 0.3 |
| | 50C | 4.01 | 4.00 | -0.2 | 4.00 | 4.00 | 0.0 | 3.97 | 3.92 | -1.3 | 4.02 | 3.97 | -1.2 |
| Mass (g) | 23C | 4.82 | 4.86 | 0.8 | 5.15 | 5.10 | -1.0 | 4.81 | 4.81 | 0.0 | 4.85 | 4.84 | -0.2 |
| | 50C | 5.46 | 5.49 | 0.5 | 4.84 | 4.79 | -1.0 | 6.09 | 6.03 | -1.0 | 5.17 | 5.38 | 4.1 |

# EPA METHOD 9090A TEST RESULTS

## Ten Cate Nicolon S600 Nonwoven Geotextile TEST RESULTS

## TRI LOG NUMBER: E2176-87-10

## NOTE ON TEST RESULTS

**This section includes generated test data provided in both tabular and graphical form. Each graph is represented by a series of "I" beam plots. Each "I" beam represents a single test population and illustrates the high and low value as the end points, and the mean as a central box on the beam.**

**At each testing period, two "I" beams are shown. The left beam represents the 23$^{o}$C exposed specimens while the right beam represents the 50$^{o}$C specimens. The initial "I" beam represents the baseline or unexposed test specimens.**

## TABLE OF CHEMICAL COMPATIBILITY TEST RESULTS
## Client: Ten Cate Nicolon

Report Date: May 2003
TRI Log Number: E2176-87-10

|  |  | Exposure Time and Temperature |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  |  | 30 Day |  | 60 Day |  | 90 Day |  | 120 Day |  |
| Test Parameters | Baseline | 23C | 50C | 23C | 50C | 23C | 50C | 23C | 50C |
| **GEOTEXTILE: S600 POLYPROPYLENE NONWOVEN EXPOSED TO PaDER MSW SYNTHETIC LEACHATE** |  |  |  |  |  |  |  |  |  |
| **Grab Tensile Properties:** | 283 | 250 | 280 | 304 | 269 | 320 | 266 | 336 | 251 |
| Maximum Strength (lbs) | 190 | 299 | 285 | 315 | 324 | 268 | 241 | 266 | 289 |
| ASTM D4632 | 241 | 273 | 272 | 309 | 303 | 229 | 244 | 310 | 251 |
| Machine Direction | 237 |  |  |  |  |  |  |  |  |
|  | 313 |  |  |  |  |  |  |  |  |
|  | 280 |  |  |  |  |  |  |  |  |
| Average | 257 | 274 | 279 | 309 | 299 | 272 | 250 | 304 | 264 |
| STD | 40 | 20 | 5 | 4 | 23 | 37 | 11 | 29 | 18 |
| Coefficient of Variation | 15 | 7 | 2 | 1 | 8 | 14 | 4 | 10 | 7 |
| % Change |  | 6 | 8 | 20 | 16 | 6 | -3 | 18 | 2 |
| **Grab Tensile Properties:** | 117 | 85 | 92 | 103 | 97 | 110 | 96 | 99 | 94 |
| Elongation @ Max. Strength (%) | 100 | 96 | 101 | 104 | 109 | 97 | 88 | 91 | 89 |
| ASTM D4632 | 115 | 89 | 95 | 105 | 107 | 87 | 90 | 95 | 87 |
| Machine Direction | 117 |  |  |  |  |  |  |  |  |
|  | 134 |  |  |  |  |  |  |  |  |
|  | 129 |  |  |  |  |  |  |  |  |
| Average | 119 | 90 | 96 | 104 | 104 | 98 | 91 | 95 | 90 |
| STD | 11 | 5 | 4 | 1 | 5 | 9 | 3 | 3 | 3 |
| Coefficient of Variation | 9 | 5 | 4 | 1 | 5 | 10 | 4 | 3 | 3 |
| % Change |  | -24 | -19 | -12 | -12 | -17 | -23 | -20 | -24 |

## TABLE OF CHEMICAL COMPATIBILITY TEST RESULTS
## Client: Ten Cate Nicolon

Report Date: May 2003
TRI Log Number: E2176-87-10

| | | Exposure Time and Temperature | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 30 Day | | 60 Day | | 90 Day | | 120 Day | |
| Test Parameters | Baseline | 23C | 50C | 23C | 50C | 23C | 50C | 23C | 50C |
| **GEOTEXTILE: S600 POLYPROPYLENE NONWOVEN EXPOSED TO PaDER MSW SYNTHETIC LEACHATE** | | | | | | | | | |
| **Grab Tensile Properties:** | 242 | 254 | 299 | 332 | 244 | 321 | 287 | 376 | 331 |
| Maximum Strength (lbs) | 256 | 305 | 293 | 307 | 326 | 272 | 279 | 316 | 291 |
| ASTM D4632 | 227 | 321 | 279 | 272 | 272 | 306 | 280 | 255 | 305 |
| Transverse Direction | 225 | | | | | | | | |
| | 261 | | | | | | | | |
| | 271 | | | | | | | | |
| Average | 247 | 293 | 290 | 304 | 281 | 300 | 282 | 316 | 309 |
| STD | 17 | 29 | 8 | 25 | 34 | 20 | 4 | 49 | 17 |
| Coefficient of Variation | 7 | 10 | 3 | 8 | 12 | 7 | 1 | 16 | 5 |
| % Change | | 19 | 18 | 23 | 14 | 21 | 14 | 28 | 25 |
| **Grab Tensile Properties:** | 113 | 115 | 118 | 117 | 102 | 109 | 103 | 127 | 107 |
| Elongation @ Max. Strength (%) | 119 | 121 | 115 | 109 | 114 | 104 | 108 | 127 | 108 |
| ASTM D4632 | 108 | 108 | 106 | 103 | 95 | 105 | 97 | 116 | 100 |
| Transverse Direction | 111 | | | | | | | | |
| | 123 | | | | | | | | |
| | 116 | | | | | | | | |
| Average | 115 | 115 | 113 | 110 | 104 | 106 | 103 | 123 | 105 |
| STD | 5 | 5 | 5 | 6 | 8 | 2 | 4 | 5 | 4 |
| Coefficient of Variation | 4 | 5 | 5 | 5 | 8 | 2 | 4 | 4 | 3 |
| % Change | | -0 | -2 | -5 | -10 | -8 | -11 | 7 | -9 |

## TABLE OF CHEMICAL COMPATIBILITY TEST RESULTS
## Client: Ten Cate Nicolon

Report Date: May 2003
TRI Log Number: E2176-87-10

| | | Exposure Time and Temperature | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 30 Day | | 60 Day | | 90 Day | | 120 Day | |
| Test Parameters | Baseline | 23C | 50C | 23C | 50C | 23C | 50C | 23C | 50C |
| **GEOTEXTILE: S600 POLYPROPYLENE NONWOVEN EXPOSED TO PaDER MSW SYNTHETIC LEACHATE** | | | | | | | | | |
| **Mullen Burst Strength:** | 560 | 530 | 490 | 460 | 520 | 450 | 600 | 570 | 550 |
| Burst Strength (psi) | 520 | 490 | 490 | 550 | 450 | 610 | 580 | 590 | 560 |
| ASTM D3786 | 430 | 540 | 570 | 630 | 590 | 430 | 490 | 450 | 490 |
| | 440 | | | | | | | | |
| | 480 | | | | | | | | |
| | 520 | | | | | | | | |
| Average | 492 | 520 | 517 | 547 | 520 | 497 | 557 | 537 | 533 |
| STD | 46 | 22 | 38 | 69 | 57 | 81 | 48 | 62 | 31 |
| Coefficient of Variation | 9 | 4 | 7 | 13 | 11 | 16 | 9 | 12 | 6 |
| % Change | | 6 | 5 | 11 | 6 | 1 | 13 | 9 | 8 |
| **Permittivity:** | 1.43 | 1.54 | 1.45 | 1.75 | 1.29 | 1.71 | 1.40 | 1.51 | 1.54 |
| (sec -1) | 1.23 | 1.57 | 1.50 | 1.43 | 1.62 | 1.72 | 1.47 | 1.54 | 1.38 |
| ASTM D4491 | 1.44 | 1.36 | 1.52 | 1.49 | 1.49 | 1.49 | 1.39 | 1.40 | 1.64 |
| | 1.47 | | | | | | | | |
| | 1.44 | | | | | | | | |
| | 1.73 | | | | | | | | |
| Average | 1.46 | 1.49 | 1.49 | 1.56 | 1.47 | 1.64 | 1.42 | 1.48 | 1.52 |
| STD | 0.15 | 0.09 | 0.03 | 0.14 | 0.14 | 0.11 | 0.04 | 0.06 | 0.11 |
| Coefficient of Variation | 10.01 | 6.22 | 1.98 | 8.92 | 9.25 | 6.47 | 2.51 | 4.06 | 7.04 |
| % Change | | 2.29 | 2.29 | 6.86 | 0.69 | 12.59 | -2.52 | 1.83 | 4.35 |

# TABLE OF CHEMICAL COMPATIBILITY TEST RESULTS
## Client: Ten Cate Nicolon

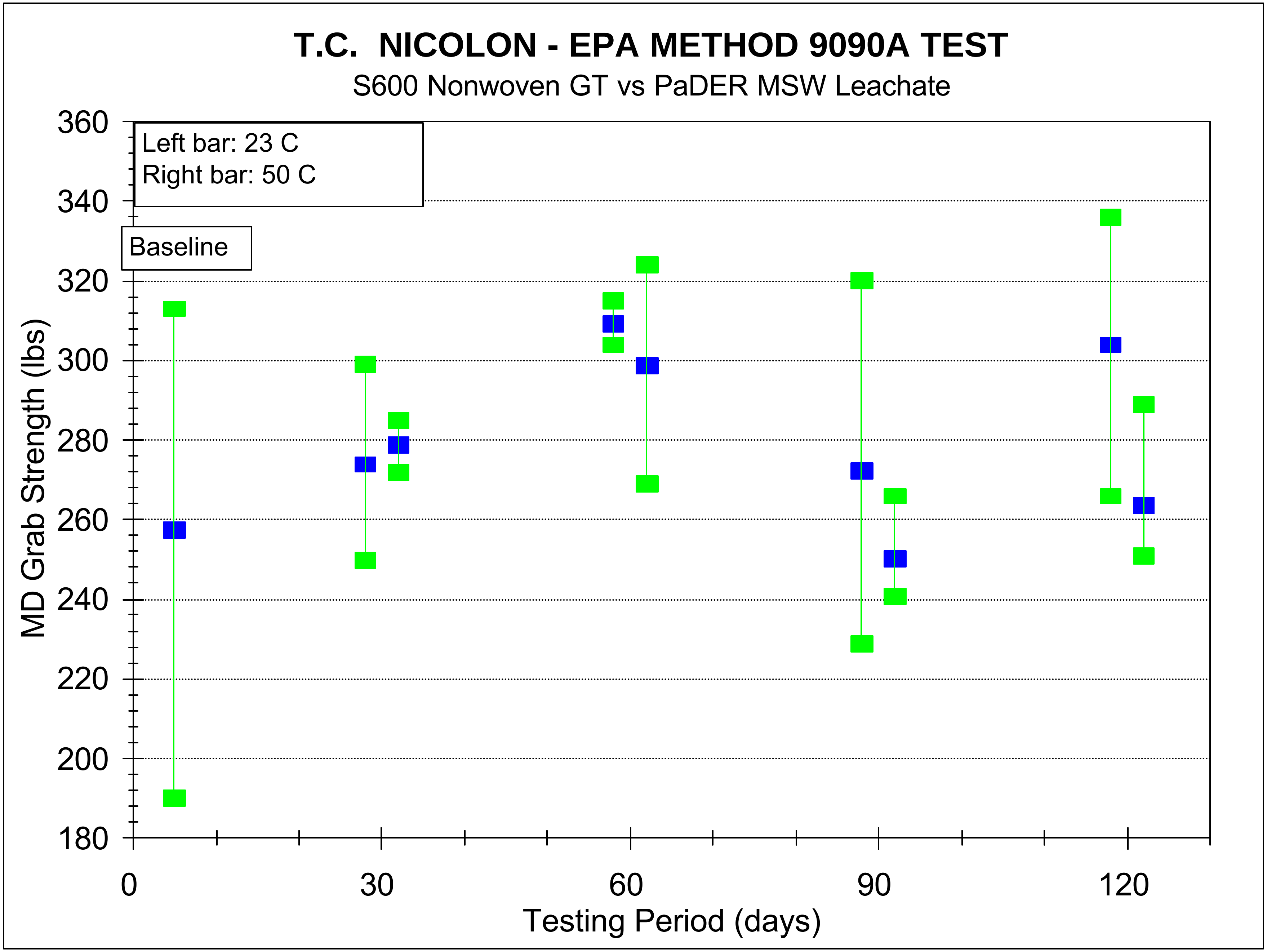
Report Date: May 2003
TRI Log Number: E2176-87-10

Exposure Time and Temperature

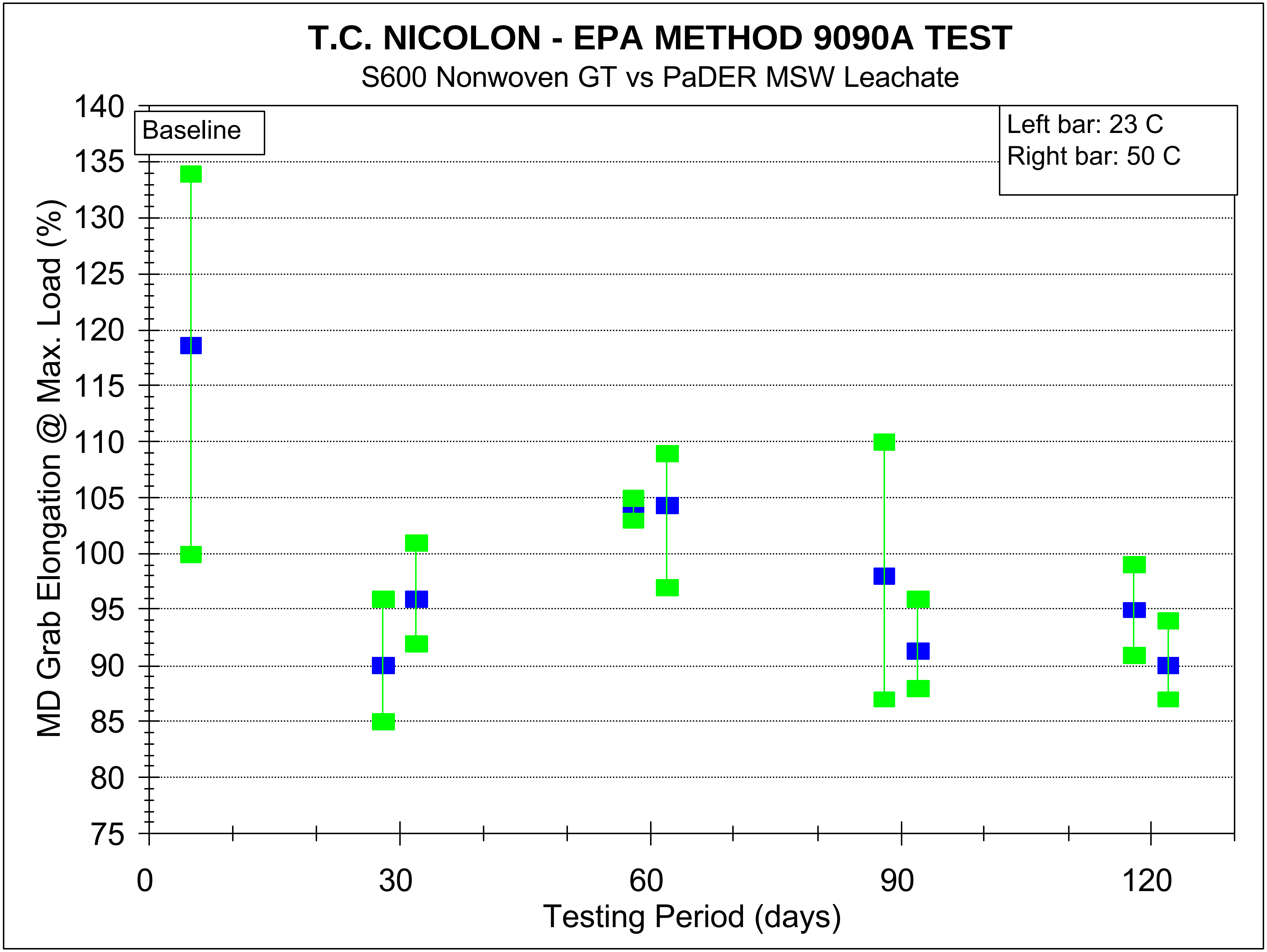
| | | 30 Day | | 60 Day | | 90 Day | | 120 Day | |
|---|---|---|---|---|---|---|---|---|---|
| Test Parameters | Baseline | 23C | 50C | 23C | 50C | 23C | 50C | 23C | 50C |

## GEOTEXTILE: S600 POLYPROPYLENE NONWOVEN EXPOSED TO PaDER MSW SYNTHETIC LEACHATE

| Test Parameters | Baseline | 30 Day 23C | 30 Day 50C | 60 Day 23C | 60 Day 50C | 90 Day 23C | 90 Day 50C | 120 Day 23C | 120 Day 50C |
|---|---|---|---|---|---|---|---|---|---|
| **Trapezoidal Tear:** | 135 | 137 | 116 | 132 | 113 | 116 | 125 | 133 | 139 |
| Tear Strength (lbs) | 131 | 125 | 135 | 125 | 127 | 129 | 116 | 117 | 120 |
| ASTM D4533 | 120 | 126 | 104 | 121 | 130 | 147 | 121 | 131 | 111 |
| Machine Direction | 179 | | | | | | | | |
| | 111 | | | | | | | | |
| | 113 | | | | | | | | |
| Average | 132 | 129 | 118 | 126 | 123 | 131 | 121 | 127 | 123 |
| STD | 23 | 5 | 13 | 5 | 7 | 13 | 4 | 7 | 12 |
| Coefficient of Variation | 17 | 4 | 11 | 4 | 6 | 10 | 3 | 6 | 9 |
| % Change | | -2 | -10 | -4 | -6 | -1 | -8 | -3 | -6 |
| **Trapezoidal Tear:** | 184 | 120 | 128 | 144 | 127 | 146 | 98 | 137 | 136 |
| Tear Strength (lbs) | 145 | 131 | 131 | 168 | 146 | 139 | 104 | 126 | 124 |
| ASTM D4533 | 161 | 128 | 126 | 128 | 134 | 117 | 133 | 134 | 122 |
| Transverse Direction | 124 | | | | | | | | |
| | 140 | | | | | | | | |
| | 165 | | | | | | | | |
| Average | 153 | 126 | 128 | 147 | 136 | 134 | 112 | 132 | 127 |
| STD | 19 | 5 | 2 | 16 | 8 | 12 | 15 | 5 | 6 |
| Coefficient of Variation | 13 | 4 | 2 | 11 | 6 | 9 | 14 | 4 | 5 |
| % Change | | -18 | -16 | -4 | -11 | -13 | -27 | -14 | -17 |
| **Puncture Resistance:** | 138 | 142 | 225 | 138 | 150 | 166 | 175 | 164 | 134 |
| Puncture Resistance (lbs) | 167 | 173 | 168 | 151 | 134 | 150 | 240 | 174 | 156 |
| ASTM D4833 | 125 | 133 | 187 | 187 | 181 | 147 | 189 | 146 | 172 |
| | 172 | | | | | | | | |
| | 225 | | | | | | | | |
| | 162 | | | | | | | | |
| Average | 165 | 149 | 193 | 159 | 155 | 154 | 201 | 161 | 154 |
| STD | 32 | 17 | 24 | 21 | 20 | 8 | 28 | 12 | 16 |
| Coefficient of Variation | 19 | 11 | 12 | 13 | 13 | 5 | 14 | 7 | 10 |
| % Change | | -9 | 17 | -4 | -6 | -6 | 22 | -2 | -7 |



TRI Geosynthetics Division Client: Ten Cate Nicolon, File: 870-nicolon-gt .WB1



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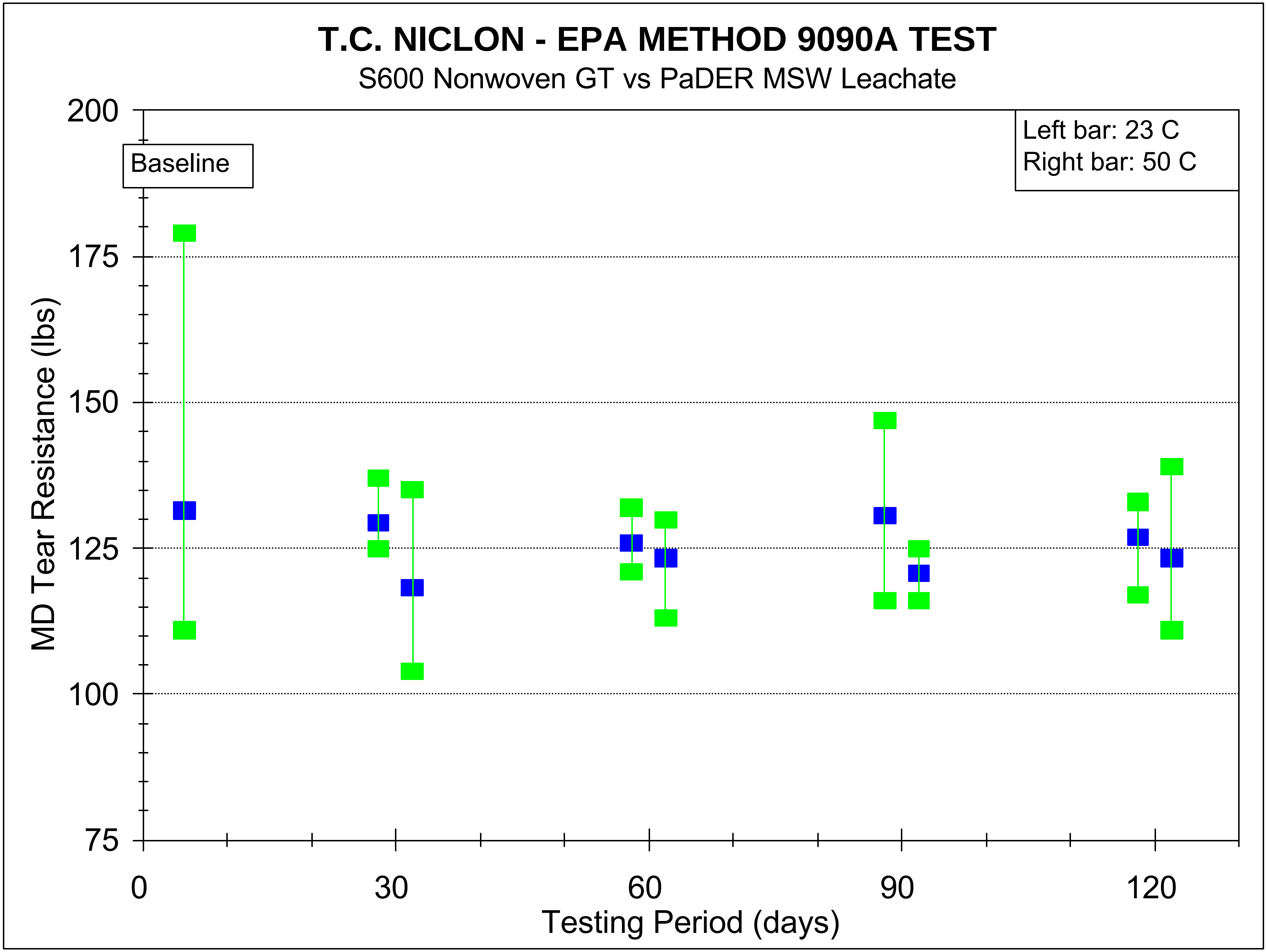

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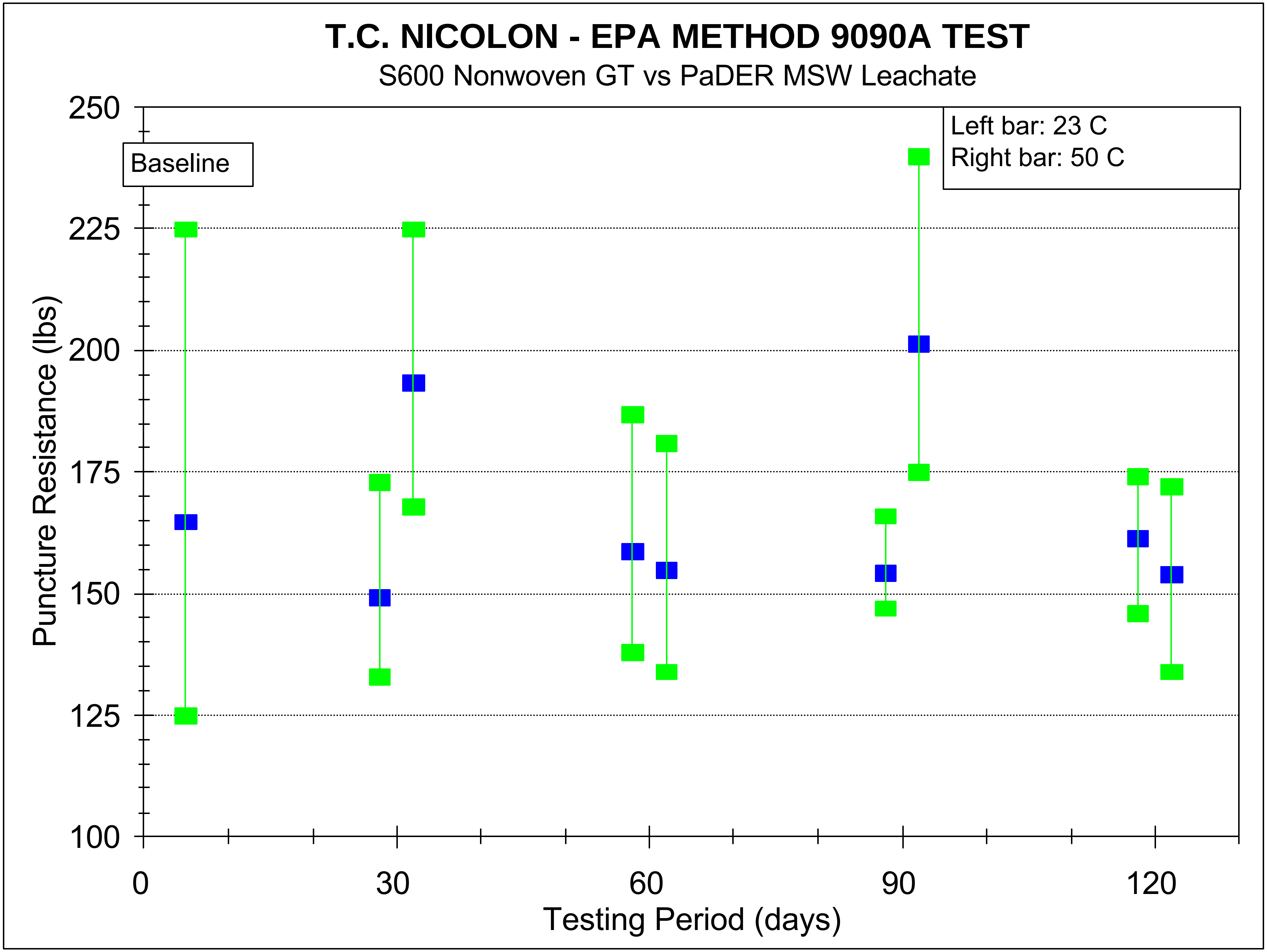
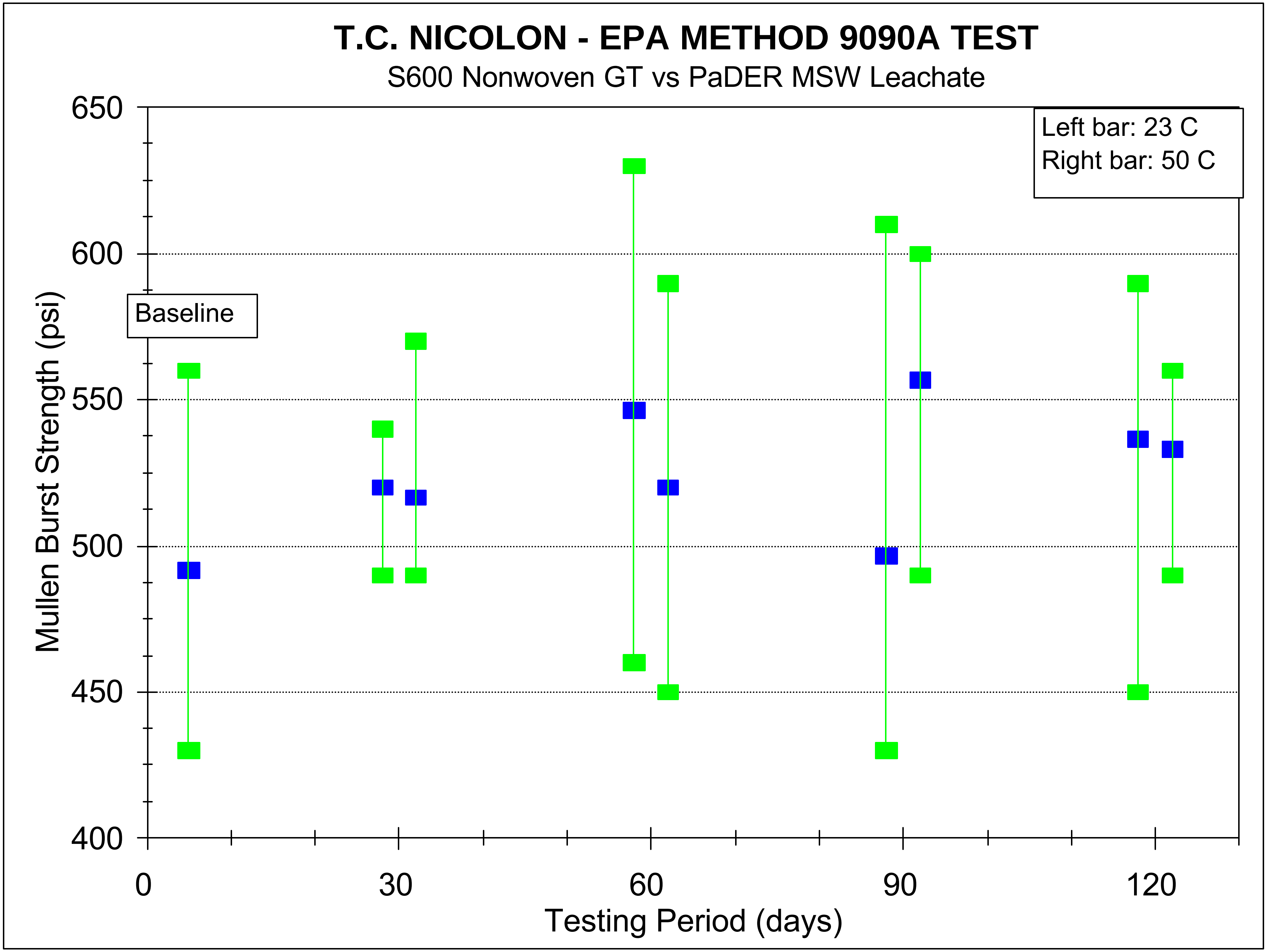
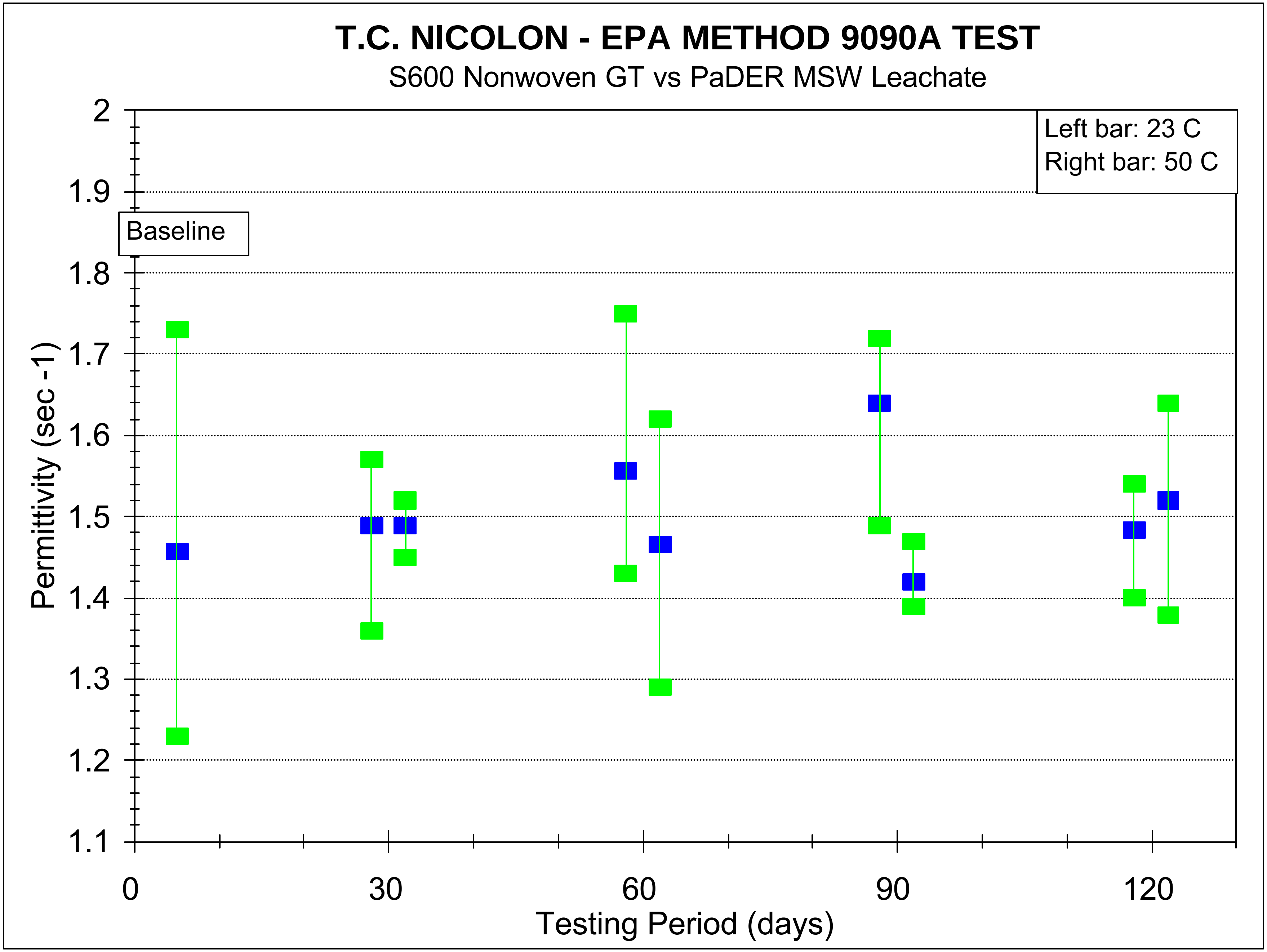


TRI Geosynthetics Division Client: Ten Cate Nicolon, File: 870-nicolon-gt .WB1


T.C. NICOLON - EPA METHOD 9090A TEST
S600 Nonwoven GT vs PaDER MSW Leachate
Left bar: 23 C
Right bar: 50 C
Baseline
Mullen Burst Strength (psi)
650
600
550
500
450
400
0
30
60
90
120
Testing Period (days)



TRI Geosynthetics Division Client: Ten Cate Nicolon,   File: 870-nicolon-gt .WB1

# Chemical Compatibility Testing of Compacted Clay Liner Specimens with Hazardous Waste Leachate Containing High Ionic Concentrations and Elevated pH Levels

By Rick Kiel[1], John Berretz[2]

## ABSTRACT

A two year Chemical Compatibility Testing Program (CCTP) was initiated to evaluate the performance and suitability of proposed clay borrow materials for use as the compacted clay liner (CCL) during construction of the triple-composite-lined Enhanced Hazardous Waste Landfill (ELF) at the Rocky Mountain Arsenal (RMA), Commerce City, Colorado. This testing program identified and evaluated first exposure effects the leachates from two distinct waste streams had on the CCL; evaluated the chemical equilibrium of the leachates after permeation; and evaluated the potential long-term effects the leachate would have on the CCL. The leachate from these waste streams exhibited very high ionic concentrations with high levels of sodium and other multivalent cations. One of the leachates was highly alkaline with a pH of 12. It was observed that density and degree of saturation were essential in minimizing the effects the leachate had on the CCL and that hydraulic conductivity was decreased due to pore space plugging caused by a soil-lime pozzolanic reaction.

## INTRODUCTION

Compacted Clay Liners are required as part of the prescriptive hydraulic barrier (i.e., low-permeability soil liner) at both solid and hazardous waste landfills, and at other industrial facilities such as mining heap leach pads and tailings impoundments. To evaluate the effect that leachate from the waste stream might have on the hydraulic conductivity of compacted CCLs, federal regulations governing hazardous waste facilities require that chemical compatibility testing be performed as part of design evaluation.

Chemical compatibility testing criteria used in this study included hydraulic conductivity testing as established by the American Standards and Testing for Materials (ASTM) D5084, Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter, and recommendations presented by the United States Environmental Protection Agency (EPA) in their seminar publication, Requirements for Hazardous Waste Landfill Design, Construction, and Closure (EPA 1989). In applying the ASTM standard, the EPA guidance document recommends comparing the hydraulic conductivity of a soil type planned for

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constructing the CCL using water as the permeant to the hydraulic conductivity of the same soil type using leachate as the permeant. Also, the guidance recommends a minimum of two pore volumes of water and leachate flow through each of the CCL soil specimens, and allowing the permeant to reach chemical equilibrium prior to terminating the hydraulic conductivity test.

This paper presents a chemical compatibility study that was conducted on soils representative of materials used to construct the CCL component of a hazardous waste landfill. The ELF is a triple-composite liner system designed and constructed at the RMA, located near Denver, Colorado, as part of the onsite Corrective Action Management Unit (CAMU). Two waste streams were planned for disposal in the ELF, the Basin F Wastepile (WP) waste stream and the Lime Basins (LB) waste stream. The Basin F WP produced leachate with high concentration of sodium and other multivalent cations such as calcium and magnesium, and other constituents resulting as by-products from the manufacture of pesticides but also chemical warfare agents produced at RMA. The LB leachate contained elevated levels of calcium, a pH in the range of 11 to 12, and numerous other organic compounds as well as heavy and alkali metals. Leachate from these two wastes were collected and shipped to TRI-Environmental in Austin, Texas for use in hydraulic conductivity testing. Bench scale studies during the design indicated that the two waste streams were incompatible; therefore, two separate waste cells were constructed within the ELF to avoid commingling of the waste and leachate.

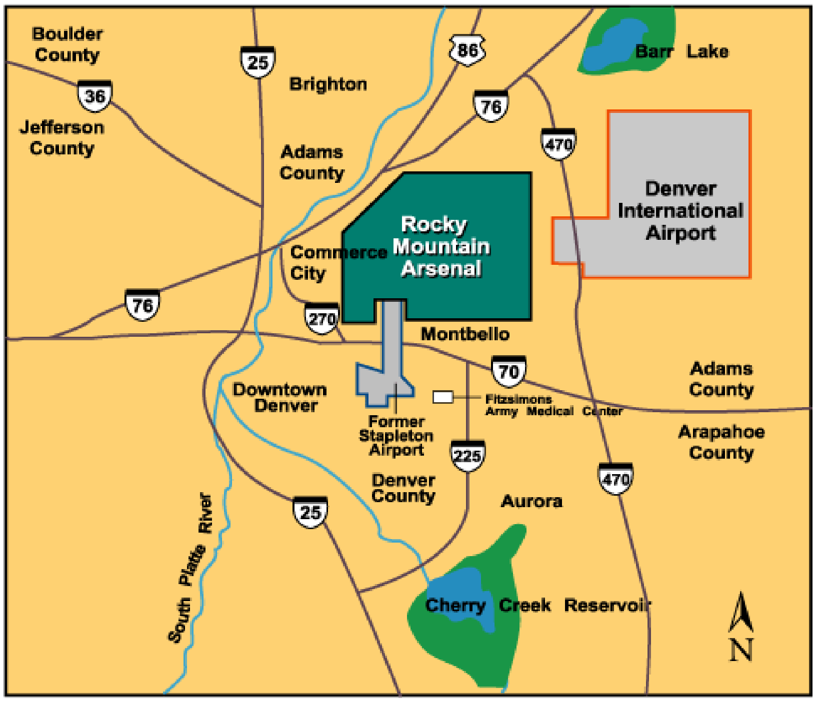
This paper includes the following:

- Site location and history;
- A brief discussion of previous studies conducted at RMA and an overview of the regulatory requirements for chemical compatibility studies;
- An overview of the selection and evaluation of soil samples from the clay borrow area used for chemical compatibility testing;
- Selection and preparation of the test leachate;
- Hydraulic conductivity test procedures and compatibility testing to include compaction (remold moisture-density) criteria for the laboratory CCL specimens and test conditions (e.g., backpressure saturation, effective confining pressure);
- Chemical equilibrium and termination criteria;
- Construction compaction criteria and overview of test results;
- Evaluation of potential effects from exposure to leachate; and
- Results of this CCTP.

## SITE LOCATION AND HISTORY

Originally a 17,000-acre site, the RMA was established in 1942 following the attack on Pearl Harbor to manufacture munitions to support World War II. Following the war, some facilities were leased in the late 1940s to private companies including Shell Oil Company to offset operational costs and maintain the facilities for national security. Common industrial and waste disposal practices of the time resulted in site contamination of structures, soil, surface water, sediment, and groundwater. All operations ceased in 1982 and the site's only mission became environmental restoration.

The RMA is listed as a National Priorities List site under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA). In addition, Basin F is subject to Colorado Department of Public Health and Environment (CDPHE) and Resource Conservation and Recovery Act (RCRA) interim status closure requirements and the conditions embodied in the Adams County Certificate of Designation issued in 1997. To accomplish the Basin F interim status closure and the CERCLA implementation projects, CDPHE designated a CAMU. The CAMU is an integral part of the Record of Decision (ROD) for RMA (HLA 1996). Pursuant to the ROD, substantially all of the waste generated during RMA cleanup and through the transition of RMA to a National Wildlife Refuge will be disposed on-post at either the Hazardous Waste Landfill (HWL) or the ELF at RMA.



## PREVIOUS COMPATIBILITY STUDIES

Previous studies at other sites have shown that solutions with high ionic strength (e.g., highly saline) and a preponderance of multivalent cations (e.g. $Ca^{+2}$ and $Mg^{+2}$) can cause an increase in hydraulic conductivity. The effects of positively charged ions, or cations, on negatively charged surfaces of clay particles lead to a zone of water and ions surrounding the clay particles, known as the diffuse double layer. The Guoy-Chapman theory (Mitchell 1990) provides an explanation of the diffuse double layer and its relationship to electrolyte concentration, cation valence, and dielectric constant. In general, as the ionic concentration and/or cation valence of the permeant increase, the thickness of the double layer shrinks, the clay has less ability to swell, and the result is a more permeable soil flow path. Studies have shown that clayey soils may be more susceptible to the effects of such aggressive permeants when evaluated at low confining stresses (Broderick and Daniel 1990, Fernandez and Quigley 1991). The studies have also shown that an increase in compacted soil density and/or an increase in the effective stress are usually sufficient to offset the effects of high ionic concentrations on the diffuse double layer.

## REGULATORY REQUIREMENTS

Chemical compatibility testing was required for this project and is based on the regulatory guidelines presented in the State of Colorado Code of Regulations (CCR), 6 CCR 1007-3, and Federal regulations, CFR Part 40, RCRA 264.301 Subpart N, which regulate hazardous waste landfills. By reference, the State of Colorado also includes the applicable RCRA guidelines for hazardous waste into the State regulations (6 CCR 1007-3-264b).

The RCRA requirements state that the landfill must be constructed using materials that are chemically resistant to the waste managed in the landfill and the leachate expected to be generated. The Colorado regulations require that 1) the lining materials be compatible with the wastes and further require a laboratory evaluation which requires that elevated pressure permeability testing be performed; 2) the samples be remolded to 95 percent of the Standard Proctor (ASTM D698) test maximum dry density (DD), using first a 0.01N solution of calcium sulfate followed with at least two pore volumes of the liquid (leachate) from the waste to be impounded; and 3) at least one test be performed at 90 percent of Standard Proctor maximum dry density. The regulations do not specify moisture contents relative to the optimum moisture content (OMC).

## SELECTION OF SOIL SAMPLES

Approximately 330,000 cubic yards of soil were used to construct the three CCLs for the triple-composite lined ELF facility. The clay came from onsite sources and were evaluated during an earlier borrow area characterization and test pad study (FWENC 2002). The borrow area was not particulary homogenous in nature, therefore a range of soil samples were selected based on index classification testing as well as color, with the primary selection made to cover the range of Plasticity Index values observed. Five representative clay samples were selected for chemical compatibility testing. Tests to evaluate soil index properties and physical characteristics were performed on each sample. These included:

- Moisture-density relationships (ASTM D698 and D1557);

- Atterberg limits (ASTM D 4318);
- Grain size distribution with hydrometer analysis (ASTM D 422);
- Soil classification (ASTM D 2487);
- X-ray diffraction;
- pH; and
- Calcium carbonate (CaCO3) content (ASTM D 4373).

In addition, the individual soil color descriptions were recorded based on the Munsell Soil Color Charts. This analysis indicated similar basic phases in all samples with either quartz and/or a magnesium calcite compound being the primary component of all samples. Additionally, the identified trace minerals appeared to consist of albite, muscovite, clintonite and protoenstatite at lower concentrations. These minerals are various forms of calcium, sodium, magnesium and potassium hydrous layered aluminosilicates typical of clays derived from the weathering of granitic and shale parent rock materials, representative of Denver Front Range alluvial deposits. While quantitative analyses were not performed, the relative concentrations indicated a higher concentration of calcium magnesium carbonate in one sample, TP-5B-1C, corresponding well with the measured concentration of 48 percent CaCO3 determined for this sample. Sample TP-10D that showed very little calcite in the x-ray diffraction testing indicated zero percent concentration of CaCO3. Gypsum was identified in sample TP-1A-1C and possibly in sample TP-6D. Table 1 presents a summary of the soil index properties for the samples tested.

Table 1. CCTP Soil Index Properties

| Soil Property | CCTP Test Samples | | | | |
|---|---|---|---|---|---|
| | Borrow Area 5 Samples | | | ELF Area Samples | |
| | 1A-1C | 4C-2D | 5B-1C | 6-D | 10-D |
| Liquid Limit, % | 47 | 31 | 39 | 39 | 31 |
| Plastic Limit, % | 19 | 17 | 22 | 16 | 19 |
| Plasticity Index, % | 28 | 14 | 17 | 23 | 12 |
| Percent Sand, #4 to #200 Sieve | 38 | 50 | 29 | 36 | 26 |
| Percent Passing #200 Sieve (% Fines) | 62 | 50 | 71 | 64 | 74 |
| Percent Clay (< 0.02 mm) | 47 | 24 | 40 | 43 | 13 |
| Percent $CaCO_3$ | 10 | 12 | 48 | 28 | 0 |
| Soil pH | 7.9 | 8.0 | 7.8 | 7.8 | 8.1 |
| OMC at 60°C – Std Proctor | 13.3 | 15.2 | 16.9 | 15.4 | 16.7 |
| OMC at 105°C – Std Proctor | 16.2 | 16.0 | 18.0 | 17.1 | 17.8 |
| Max DD by Mod Proctor | 114.5 | 123.0 | 107.5 | 123.0 | 123.0 |
| Max DD by Std Proctor | 102.5 | 115.5 | 98.5 | 105.0 | 109.5 |

## SELECTION AND PREPARATION OF TEST LEACHATE

In order to determine the analytical properties of the worst-case leachate that might be anticipated to occur for each of the two waste streams, data on concentrations of the WP leachate and groundwater obtained from piezometers in the LB area was analyzed from the historical database. After this review, select constituents were identified to be used to spike the test leachates. The base leachate samples were modified by addition of select spiking compounds in order to simulate the highest historical concentrations determined during the database review. The RMA Environmental Laboratory performed chemical analyses of the samples selected prior to shipping offsite. TRI-Environmental then spiked the samples, using selected compounds. Subsequent analysis was performed by TRI-Environmental to determine the final levels of the target components in the test leachates. The main constituents of concern with respect to this study (i.e., highest concentrations) are shown in Table 2.

Table 2. Select Constituents in Test Leachates (spiked samples)

| Constituent | Concentration in WP Leachate (ppb) | Concentration in LB Groundwater (ppb) |
|---|---|---|
| Ammonia | 122,000,000 | 25,900 |
| Potassium | 1,300,000 | 178,000 |
| Sodium | 102,000,000 | 2,290,000 |
| Total Kjeldahl Nitrogen | 100,000,000 | 48,800 |
| Chloride | 177,000,000 | 3,030,000 |
| Fluoride | 2,700,000 | <TDL |
| Sulfate | 28,500,000 | 289,000 |

## TEST PROCEDURES AND COMPATIBILITY TESTING

A series of laboratory tests were conducted to determine the hydraulic conductivity of the CCL samples using nonpotable site water and test leachates as the permeants. Two replicate tests were performed with each permeant (e.g., nonpotable site water and test leachate), resulting in a total of 10 baseline tests with water and 20 leachate tests in the first series of compatibility testing. Additional testing was performed with the test leachates, increasing the dry density and degree of saturation with each series of tests until it was observed that the hydraulic conductivity for each sample was less than or equal to $1 \times 10^{-7}$ centimeters per second (cm/s) and that no increase in the hydraulic conductivity was observed with increased leachate exposure time.

For each test using leachate as the permeant, new remolded CCL samples were prepared to allow for the simulation of “first exposure” where the samples were only permeated with test leachate and not water. This duplicated a scenario where a leak in the geomembrane component of the composite liner would allow leachate to come in contact with the CCL. The test conditions and final hydraulic conductivity results for each of the samples are presented on Table 3.

# Table 3. Summary of Hydraulic Conductivity Test Results
## Chemical Compatibility Testing Program
## Enhanced Hazardous Waste Landfill

| **Lab Sample Identification** | **Permeant[1]** | **Modified Proctor (D1557)** | | **Remolded Sample Conditions[2] (TRI - Austin, TX Lab)** | | | **Degree of Saturation[2] (%)** | **Hydraulic Conductivity (Permeant[1]) at 5 psi cp Avg k (cm/s) of Last 4 Readings** | **Cum. Pore Volumes** | **Pass/Fail**<br>**(Min Required to Pass $k \leq 1.0 \times 10^{-7}$ cm/s)** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **Maximum DD (pcf)** | **Optimum Moisture Content (%)** | **Dry Density (pcf)** | **Moisture Content (%)** | **Percent Compaction (D1557)** | | | | |
| TP-1A-1C | Baseline - 1 | 117.0 | 12.5 | 105.3 | 17.6 | 90.0% | 78.7% | 7.7E-08 | < 1 | Pass |
| TP-1A-1C | Baseline - 2 | 117.0 | 12.5 | 105.3 | 17.6 | 90.0% | 78.7% | 1.0E-07 | < 1 | Pass |
| TP-1A-1C (1) | Lime Basin | 117.0 | 12.5 | 104.4 | 17.5 | 89.2% | 76.5% | 1.8E-07 | 4.74 | Fail |
| TP-1A-1C (2) | Lime Basin | 117.0 | 12.5 | 104.9 | 17.5 | 89.7% | 77.5% | 3.1E-07 | 5.66 | Fail |
| TP-1A-1C (5) | Lime Basin | 117.0 | 12.5 | 108.6 | 16.1 | 92.8% | 78.3% | 8.2E-07 | 1.82 | Fail |
| TP-1A-1C (6) | Lime Basin | 117.0 | 12.5 | 108.6 | 16.1 | 92.8% | 78.3% | 2.8E-07 | 0.87 | Fail |
| TP-1A-1C (9) | Lime Basin | 117.0 | 12.5 | 112.8 | 14.2 | 96.4% | 77.1% | 3.7E-08 | 10.48 | Pass |
| TP-1A-1C (10) | Lime Basin | 117.0 | 12.5 | 112.7 | 14.2 | 96.3% | 76.9% | 9.1E-08 | 3.29 | Power Failure - Note spike in plot. Pass |
| TP-1A-1C (13) | Lime Basin | 117.0 | 12.5 | 108.8 | 18.4 | 93.0% | 90.0% | 7.6E-09 | 2.07 | Pass |
| TP-1A-1C (3) | Basin F | 117.0 | 12.5 | 105.0 | 17.5 | 89.7% | 77.7% | 7.0E-07 | 2.97 | Fail |
| TP-1A-1C (4) | Basin F | 117.0 | 12.5 | 104.9 | 17.5 | 89.7% | 77.5% | 3.6E-07 | 3.98 | Fail |
| TP-1A-1C (7) | Basin F | 117.0 | 12.5 | 108.6 | 16.1 | 92.8% | 78.3% | 1.2E-07 | 0.57 | Fail |
| TP-1A-1C (8) | Basin F | 117.0 | 12.5 | 108.6 | 16.1 | 92.8% | 78.3% | 1.9E-07 | 0.61 | Fail |
| TP-1A-1C (11) | Basin F | 117.0 | 12.5 | 112.9 | 14.2 | 96.5% | 77.3% | 1.2E-07 | 2.19 | Power Failure - Note plot spike. Trending Down. Fail |

# Table 3. Summary of Hydraulic Conductivity Test Results
# Chemical Compatibility Testing Program
# Enhanced Hazardous Waste Landfill

| Lab Sample Identification | Permeant[1] | Modified Proctor (D1557) | | Remolded Sample Conditions[2] (TRI - Austin, TX Lab) | | | Degree of Saturation[2] (%) | Hydraulic Conductivity (Permeant[1]) at 5 psi cp Avg k (cm/s) of Last 4 Readings | Cum. Pore Volumes | Pass/Fail (Min Required to Pass k ≤ 1.0 x $10^{-7}$ cm/s) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Maximum DD (pcf) | Optimum Moisture Content (%) | Dry Density (pcf) | Moisture Content (%) | Percent Compaction (D1557) | | | | |
| TP-1A-1C (12) | Basin F | 117.0 | 12.5 | 112.8 | 14.2 | 96.4% | 77.1% | 1.3E-07 | 3.25 | Power Failure - Note spike in plot. Fail. |
| TP-1A-1C (14) | Basin F | 117.0 | 12.5 | 108.2 | 18.4 | 92.5% | 88.6% | 4.5E-09 | 2.03 | Pass |
| TP-1A-1C (15) | Basin F | 117.0 | 12.5 | 108.5 | 19.0 | 92.7% | 92.2% | 2.8E-09 | 0.90 | Pass |
| TP4C-2-D | Baseline - 1 | 124.0 | 10.5 | 113.1 | 15.7 | 91.2% | 85.9% | 4.0E-08 | < 1 | Pass |
| TP4C-2-D | Baseline - 2 | 124.0 | 10.5 | 112.9 | 15.9 | 91.0% | 86.6% | 3.7E-08 | < 1 | Pass |
| TP4C-2-D (1) | Lime Basin | 124.0 | 10.5 | 112.8 | 15.8 | 91.0% | 85.8% | 2.6E-08 | 13.69 | Pass |
| TP4C-2-D (2) | Lime Basin | 124.0 | 10.5 | 113.0 | 15.8 | 91.1% | 86.2% | 2.7E-08 | 6.18 | Pass |
| TP4C-2-D (3) | Basin F | 124.0 | 10.5 | 112.7 | 15.8 | 90.9% | 85.6% | 4.0E-08 | 2.88 | Pass |
| TP4C-2-D (4) | Basin F | 124.0 | 10.5 | 113.1 | 15.8 | 91.2% | 86.5% | 3.4E-08 | 2.98 | Pass |
| TP5B-1-C | Baseline - 1 | 108.5 | 16.0 | 100.3 | 23.2 | 92.4% | 91.7% | 7.5E-08 | < 1 | Pass |
| TP5B-1-C | Baseline - 2 | 108.5 | 16.0 | 99.7 | 23.2 | 91.9% | 90.3% | 8.7E-08 | < 1 | Pass |
| TP5B-1-C (1) | Lime Basin | 108.5 | 16.0 | 99.4 | 23.1 | 91.6% | 89.3% | 1.3E-07 | 3.68 | Fail |
| TP5B-1-C (2) | Lime Basin | 108.5 | 16.0 | 99.7 | 23.1 | 91.9% | 89.9% | 1.5E-07 | 3.60 | Fail |
| TP5B-1-C (5) | Lime Basin | 108.5 | 16.0 | 107.2 | 17.9 | 98.8% | 84.0% | 8.6E-08 | 3.47 | Pass |

# Table 3. Summary of Hydraulic Conductivity Test Results
# Chemical Compatibility Testing Program
# Enhanced Hazardous Waste Landfill

| Lab Sample Identification | Permeant[1] | Modified Proctor (D1557) | | Remolded Sample Conditions[2] (TRI - Austin, TX Lab) | | | Degree of Saturation[2] (%) | Hydraulic Conductivity (Permeant[1]) at 5 psi cp Avg k (cm/s) of Last 4 Readings | Cum. Pore Volumes | Pass/Fail (Min Required to Pass $k \leq 1.0 \times 10^{-7}$ cm/s) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Maximum DD (pcf) | Optimum Moisture Content (%) | Dry Density (pcf) | Moisture Content (%) | Percent Compaction (D1557) | | | | |
| TP5B-1-C (6) | Lime Basin | 108.5 | 16.0 | 107.2 | 17.9 | 98.8% | 84.0% | 1.0E-07 | 4.66 | Pass |
| TP5B-1-C (3) | Basin F | 108.5 | 16.0 | 99.8 | 23.1 | 92.0% | 90.1% | 4.1E-08 | 5.55 | Pass |
| TP5B-1-C (4) | Basin F | 108.5 | 16.0 | 99.4 | 23.1 | 91.6% | 89.3% | 4.9E-08 | 4.22 | Pass |
| TP-6-D | Baseline - 1 | 124.5 | 10.0 | 103.3 | 19.3 | 83.0% | 82.1% | 1.0E-07 | < 1 | Pass |
| TP-6-D | Baseline - 2 | 124.5 | 10.0 | 103.4 | 19.3 | 83.1% | 82.3% | 1.4E-07 | < 1 | Fail |
| TP-6-D (1) | Lime Basin | 124.5 | 10.0 | 103.4 | 19.3 | 83.1% | 82.3% | 2.1E-07 | 4.30 | Fail |
| TP-6-D (2) | Lime Basin | 124.5 | 10.0 | 103.4 | 19.3 | 83.1% | 82.3% | 1.9E-07 | 4.05 | Fail |
| TP-6-D (5) | Lime Basin | 124.5 | 10.0 | 107.5 | 17.3 | 86.3% | 81.8% | 4.2E-07 | 1.35 | Fail |
| TP-6-D (6) | Lime Basin | 124.5 | 10.0 | 107.5 | 17.3 | 86.3% | 81.8% | 2.0E-07 | 0.76 | Fail |
| TP-6-D (9) | Lime Basin | 124.5 | 10.0 | 112.3 | 14.5 | 90.2% | 77.7% | 2.5E-07 | 1.80 | Fail |
| TP-6-D (10) | Lime Basin | 124.5 | 10.0 | 112.5 | 14.5 | 90.4% | 78.1% | 2.2E-06 | 3.16 | Fail |
| TP-6-D (11) | Lime Basin | 124.5 | 10.0 | 112.3 | 15.1 | 90.2% | 80.9% | 1.2E-06 | 1.09 | Fail |
| TP-6-D (12) | Lime Basin | 124.5 | 10.0 | 112.3 | 15.3 | 90.2% | 82.0% | 7.0E-08 | 2.88 | Pass |
| TP-6-D (13) | Lime Basin | 124.5 | 10.0 | 111.2 | 17.4 | 89.3% | 90.6% | 2.9E-08 | 2.12 | Pass |

# Table 3. Summary of Hydraulic Conductivity Test Results
Chemical Compatibility Testing Program
Enhanced Hazardous Waste Landfill

| **Lab Sample Identification** | **Permeant[1]** | **Modified Proctor (D1557)** | | **Remolded Sample Conditions[2] (TRI - Austin, TX Lab)** | | | **Degree of Saturation[2] (%)** | **Hydraulic Conductivity (Permeant[1]) at 5 psi cp Avg k (cm/s) of Last 4 Readings** | **Cum. Pore Volumes** | **Pass/Fail (Min Required to Pass k $\le$ 1.0 x $10^{-7}$ cm/s)** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **Maximum DD (pcf)** | **Optimum Moisture Content (%)** | **Dry Density (pcf)** | **Moisture Content (%)** | **Percent Compaction (D1557)** | | | | |
| TP-6-D (14) | Lime Basin | 124.5 | 10.0 | 111.1 | 18.5 | 89.2% | 96.0% | 1.2E-08 | 2.09 | Pass |
| TP-6-D (3) | Basin F | 124.5 | 10.0 | 103.4 | 19.3 | 83.1% | 82.3% | 3.0E-07 | 3.20 | Fail |
| TP-6-D (4) | Basin F | 124.5 | 10.0 | 103.5 | 19.3 | 83.1% | 82.5% | 1.4E-07 | 3.14 | Fail |
| TP-6-D (7) | Basin F | 124.5 | 10.0 | 107.5 | 17.3 | 86.3% | 81.8% | 7.9E-08 | 3.38 | Pass |
| TP-6-D (8) | Basin F | 124.5 | 10.0 | 107.5 | 17.3 | 86.3% | 81.8% | 5.6E-08 | 3.17 | Pass |
| TP-10-D | Baseline - 1 | 123.5 | 10.5 | 106.2 | 18.6 | 86.0% | 85.1% | 4.9E-08 | < 1 | Pass |
| TP-10-D | Baseline - 2 | 123.5 | 10.5 | 106.6 | 19.1 | 86.3% | 88.3% | 6.0E-08 | < 1 | Pass |
| TP-10-D (1) | Lime Basin | 123.5 | 10.5 | 105.6 | 18.9 | 85.5% | 85.2% | 4.7E-08 | 15.40 | Pass |
| TP-10-D (2) | Lime Basin | 123.5 | 10.5 | 106.5 | 18.9 | 86.2% | 87.1% | 6.0E-08 | 8.26 | Pass |
| TP-10-D (3) | Basin F | 123.5 | 10.5 | 106.5 | 18.9 | 86.2% | 87.1% | 7.2E-08 | 3.51 | Pass |
| TP-10-D (4) | Basin F | 123.5 | 10.5 | 106.2 | 18.9 | 86.0% | 86.5% | 5.7E-08 | 3.92 | Pass |

Note 1 - Permeants consist of Nonpotable RMA Water for Baseline Tests; Spiked Leachate from Basin F and Spiked Groundwater from Lime Basins Wells (Refer to Table 2).

Note 2 - Moisture was determined for samples TP-6D and TP-1A-1C at 60°C due to the presence of gypsum in these samples during the fourth round of testing. Dry Density, Moisture Content and Degree of Saturation for samples where moisture content was initially determined at 105°C have been corrected to indicate values for moisture content determined at 60°C.

The test procedures consisted of falling head, rising tailwater, with initial backpressure saturation (ASTM D5084, Method C). An effective stress of 5 psi was applied to all samples. While it was recognized that the ultimate field conditions after landfilling operations were completed would result in greater effective stresses, up to 45 psi at the sump elevations, regulatory agency concerns over initial landfill conditions resulted in conservancy in the hydraulic conductivity evaluation in order to simulate low confining stress conditions during early waste placement.

Termination criteria for samples tested with the nonpotable site water were established based on the ASTM D5084 termination criteria. This criterion allows for termination after four values of hydraulic conductivity are obtained over an interval of time in which the ratio of outflow to inflow rate is between 0.75 and 1.25, and the hydraulic conductivity is steady (e.g. the plot of hydraulic conductivity versus time shows no significant upward or downward trend). For the samples tested with test leachate an additional criteria was established requiring a minimum of two pore volumes of liquid to pass through the sample (EPA 1989). Additionally, several samples were selected for long-term testing. Long-term testing involved allowing the permeation of samples well beyond the two-pore volume criteria. This long-term testing was performed to provide data to assist in evaluating continued leachate exposure affect on the hydraulic conductivity properties of the soils. As discussed below, the samples tested with WP leachate (lower pH) tended to reach chemical equilibrium sooner than for samples permeated with LB leachate (higher pH). Therefore, samples permeated with LB leachate were selected for long-term testing (up to 15 pore volumes of flow).

## Evaluation of Chemical Equilibrium

Based on the EPA guidance document (EPA 1989) recommendations it was desired to allow the testing to proceed until chemical equilibrium had been obtained. Therefore, pH and Electrical Conductivity (EC) were monitored as a measure of the chemical equilibrium of the samples. A chemical equilibrium goal was defined for the project with the ratio of effluents to influents (e.g. $EC_{effluent}$ to $EC_{influent}$ and $pH_{effluent}$ to $pH_{influent}$) within 10 percent of each other.

Samples of leachate were obtained from each of the individual test cell influent and effluent bladders at designated sampling intervals. Sampling began at an approximate frequency of every 0.5 pore volume, and then at approximately every 0.25 pore volumes thereafter. For the longer-term tests (i.e., those tests that were allowed to run for more than two pore volumes) the pore volume frequency of sampling and testing was reduced to every 0.5- to 1.0-pore volume to minimize loss of fluids from the sample bladders. The EC samples were diluted to 1/100 for the LB samples and 1/1,000 for the WP samples in order to allow for measurement within the limits of the laboratory instrumentation.

Ratios of the $EC_{effluent}$ to the $EC_{influent}$ for the samples permeated with WP leachate tended to increase nearing equilibrium within 3 to 4 pore volumes, while the ratios for samples permeated with the LB leachate tended to slightly decrease with time or show no effective change. The equilibrium relationships are shown on Figures 1 and 2.

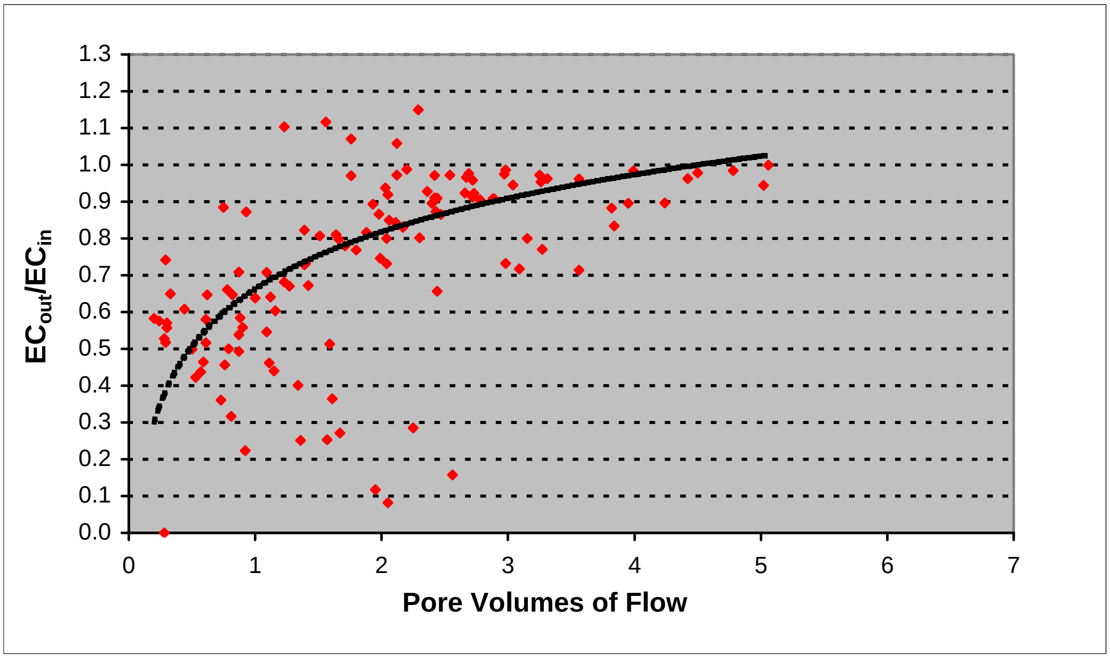


Figure 1. Ratio of $EC_{effluent}$ to $EC_{influent}$ versus Pore Volumes of Flow For Samples Tested with the Basin F Leachate

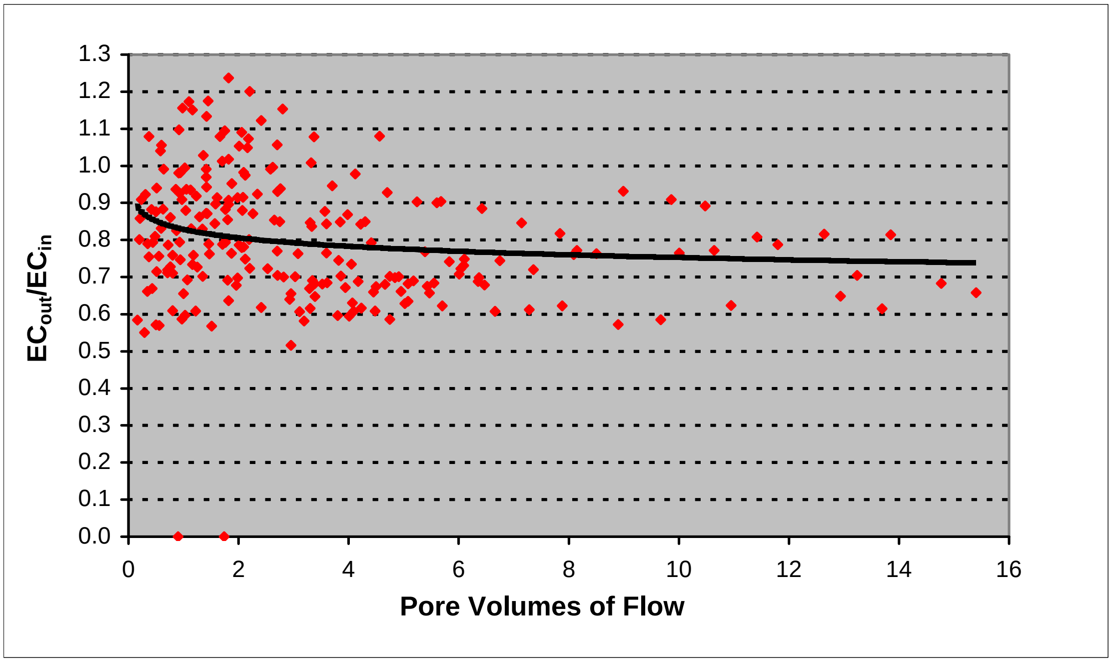


Figure 2. Ratio of $EC_{effluent}$ to $EC_{influent}$ versus Pore Volumes of Flow For Samples Tested with the Lime Basins Groundwater

The pH trends for the samples permeated with WP leachate ($pH_{influent}$ 8.2) indicate that the leachate trended toward pH equilibrium within 3 to 4 pore volumes. However, the samples permeated with the LB leachate ($pH_{influent}$ 12) tended to not reach pH equilibrium during the duration of the testing program. The relatively large buffering capacity of the clayey soils resulted in a long term trend of the effluent pH to approximately that of the soil (average pH ~ 7.9). These relationships are shown on Figures 3 and 4.

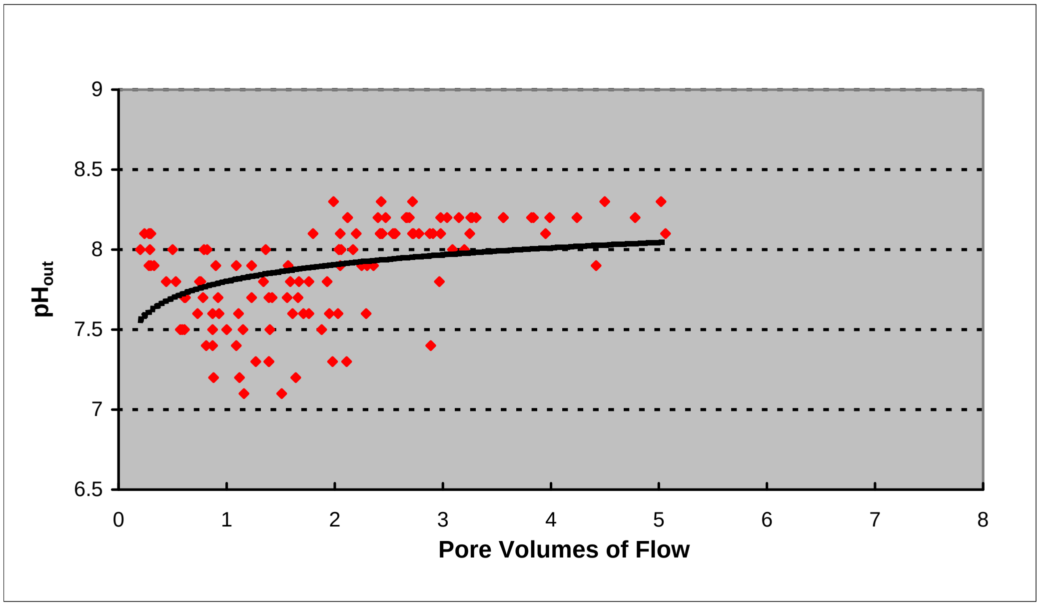


Figure 3. $pH_{effluent}$ versus Pore Volumes of Flow
For Samples Tested with the WP Leachate ($pH_{influent}$ ~ 8.2)

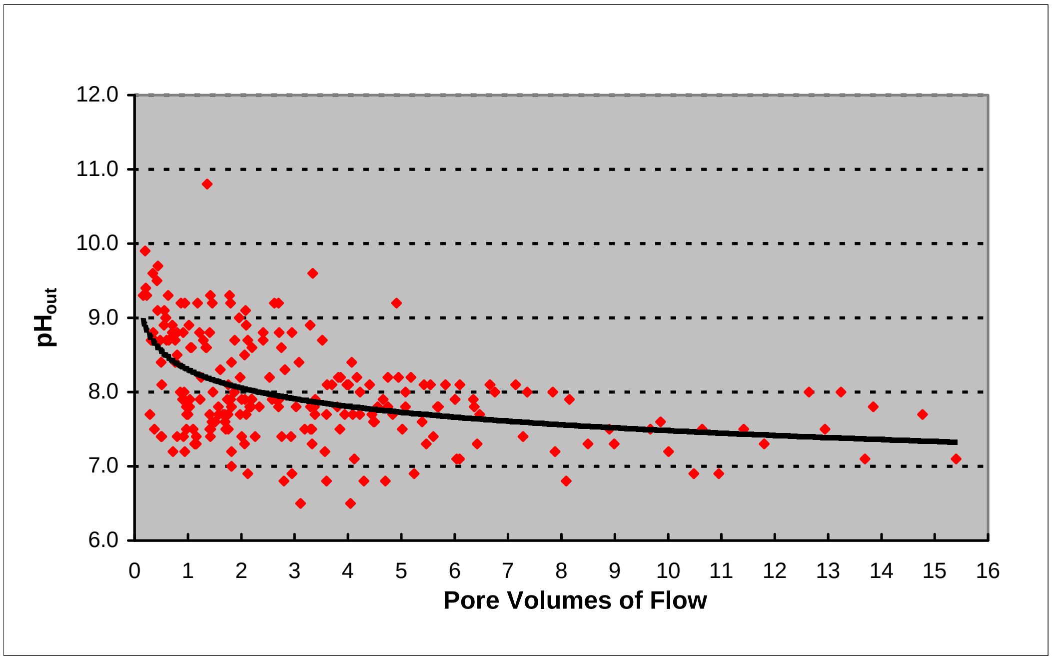


Figure 4. $pH_{effluent}$ versus Pore Volumes of Flow
For Samples Tested with the LB Leachate ($pH_{influent}$ ~ 12)

## Construction Compaction Criteria and Overview of Test Results

Procedures for development of construction compaction control criteria are well documented. Othman and Luettich (1994) summarized two of the most popular procedures: Line-of-Optimums and Degree-of-Saturation.

The Line-of-Optimums approach provides for development of an acceptable compaction zone, for a particular soil, based on the maximum dry densities and optimum moisture contents as determined from three separate moisture-density relationships tests (i.e., Modified Proctor, Standard Proctor, and Reduced Proctor).

The Degree-of-Saturation approach defines an acceptable lower bound of the degree of saturation. This approach is favorable in that it requires less laboratory testing (and its associated costs) and minimizes inherent variability of laboratory testing in determining the construction compaction criteria.

For the RMA ELF project it was determined that a Line-of-Optimums approach would be used to develop the construction compaction criteria as a similar approach had been used successfully in development of the specifications for the RMA HWL project (USACE 1998). The approach defined by Othman and Luettich was revised and the reduced Proctor tests were not performed. Using modified and standard Proctor tests, with several of each test performed for each soil type, the Line-of-Optimums tended to be parallel to the zero-air-voids curve. As expected with repeated testing, some scatter in data was noted in the test results.

The initial hydraulic conductivity tests were performed on select samples remolded to represent the lower limit moisture-density values based on the Line-of-Optimums at 95 percent of Standard Proctor maximum dry density. The first series of laboratory results of leachate hydraulic conductivity testing indicated that 50 percent (10 out of 20) of the samples did not meet a hydraulic conductivity criteria of 1 x $10^{-7}$ cm/sec or less, while corresponding tests at similar remold values using nonpotable water as the permeant did result in hydraulic conductivities of 1 x $10^{-7}$ cm/sec or less in all 20 baseline samples.

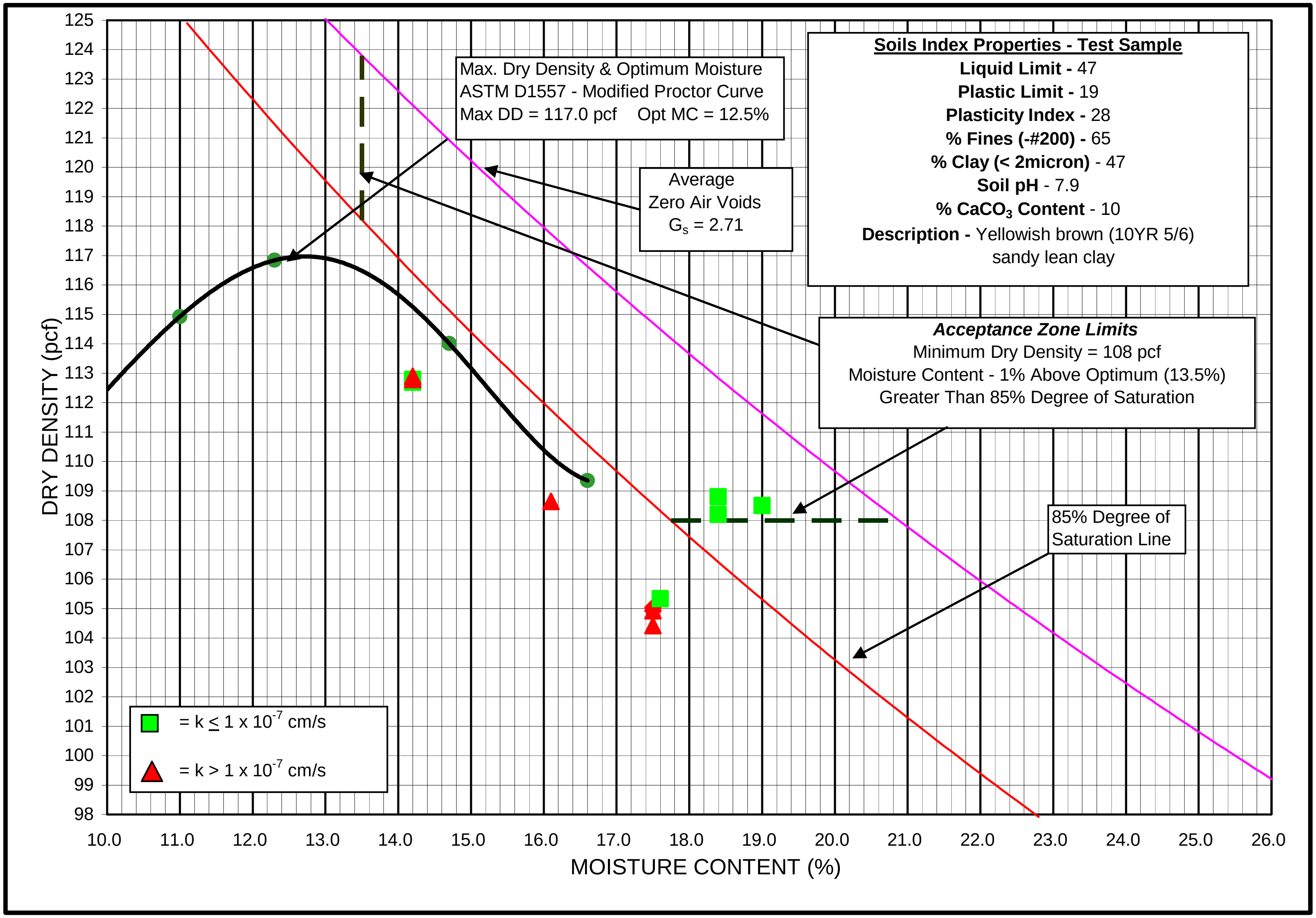
A second series of tests were conducted with minimum densities increased to 106 pounds per cubic foot (pcf) and at degree of saturation in excess of 85 percent. This range was selected based on the results of water hydraulic conductivity testing on samples taken from the Test Pad constructed for the ELF project. For the second round of tests, four of the ten samples retested had values of 1 x $10^{-7}$ cm/sec or less, while the remaining six samples failed to meet the required value. Additional revisions to the target moisture and density criteria were then established.

A third series of testing included tests on select samples tested at 90 percent of the maximum dry density based on the Modified Proctor (ASTM D1557) or 110 pcf, whichever was higher, and at moisture contents equivalent to a degree of saturation of 85 percent or greater. Early results on some of the tests from the third series continued to indicate failing test results for samples with high clay content and a sensitivity to moisture content was suspected. An evaluation of the moisture content and oven-drying temperatures was performed for all samples. It was determined that the moisture content determined at 105ºC was from 2 to 3 percent higher than that determined at 60ºC for those samples with higher clay content and approximately 1 percent higher for those samples with low to moderate clay content. This effect is documented in the literature and has been observed in some Rocky Mountain Front Range clayey soils (Barrett 2002) containing gypsum. Grim (Grim 1962) also notes that effective dehydration of the clay minerals by elimination of interlayer, or “non-ordinary” water occurs at temperatures from 100 to 150ºC, and in many cases the reaction is not reversible or the rehydration can be completed only with great difficulty. It was determined that this was the most influential factor in determining the proper moisture and density range to achieve acceptable hydraulic conductivity results. Due to this variance, many of the samples that initially failed to meet the hydraulic conductivity criteria appeared to be remolded wet of the Line-of-Optimums, but subsequently were determined to have been remolded dry of the Line-of-Optimums. During the previous HWL construction at the RMA, temperature variability evaluation had been performed on select samples, and had not indicated any significant variance. Therefore, this was not considered a concern during the index testing for the ELF project. In any environment where gypsum is known to be present, the initial evaluation should consider its effects during index testing.

Moisture contents were re-determined for the soils at the lower 60ºC oven temperature and a fourth round of tests was performed on five select samples. These samples were remolded to a minimum of 90 percent of the maximum dry density based on the Modified Proctor, or 108 pcf, whichever was greater, and at a degree of saturation of

85 percent or greater.  While some soil types were shown to meet the minimum hydraulic conductivity criteria at values less than these moisture contents and dry densities, these values were required to consistently allow all materials permeated with both the WP and LB leachate to meet the hydraulic conductivity criteria (Figure 6). Some samples with degrees of saturation below 85 percent still met the minimum hydraulic conductivity criteria, while two samples with degrees of saturation above 85 percent did not.  These two failing samples were remolded to significantly lower dry densities, close to 99 pcf, which may have attributed to the lower hydraulic conductivities.

The final selection resulted in an Acceptance Zone (AZ) that included an 85 percent degree of saturation and added some degree of conservativeness to the design.  By comparison, the typical Line-of-Optimums resulted in an acceptable range of compaction being defined between 78 and 80 percent degree of saturation.  Figure 5 presents the results of the laboratory hydraulic conductivity tests and the development of the AZ criteria used during construction for one of the five typical samples.



Max. Dry Density & Optimum Moisture
ASTM D1557 - Modified Proctor Curve
Max DD = 117.0 pcf    Opt MC = 12.5%

Average
Zero Air Voids
$G_s$ = 2.71

**Soils Index Properties - Test Sample**
**Liquid Limit -** 47
**Plastic Limit -** 19
**Plasticity Index -** 28
**% Fines (-#200) -** 65
**% Clay (< 2micron)** - 47
**Soil pH** - 7.9
**% $CaCO_3$ Content** - 10
**Description -** Yellowish brown (10YR 5/6) sandy lean clay

***Acceptance Zone Limits***
Minimum Dry Density = 108 pcf
Moisture Content - 1% Above Optimum (13.5%)
Greater Than 85% Degree of Saturation

85% Degree of
Saturation Line

Figure 5. Final Acceptance Zone
Sample TP-1A-1C

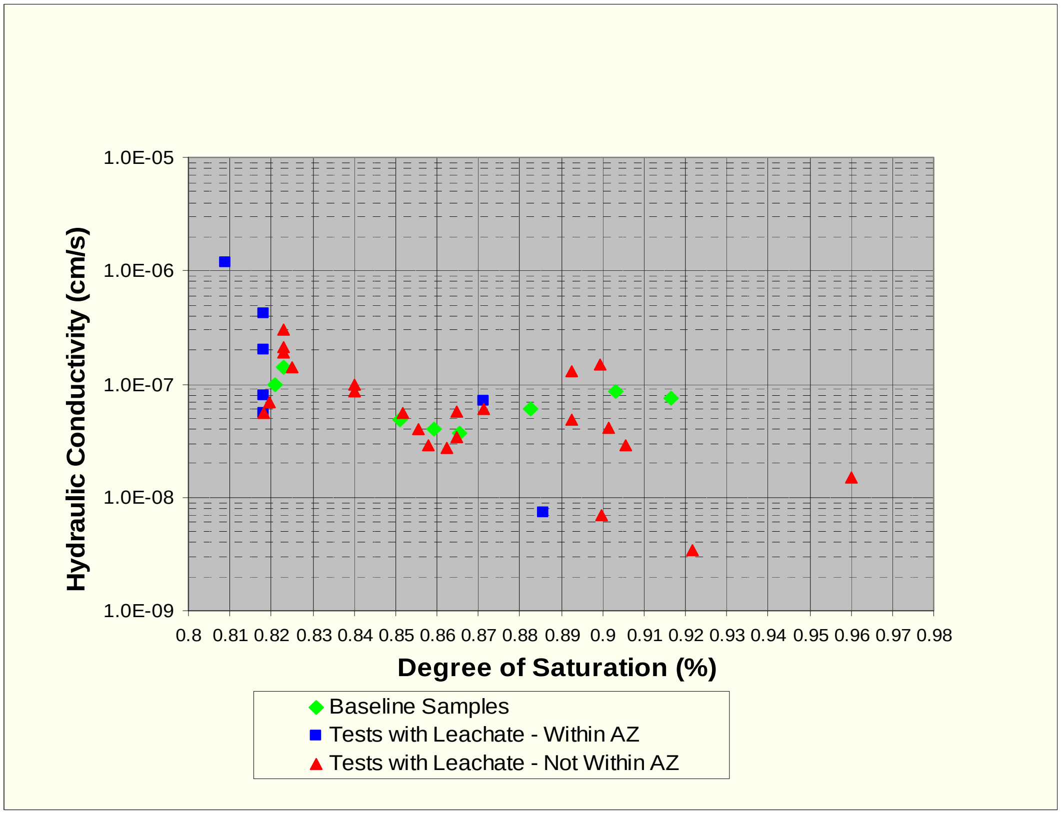


Figure 6. Degree of Saturation versus Hydraulic Conductivity

## Evaluation of Potential Effects from Exposure to Leachate

The study included an evaluation of the first exposure effects and potential long-term chemical reactions. The following briefly discusses each of these.

### *First Exposure Effects*

The testing program was designed such that first exposure effects were accounted for by direct exposure of the CCL materials to the surrogate leachates in all of the leachate conductivity tests without prior saturation with clean water. In each of the tests, the sample was backpressure saturated using the surrogate leachate then permeated with at least 2 pore volumes of leachate. In all cases, where the soil samples were remolded within the final AZ, test results of less than 1 x $10^{-7}$ cm/sec were achieved.

As previously discussed, during the early phases of the testing program some samples compacted at lower densities and at a degree of saturation less than 85 percent did not meet the hydraulic conductivity criteria. Samples with higher clay content tended to have higher hydraulic conductivity values on the order of 2 to 6 times greater than similar samples remolded to equivalent moisture-density conditions using nonpotable water. This difference is supported in the literature where the presence of high concentrations of multivalent cations, primarily calcium, have been shown to react by cation exchange with clays to limit the amount of ordinary interlayer swelling of clay particles, thereby causing the increases in the hydraulic conductivity. As shown on Table 2 the WP and LB leachate contained high levels of multivalent cations. This effect was observed to be more pronounced in the LB samples. Again, Table 2 indicates a 14-fold higher level of calcium in the LB leachate than the WP leachate.

The subsequent testing series, previously discussed in this study, verified that increasing the compacted density and degree of saturation could lower hydraulic conductivities.

*Potential Long-Term Effects*

The potential long-term effects for the samples permeated with the LB-surrogate leachate were further evaluated in two manners:

1) By literature review to document the chemical behavior and reactions which occur during lime amendment of clayey soils in the transportation industry (Diamond, et.al, 1963 and Fossberg, 1964), and

2) By longer-term leachate conductivity testing and observation on three select samples permeated with as many as 15 pore volumes of flow in tests lasting up to 20 months.

Where WP-surrogate leachate was used, chemical equilibrium (based on the pH and EC influent to effluent ratios) was typically established after 3 to 5 pore volumes of flow. No indication was noted in these samples of an increase in hydraulic conductivity with time. In the case of the tests with LB- surrogate leachate, chemical equilibrium after as many as 15 pore volumes was not indicated (Figures 3 and 4), with the ratio of effluent to influent typically on the order of 0.6 to 0.8. This indicates the relatively high buffering capacity of the clayey soils. The laboratory test results in fact indicate a decrease in the hydraulic conductivity with time very likely due to a plugging effect.

The literature search provided the basis for an understanding of the long-term reaction that occurs between clay soils and lime solutions. This process, known as the soil-lime-pozzolanic reaction, occurs through a dissolution process at the edges of the clay particles and subsequent precipitation process resulting in the formation of the calcium silica hydrate (CSH) and calcium alumina hydrate (CAH) phases (Diamond, et.al. 1963). Researchers engaged in lime-stabilization work refer to these compounds as "gels." The chemical reaction can be generally defined as follows for illitic clay in reaction with a calcium hydroxide rich (pH ~ 12) solution:

$$\mathrm{K\ (AlOH)_4\ Si_7AlO_{20} * nH_2O + Ca(OH)_2} \longrightarrow \boldsymbol{C}\mathrm{aO}\ \boldsymbol{S}\mathrm{i_4O_{10}}\ 6\boldsymbol{H}_2\mathrm{O} + (\boldsymbol{C}\mathrm{aO})_4\ 5(\boldsymbol{A}\mathrm{l_2O_3}) * 13\boldsymbol{H}_2\mathrm{O} + \mathrm{K} \qquad (1)$$

[ Illite variety clay + water + solution ] = [CSH (silica gel) + CAH (alumina gel) within clay matrix ] (2)

The precipitation process resulting in the formation of the complex hydrated silicates or "gels" has been shown to result in plugging or cementation of pore spaces and an overall decrease in hydraulic conductivity with time (Fossberg 1964). Furthermore, for the soil-lime-pozzolanic reaction to occur, a strongly basic solution (pH on the order of 12) is required (Diamond, et.al. 1963). The authors conclude that this effect was occurring in the LB samples, subjected to the high pH leachate and was to a degree responsible for the slight decreases in hydraulic conductivity noted. Figure 7 presents the results of one sample which was tested for over 15 pore volumes showing the gradual decrease in hydraulic conductivity with time.

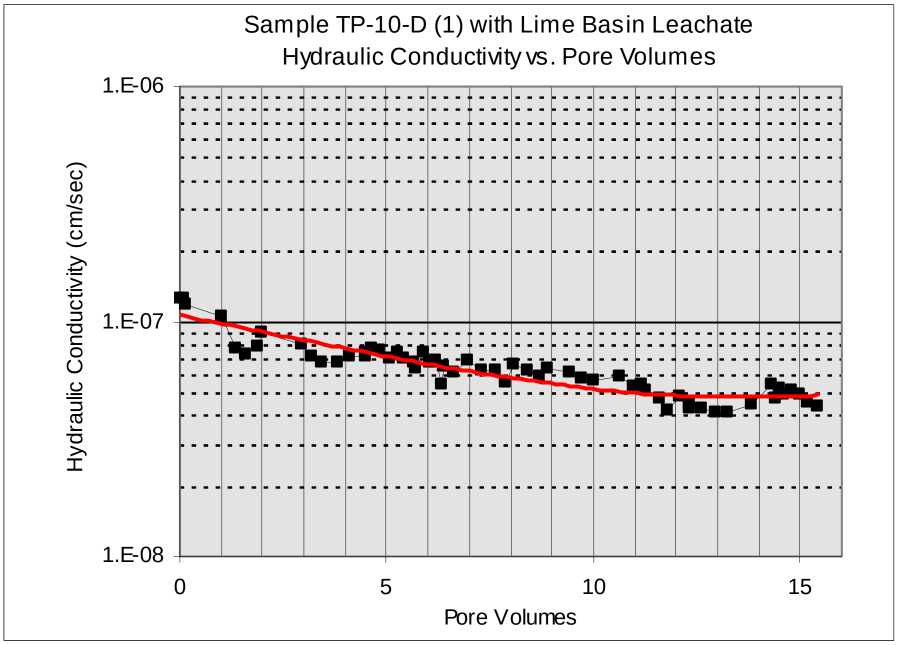


Figure 7. Long-Term Test Results

## CONCLUSION

Results of this study indicate that CCLs with higher clay content exposed to the test leachate used in this study that were high in multivalent cations and highly alkaline may be adversely affected only when compacted to low densities (less than 90 percent of modified Proctor) and low degree of saturation (less than 85 percent). The study indicates that the apparent primary cause of the potential adverse effects are increased levels of multivalent cations, primarily calcium, as opposed to other components found in high concentrations such as ammonia, sodium, chloride, or various other metals. The high levels of calcium may have a potentially greater adverse effect than high pH, which was shown to be effectively buffered by the proposed clay.

Most importantly, the study shows that these adverse effects can be offset by simply increasing the density and degree of saturation to a degree well within a workable range and within standard industry compaction norms.

In addition, the results show a slight trend of decreasing hydraulic conductivity with time which the authors believe is due to plugging or cementation of pore spaces.

## ACKNOWLEDGEMENTS

The laboratory-testing program was supported as part of the design for the ELF at the RMA, funded by the Remediation Venture Organization a remediation group consisting of the U.S. Army, Shell Oil Co. and the U.S. Fish and Wildlife Service. The following team members and working group provided useful review and insight into the development of this program: Leo Chen of Washington Group International, Steve Garland (formerly of KBR) and John Berretz of KBR, Robert Benmark formerly of Golder Associates, Dave Bradfield formerly of Tetra-Tech EC, Inc., Dr. Robert Gilbert of the University of Texas at Austin, Michael Malusis now Assistant Professor at Bucknell University, Larry Bruskin of the CDPHE, Rick Kinshella (Golder) formerly with the Tri-County Health Department, and Dr. Chuck Shackelford of the Colorado State University. The authors would also like to specially acknowledge Mark Sebesta, former Laboratory Manager for TRI-Environmental for his diligent performance of the laboratory testing and to Annette Moltzan for support in technical editing.

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# K.2 – Loads on the Leachate Collection System

**Client:** **Zion Landfill, Inc.**
**Project:** **Zion Landfill – Site 2 North Expansion**
**Project #:** **631020105**
**Calculated By:** **SJW** **Date: 05/2022**
**Checked By:** **DAM** **Date: 05/2022**

**TITLE:** **LOADS ON THE LEACHATE COLLECTION SYSTEM**

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## Problem Statement

Determine the maximum loading (W) on the leachate collection pipes. Two loading scenarios are considered on the leachate collection pipes:

1. Full Loading over the vertical expansion (existing landfill and proposed expansion) and horizontal expansion:

   $W_{FL}$ = Loading on pipe due to landfill at final grade.

2. Point-Source Loading over the horizontal expansion during construction:

   $W_{IL}$ = Loading on pipe due to 5 ft. of waste and a compactor concentrated load. This represents the minimum thickness of waste that a compactor is anticipated to drive over and is one third of a typical 15-ft lift

The greatest loading will be used in subsequent calculations to determine the leachate collection pipes' ability to resist the maximum load.

## Given

☐ Joint Task Force on Sanitary Sewers of the American Society of Civil Engineers and Water Pollution Control Federation. (2007). *Gravity Sanitary Sewer Design and Construction*. American Society of Civil Engineers, Manuals and Reports on Engineering Practice, No. 60 (refer to attached pages).

☐ Uponor Infra Ltd. (2015). *Sclairpipe®: Versatile High Density Polyethylene Pipe*.

☐ Caterpillar 836K, Landfill Compactor Specifications (refer to attached pages).

☐ Final Cover Design, thickness of approximately 5-ft. consists of (from top to bottom):
  - 0.5 ft. vegetative cover soils,
  - 2.5 ft. protective cover soils
  - Double sided Geocomposite,
  - Textured 40-mil LLDPE geomembrane, and
  - 2.0 ft. compacted low permeable soil layer

☐ One foot of granular drainage layer material is installed on top of the 6-inch perforated HDPE leachate collection pipe in the trench locations.

☐ Leachate collection system pipes within the trenches underlying the vertical expansion are all 6-inch Standard Dimension Ratio (SDR) 17 HDPE pipe.

☐ All leachate collection pipes within the horizontal expansion will be 6-inch SDR-17 HDPE pipe.

☐ The average outer pipe diameter for 6 in. pipes is 6.63 in. = 0.55 ft. (see Sclairpipe® "General Information").

☐ Soil and aggregate material properties obtained from Geotechnical Analysis Report, **Appendix J**.

## Assumptions

Full Loading Assumptions (Constructed Final Landform)

☐ Marston's formula utilized to calculate the fill load on a positive projecting pipe (Equation 9-8, Pg. 252 in reference ASCE No. 60):

$$W_c = C_c \, w \, B_c^{\ 2}$$

Where,

$W_c$ = Linear load on pipe (lb/ft)
$C_c$ = Load coefficient, a function of $B_c$ /2H (obtained from Table 9-3, Pg. 268 of ASCE No. 60)
w = Unit weight of overlying fill (pcf)
$B_c$ = Outer diameter of pipe (ft)

☐ Assume embankment conditions over a positive projecting pipe because the pipe is located in a wide trench and the top of the pipe is above the surface of the compacted soil layer. Therefore, Marston's formula can be simplified to include the height of fill above the top of pipe (H):

$$W_c = H \, w \, B_c$$

☐ The maximum waste thickness in the horizontal expansion area is 196 feet. The maximum waste thickness in the vertical expansion area is 207 feet. Due to the similarity in waste thickness, all calculations conservatively assume that a 207-ft waste column is acting on the underlying leachate pipes.

☐ Assume waste density is 75 pcf, from Geotechnical Analysis Report, **Appendix J**.

☐ Cohesive soil density for final cover soils is 130.3 pcf, from Geotechnical Analysis Report, **Appendix J**.

☐ Assume density of granular material used in leachate collection trench is 130 pcf, from Geotechnical Analysis Report, **Appendix J**.

**TITLE:** **LOADS ON THE LEACHATE COLLECTION SYSTEM**

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Point-Source Loading Assumptions – Concentrated Equipment Loading During Initial Lift

- ☐ D.L. Holl's integration of Boussinesq's formula utilized to calculate the load on the pipe due to a superimposed concentrated load, corresponding to a landfill compactor wheel load (Equation 9-19, Pg. 266 in reference ASCE No. 60):

$$W_{sc} = C_s \frac{P*F}{L}$$

Where,

$W_{sc}$ = Load on pipe (lb/ft)
$C_s$ = Load Coefficient, a function of $B_c/2H$
  $B_c$ = Outer diameter of pipe (ft)
  H = Height of fill above top of pipe (ft.
P = Concentrated load (lb)
F = Impact Factor
L = Effective length of pipe (ft)

- ☐ Five (5) feet of waste is placed on top of the leachate collection system pipe (minimum waste thickness prior to use of landfill compactor). It is noted that this thickness is less than the typical waste lift thickness (15 feet) assumed in other calculations.

- ☐ A landfill compactor will be the heaviest piece of equipment that will pass over a leachate pipe during placement of the initial lift of waste.

- ☐ Concentrated Load (P) = Total weight of CAT 836K compactor divided by 2 axles = 123,319 lb. divided by 2 = 61,660 lb. (Caterpillar 836K, Landfill Compactor Specifications).

- ☐ Impact Factor (F) = 1.0 (recommended per ASCE No. 60 for H > 3 ft., Table 9-4, Pg. 272)

- ☐ Effective length of pipe (L) = 3 ft. (recommended per ASCE No. 60 for pipe lengths > 3 ft.)

- ☐ Height of fill above top of pipe (H) = 1 ft. of drainage layer + 5 ft. of waste (1/2 lift) = 6 ft.

- ☐ Load coefficient ($C_s$) obtained from ASCE No. 60, Table 9-3, based on the following ratios:

| **Pipe to be Analyzed** | **Expansion Variables** | | | **Calculated Values** | | **Obtained from Table 9-3** |
|---|---|---|---|---|---|---|
| | **Outer Diameter of pipe** | **Height of fill above the top of pipe** | **Effective length of pipe** | **Concentrated Load ratio** | **Distributed Load ratio** | **Load Coefficient** |
| | **$B_c$** (ft.) | **H** (ft.) | **L** (ft.) | **$B_c$/2H** | **L/2H** | **$C_s$** |
| 6-inch pipe | 0.55 | 6.0 | 3 | 0.046 | 0.25 | 0.053 |

## Calculations

Full Loading – Final Landform Constructed ($W_{FL}$)

| **Maximum Load on 6-inch Leachate Collection Pipe** | | | |
|---|---|---|---|
| **Layer** | **Thickness, t (ft)** | **Density, $\gamma_{sat}$ (pcf)** | **t x $\gamma_{sat}$ (psf)** |
| Final Cover | 5 | 130.3 | 651.5 |
| Waste | 207 | 75 | 15,525 |
| Granular Drainage Material | 1 | 130 | 130 |
| **TOTAL THICKNESS, H:** | **213** | **SUM OF (t x γ):** | **16,306.5** |
| **(t x γ)/total thickness = AVERAGE DENSITY, w (pcf):** | | | **76.6** |

The total weight is divided by the 6-inch pipe thickness to get a load per linear unit for comparison to the value that is reported for point-source loading:

$$W_{FL} = H \times w \times B_c = (213\text{ ft})(76.6\text{ pcf})(0.55\text{ ft}) = 8{,}973.7\text{ lb/ft} = \mathbf{747.8\ lb/in}$$

Point Source Loading – Concentrated Compactor Load ($W_{IL}$)

| **Maximum Load on Leachate Collection Pipe – Half of Initial Lift of Waste** | | | |
|---|---|---|---|
| **Layer** | **Thickness, t (ft)** | **Density, $\gamma_{sat}$ (pcf)** | **t x $\gamma_{sat}$ (psf)** |
| Waste | 5 | 75 | 375 |
| Granular Drainage Material | 1 | 130 | 130 |
| **TOTAL THICKNESS:** | **6** | **SUM OF (t x γ):** | **505** |
| **(t x γ)/total thickness = AVERAGE DENSITY, w (pcf):** | | | **84.2** |

$$W_C = H \times w \times B_c = (6\text{ ft})(84.2\text{ lb/ft}^3)(0.55\text{ ft}) = 277.9\text{ lb/ft} = \mathbf{23.2\ lb/in}\text{ (half initial lift of waste)}$$

$$W_{sc} = C_s\frac{PF}{L} = (0.053)\frac{(61{,}660\text{ lb})(1.0\text{ lb})}{3\text{ ft}} = 1{,}089.3\frac{\text{lb}}{\text{ft}} = \mathbf{90.8\ lb/in}\text{ (compactor load)}$$

$$W_{IL} = W_c + W_{sc} = 23.2\text{ lb./in.} + 90.8\text{ lb./in.} = \mathbf{114.0\ lb/in}$$

## Results

Full-loading for final buildout conditions of the vertical and horizontal expansion as well as point-source loads have been evaluated to determine which load type provides the most significant stresses on the leachate collection system piping. The maximum loads per unit length on the leachate collection system piping are summarized in the tables below.

| Load from Final Landform ($W_{FL}$) (lb/in) | Load from Initial Lift ($W_{IL}$) (lb/in) |
|---|---|
| 747.8 | 114.0 |

Based on this review, the full-loading scenario has been determined to provide a greater loading on the pipe than point-source loading. Therefore, all subsequent pipe strength calculations will use the full-loading values to analyze pipe strength. The loading associated with this parameter are summarized in the table below.

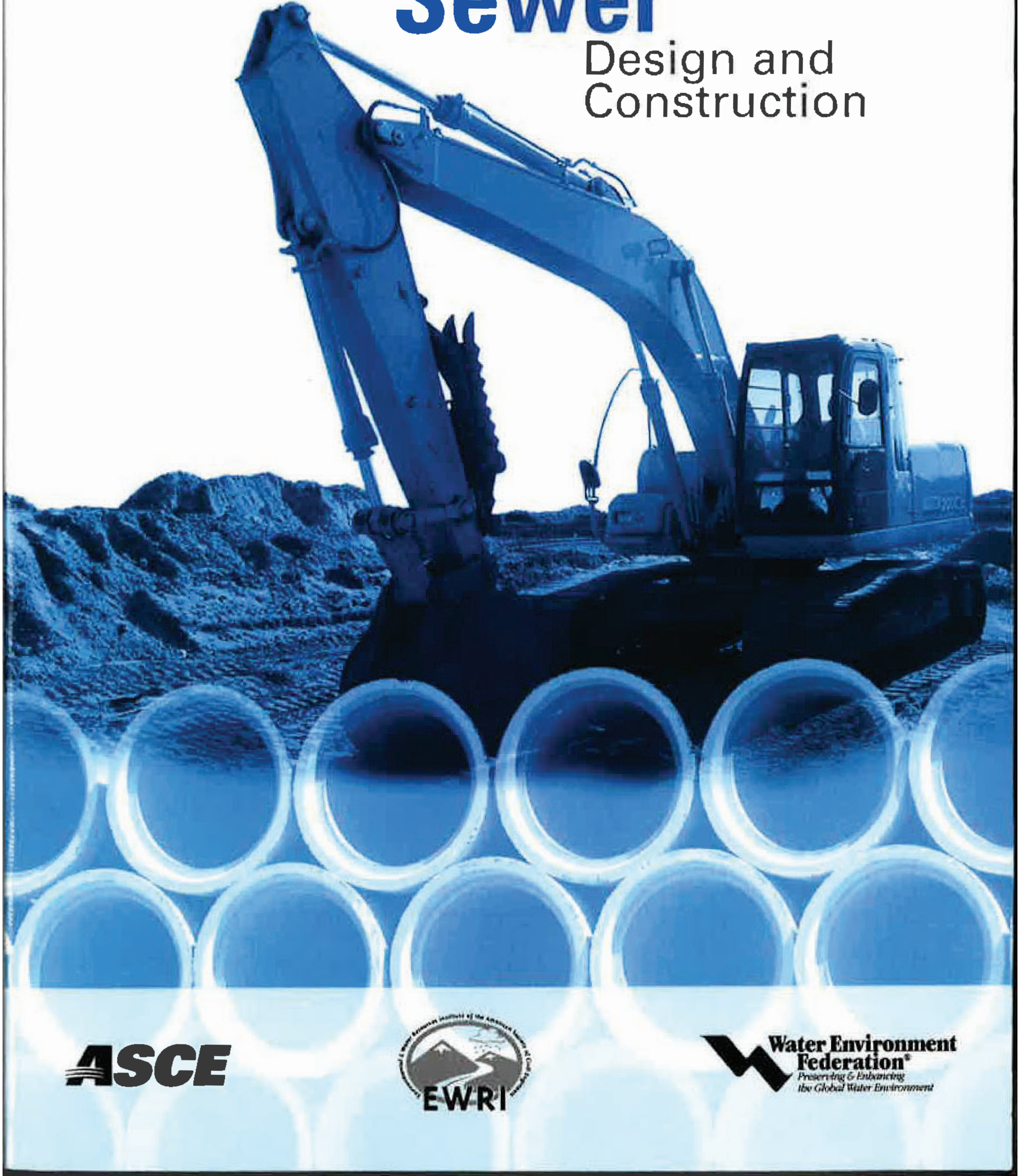
| Load from Final Grade (psf) |
|---|
| 16,306.5 |

ASCE MANUALS AND REPORTS ON ENGINEERING PRACTICE NO. 60
WEF MANUAL OF PRACTICE NO. FD-5

SECOND EDITION

# Gravity Sanitary Sewer

## Design and Construction



ASCE

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Preserving & Enhancing the Global Water Environment

particular piping material. These
s piping organizations, are outlined

thods are typically preferred, there
-Spangler load analysis may be pre-
or determining the vertical load on
n all of the most commonly encoun-
ston and Anderson 1913; Marston
based on both theory and experi-
cceptance as being useful and reli-
ative.
e load on a buried pipe is equal to
y over it, called the interior prism,
forces transferred to that prism by
itude and direction of the frictional
settlement between the interior and
s the following assumptions:

at will develop when ultimate set-

ressures that induce the shearing
djacent soil prisms is computed in

tion is:

(9-3)

it length acting on the sewer pipe
unit weight of soil; *B* is the trench
g on installation conditions; and *C*
arries the effect of the following

dth of trench or sewer pipe.
ior and adjacent soil prisms.
ative settlement between interior
nkment conditions.

on's equation includes all the fac-
stallation conditions, it is conven-
specialized form of the equation,

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and prepare separate graphs and tables of coefficients for each. In performing a Marston-Spangler load analysis, there are three types of open-cut installation methods. These are:

- Trench.
- Negative-projecting embankment.
- Positive-projecting embankment.

Figure 9-2 shows the various types of installation.

Trench conditions are defined as those in which a sewer pipe is installed in a relatively narrow trench cut in undisturbed ground and covered with soil backfill to the original ground surface.

Embankment conditions are defined as those in which the sewer pipe is covered above the original ground surface or when a trench in undisturbed soil is so wide that trench wall friction does not affect the load on the sewer pipe. The embankment classification is further subdivided into two major subclassifications—positive-projecting and negative-projecting. Sewer pipes are defined as positive-projecting when the top of the sewer pipe is above the original adjacent ground surface. Negative-projecting sewer pipe is that installed with the top of the sewer pipe below the adjacent original ground surface in a trench which is narrow with respect to the size of pipe and the depth of cover, as shown on Fig. 9-2, and when the

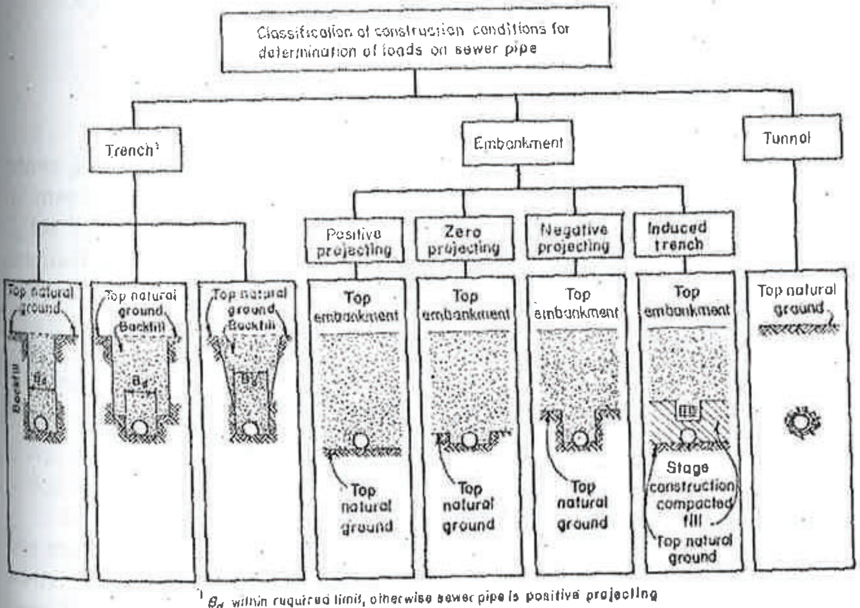

FIGURE 9-2. *Classification of construction conditions.*

a computer program designed for a particular piping material. These methods, which are specific to various piping organizations, are outlined in greater detail below.

Although these Direct Design methods are typically preferred, there may be times when the older Marston-Spangler load analysis may be preferred. Marston developed methods for determining the vertical load on buried conduits caused by soil forces in all of the most commonly encountered construction conditions (Marston and Anderson 1913; Marston 1930). These methods are historically based on both theory and experiment and have generally achieved acceptance as being useful and reliable, although perhaps overly conservative.

In general, the theory states that the load on a buried pipe is equal to the weight of the prism of soil directly over it, called the interior prism, plus or minus the frictional shearing forces transferred to that prism by the adjacent prisms of soil—the magnitude and direction of the frictional forces being a function of the relative settlement between the interior and adjacent soil prisms. The theory makes the following assumptions:

- The calculated load is the load that will develop when ultimate settlement has taken place.
- The magnitude of the lateral pressures that induce the shearing forces between the interior and adjacent soil prisms is computed in accordance with Rankin's theory.

The general form of Marston's equation is:

$$W = C\omega B^2 \tag{9-3}$$

in which $W$ is the vertical load per unit length acting on the sewer pipe because of gravity soil loads, $\omega$ is the unit weight of soil; $B$ is the trench width or sewer pipe width, depending on installation conditions; and $C$ is a dimensionless coefficient that marries the effect of the following variables:

- The ratio of the height of fill to width of trench or sewer pipe.
- The shearing forces between interior and adjacent soil prisms.
- The direction and amount of relative settlement between interior and adjacent soil prisms for embankment conditions.

### 9.2.2.2. *Types of Loading Conditions*

Although the general form of Marston's equation includes all the factors necessary to analyze all types of installation conditions, it is convenient to classify these conditions, write a specialized form of the equation,

## Sample Calculations

*Example 9-1.* Determine the load on a 24-inch-diameter rigid sewer pipe under 14 ft of cover in trench conditions.

Assume that the sewer pipe wall thickness is 2 inches; $B_c = 24 + 4 = 28$ inches $= 2.33$ ft; $B_d = 2.33 + 2.00 = 4.33$ ft; and $w = 120\ \text{lb/ft}^3$ for saturated top soil backfill. Then $H/B_d = 14/4.33 = 3.24$; $C_d$ (from Fig. 9-4) $= 2.1$; and $W_c = 2.1 \times 120 \times (4.33)^2 = 4{,}720$ lb/ft (68,880 N/m).

*Example 9-2.* Determine the load on the same-sized sewer laid on a concrete cradle and with trench sheeting to be removed.

Assume that the wall thickness is 2 inches; the cradle projection outside of the sewer pipe is 8 inches (4 inches on each side); and the maximum clearance between cradle and outside of sheeting is 14 inches. Then $B_d = 24 + (2 \times 2 \text{ inches}) + 8 + (2 \times 14) = 64$ inches $= 5.33$ ft.

As this seems to be an extremely wide trench, a check should be made on the transition width of the trench; $B_c = 2.33 = 2.33$ ft; $H = 14$ ft; $r_{sd}p = 0.5$; and $H/B_c = 14/2.33 = 6$.

From Fig. 9-5, $B_d/B_c = 2.39$ (the ratio of the width of the trench to the width of the sewer at which loads are equal by both trench sewer theory and projecting-sewer theory); $B_d = 2.33 \times 2.39 = 5.57 > 5.33$; $H/B_d = 14/5.33 = 2.63$; $C_d$ (from Fig. 9-4) $= 1.85$; and $W_c = 1.85 \times 120 \times (5.33)^2 = 6{,}300$ lb/ft (91,700 N/m).

*Example 9-3.* Determine the load on the same sewer if (rough) sheeting is left in place.

$B_d$ becomes 4 inches less $= 5$ ft; $H/B_d = 14/5 = 2.8$; $C_d$ (from Fig. 9-4) $= 1.92$; and $W_c = 1.92 \times 120 \times (5)^2 = 5{,}750$ lb/ft (84,040 N/m).

*Example 9-4.* Determine the load on a 30-inch-diameter flexible sewer pipe installed in a trench 4 ft, 6 inches wide at a depth of 12 ft.

Assume the soil is clay weighing $120\ \text{lb/ft}^3$ and that it will be well-compacted at the sides of the sewer pipe. Then $H = 12$ ft; $B_d = 4.5$ ft; $B_c = 2.5$ ft; $H/B_d = 2.67$; $C_d = 1.9$; and $W_c = 1.9 \times 120 \times 4.5 \times 2.5 = 2{,}565$ lb/ft (37,450 N/m).

For conservative design, the prism load should be determined. The prism load on flexible sewer pipe will be $W = 2.5 \times 12 \times 120 = 3{,}600$ lb/ft (52,460 N/m).

### 9.2.2.4. *Loads for Positive-Projecting Embankment Conditions*

This type of installation is normally used when the pipe is installed in a relatively flat stream bed or drainage path. The pipe is installed on the original ground or compacted fill, and then covered by an earth fill or embankment.

d on a 24-inch-diameter rigid sewer pipe
nditions.
wall thickness is 2 inches; $B_c = 24 + 4 =$
2.00 = 4.33 ft; and $w = 120\ \text{lb/ft}^3$ for satu-
$_d = 14/4.33 = 3.24$; $C_d$ (from Fig. 9-4) =
$^2 = 4{,}720$ lb/ft (68,880 N/m).

l on the same-sized sewer laid on a con-
eting to be removed.
s is 2 inches; the cradle projection outside
inches on each side); and the maximum
itside of sheeting is 14 inches. Then $B_d =$
4) = 64 inches = 5.33 ft.
ely wide trench, a check should be made
nch; $B_c = 2.33 = 2.33$ ft; $H = 14$ ft; $r_{sd}p =$

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ds are equal by both trench sewer theory
$_d = 2.33 \times 2.39 = 5.57 > 5.33$; $H/B_d =$
= 1.85; and $W_c = 1.85 \times 120 \times (5.33)^2 =$

on the same sewer if (rough) sheeting is

; $H/B_d = 14/5 = 2.8$; $C_d$ (from Fig. 9-4) =
= 5,750 lb/ft (84,040 N/m).

on a 30-inch-diameter flexible sewer pipe
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ning 120 lb/ft$^3$ and that it will be well-
er pipe. Then $H = 12$ ft; $B_d = 4.5$ ft; $B_c =$
$W_c = 1.9 \times 120 \times 4.5 \times 2.5 = 2{,}565$ lb/ft

prism load should be determined. The
will be $W = 2.5 \times 12 \times 120 = 3{,}600$ lb/ft

*ting Embankment Conditions*

nally used when the pipe is installed in a
nage path. The pipe is installed on the
ll, and then covered by an earth fill or

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The load on a positive-projecting sewer pipe is equal to the weight of the prism of soil directly above the structure, plus (or minus) vertical shearing forces which act on vertical planes extending upward into the embankment from the sides of the sewer pipe. For an embankment installation of sufficient height, these vertical shearing forces may not extend to the top of the embankment, but terminate in a horizontal plane at some elevation above the top of the sewer pipe known as the "plane of equal settlement," as shown in Fig. 9-7.

The shear increment acts downward when $(s_m + s_g) > (s_f + d_c)$ and vice versa. In this expression, $s_m$ is the compression of the columns of soil of height $pB_c$; $s_g$ is the settlement of the natural ground adjacent to the sewer pipe; $s_f$ is the settlement of the bottom of the sewer pipe; and $d_c$ is the deflection of the sewer pipe.

The location of the plane of equal settlement is determined by equating the total strain in the soil above the pipe to that in the side fill plus the settlement of the critical plane. When the plane of equal settlement is an imaginary plane above the top of the embankment (i.e., shear forces extend to the top of the embankment), the installation is called either "complete trench condition" or "complete projection condition," depending on the direction of the shear forces. When the plane of equal settlement

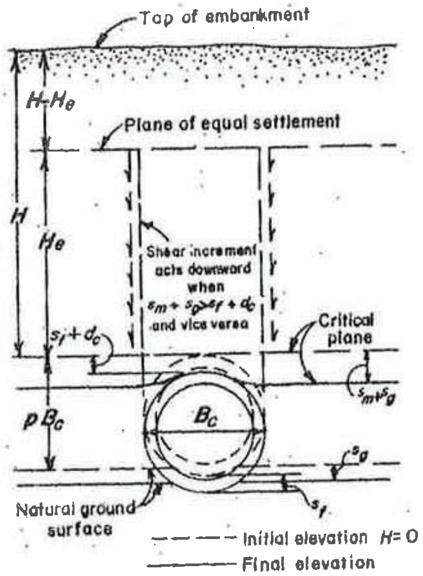

FIGURE 9-7. *Settlements that influence loads on positive-projecting sewer pipe.* $s_g$, *settlement of natural ground adjacent to sewer pipe;* $s_m$, *compression of columns of soil of height* $pB_c$; $d_c$, *deflection of sewer pipe; and* $s_f$, *settlement of bottom of sewer pipe.*

Courtesy of American Concrete Pipe Association, Irving, Tex.

is located within the embankment as shown in Fig. 9-7, the installation is called an "incomplete trench condition" or "incomplete projection condition," as shown in Fig. 9-8.

In computing the settlement values, the effect of differential settlement caused by any compressible layers below the natural ground surface also must be considered. An exceptional situation for a sewer pipe in a trench can be encountered where the natural soil settles more than the trench backfill, such as where the natural soils are organic or peat and the trench backfill is relatively incompressible compacted fill. A more common situation is where the sewer pipe is pile-supported in organic soils. In such cases, the load on the sewer pipe is greater than that of the prism above the pipe, and down-drag loads should be considered in the design of the piles.

*9.2.2.4.1. Fill Loads*

The fill load on a pipe installed in a positive-projecting embankment condition is computed by the equation:

$$\boxed{W_c = C_c w B_c^2} \tag{9-8}$$

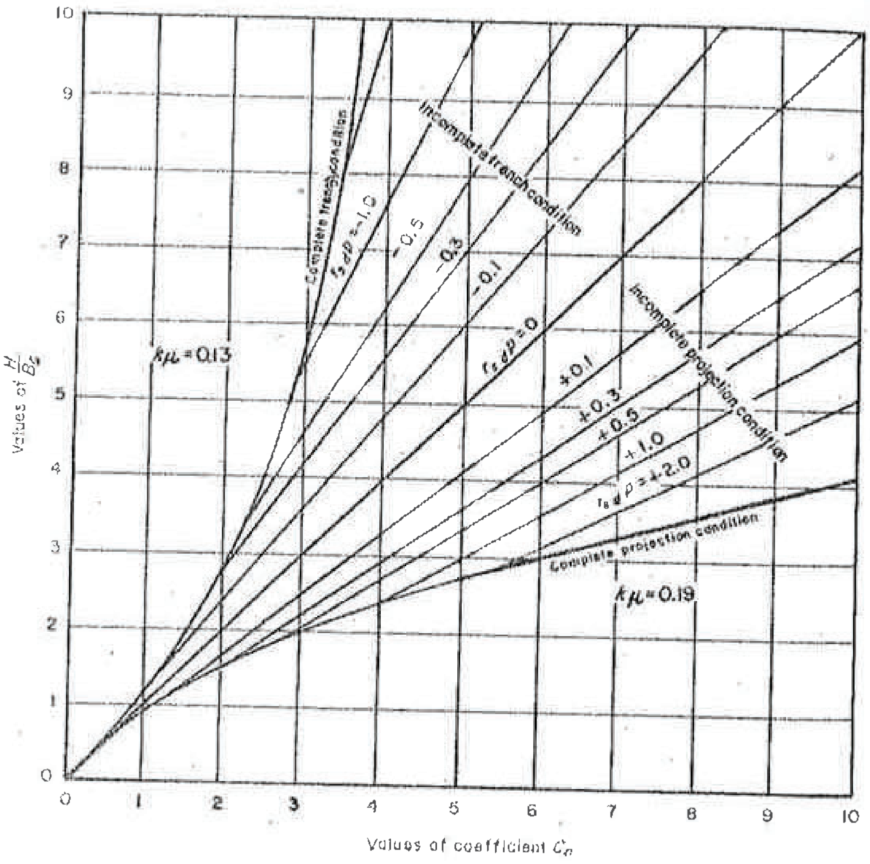

*FIGURE 9-8. Diagram for coefficient $C_c$ for positive-projecting sewer pipes.* Courtesy of American Concrete Pipe Association, Irving, Tex.

as shown in Fig. 9-7, the installation is
tion" or "incomplete projection condi-

lues, the effect of differential settle-
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ceptional situation for a sewer pipe in
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pe is pile-supported in organic soils,
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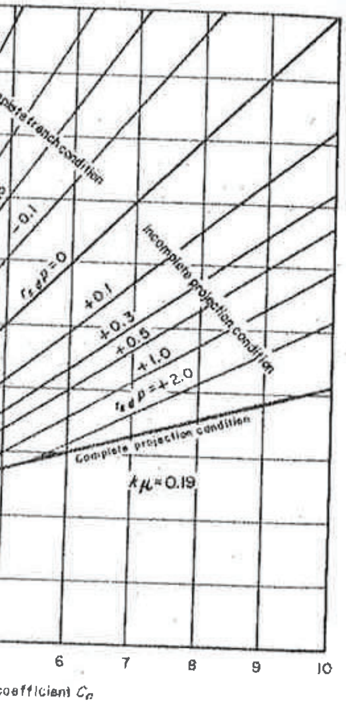
n a positive-projecting embankment
on:

$$vB_c^2 \qquad (9\text{-}8)$$



for positive-projecting sewer pipes.
ssociation, Irving, Tex.

where
$W_c$ = load, lb/ft (N/m)
$w$ = density of backfill material, lb/ft$^3$ (kg/m$^3$)
$B_c$ = outside horizontal span of the pipe, ft (m)

and

$$C_c = \frac{e^{-2K\mu\frac{H}{B_c}} - 1}{2K\mu} \text{ when } H \le H_e \qquad (9\text{-}9)$$

and

$$C_c = \frac{e^{-2K\mu\frac{H}{B_c}} - 1}{2K\mu} + \left(\frac{H}{B_c} - \frac{H_e}{B_c}\right) e^{2K\mu\frac{H_e}{B_c}} \text{ when } H > H_e \qquad (9\text{-}10)$$

The settlements that influence loads on positive-projecting embankment installations are shown in Fig. 9-7. To evaluate the $H_e$ term in Eq. (9-9), it is necessary to determine, numerically, the relationship between the pipe deflection and the relative settlement between the prism of fill directly above the pipe and the adjacent soil. This relationship is defined as a settlement ratio, expressed as:

$$r_{sd} = \frac{(s_m + s_g) - (s_f + d_c)}{s_m} \qquad (9\text{-}11)$$

where $s_g$ is the settlement of the natural ground adjacent to the sewer pipe, $s_m$ is the compression of the columns of soil of height $pB_c$, $(s_m + s_g)$ is the settlement of the critical plane, $s_f$ is the settlement of the bottom of the sewer pipe, and $d_c$ is the deflection of the sewer pipe.

The fill load on a pipe installed in a positive-projecting embankment condition is influenced by the product of the settlement ratio, $r_{sd}$, and the projection ratio, $p$. The projection ratio $p$ is the vertical distance the pipe projects above the original ground surface, divided by the outside vertical height of the pipe ($B_c'$). Recommended settlement ratio design values are listed in Table 9-1.

Figure 9-8 is a graphical solution by Spangler that permits reasonable estimates of $C_c$ for various conditions of $H/B_c r_{sd}$ and $p$. Since the effect of $\mu'$ is nominal, $K\mu'$ was assumed to be 0.19 for the projection condition and 0.13 for the trench condition. Figure 9-8 will provide an estimate of $C_c$, which is well within the accuracy of the theoretical assumptions.

In Fig. 9-8, the family of straight lines represents the incomplete conditions, whereas the curves represent the complete conditions. The straight

If the material within the subtrench is densely compacted, Eq. (9-12) can be expressed as:

$$W_c = C_n w B_d B_d' \tag{9-15}$$

where $B_d'$ is the average of the trench width and the outside diameter of the pipe.

In the case of the induced trench sewer pipe, $B_c$ is substituted for $B_d$ in Eq. (9-12). $B_c$ is the width of the sewer pipe in feet or meters, assuming the trench in the fill is no wider than the sewer pipe.

The settlements that influence loads on negative-projecting embankment installations are shown in Fig. 9-10. To evaluate the $H_e$ term in Eqs. (9-13) and (9-14), it is necessary to determine, numerically, the relationship between the pipe deflection and the relative settlement between the prism of fill directly above the pipe and the adjacent soil. This relationship is defined as a settlement ratio, expressed as:

$$r_{sd} = \frac{s_g - (s_d + s_f + d_c)}{s_d} \tag{9-16}$$

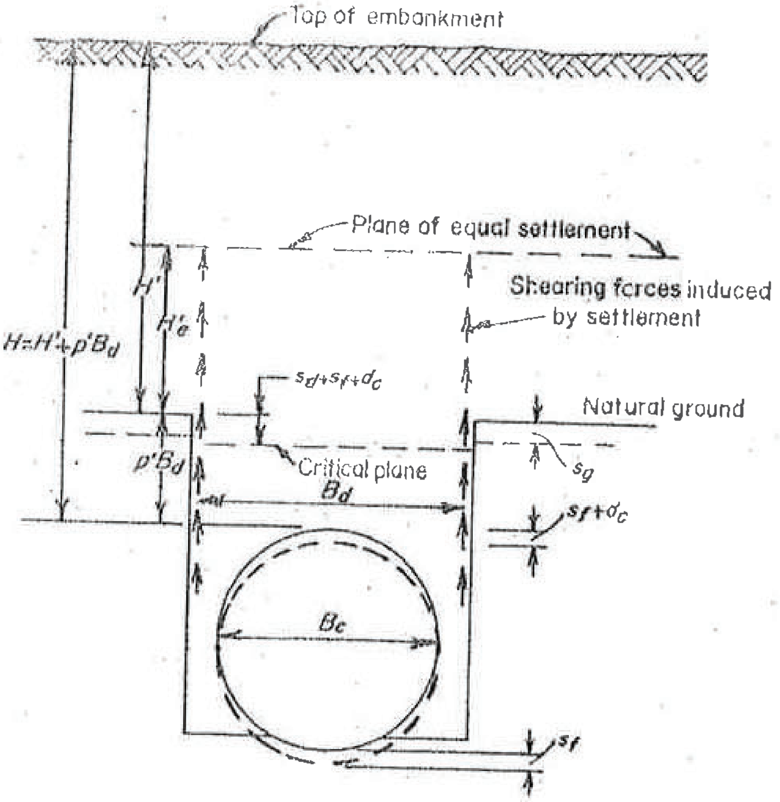


FIGURE 9-10. *Settlements that influence loads on negative-projecting sewer pipes.*

Recommended settlement ratio design values are listed in Table 9-1. For negative-projecting embankment installations, the projection ratio, $p'$, is the vertical distance from the top of the pipe to the original ground surface or compacted fill, at the time of installation, divided by the width of the trench.

In general, the notation for calculation of loads on negative-projection conditions follows that given for positive projections. The depth of the top of pipe below the critical plane is defined by $p'B_d$, in which $p'$ is defined as the negative projection ratio. If the natural ground surface is on a transverse slope, the vertical distance may be taken as the average distance from the top of the pipe to the top of the trench, at both sides of the trench. Furthermore, $s_d$ is defined as the compression within the fill, for height $p'B_d$.

Present knowledge of the value of the settlement ratio for induced trench sewer pipe is meager. Research reported by Taylor (1971) of the Illinois Department of Highways indicated that the measured settlement ratio of 48-inch (1,200-mm) reinforced concrete pipe culvert installed under induced trench conditions under 30 ft (9 m) of fill, varied from $-0.25$ to $-0.45$.

Figure 9-11 provides values of $C_n$ versus $H/B_d$ for various values of $r_{sd}$, for values of $p'$ equal to 0.5, 1, 1.5, and 2. For other values of $p'$ between 0.5 and 2, values of $C_n$ may be obtained by interpolation. As with the previous figures, only one value of $K\mu$ is used. The family of straight lines represents the incomplete conditions, whereas the curves represent the complete conditions. The straight lines intersect the curves at the point where the height of the plane of equal settlement, $H_e$, equals the height of the top of embankment, $H$. These diagrams can therefore be used to determine the height of the plane of equal settlement above the top of the pipe.

### 9.2.2.6. *Sewer Pipe under Sloping Embankment Surfaces*

Cases arise where the sewer pipe has different heights of fill on the two sides because of the sloping surface of the embankment or when an embankment exists on one side of the sewer pipe only. Design based on the larger fill height may not yield conservative values. When yielding ground may envelope the sewer pipe, a surcharge on one side of the sewer pipe may result in vertical displacement.

## Sample Calculations

*Example 9-5.* Determine the load on a 48-inch-diameter reinforced concrete sewer pipe installed as a positive-projecting pipe under a fill 32 ft high above the top of the pipe. The wall thickness of the sewer pipe is 5 inches and the density of fill is 125 lb/ft$^3$.

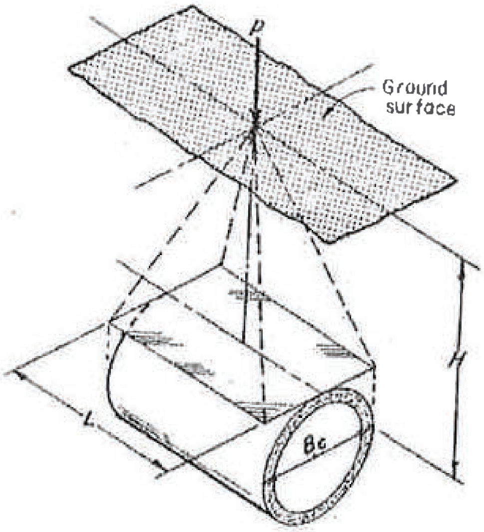


*FIGURE 9-14. Concentrated superimposed load vertically centered over sewer pipe.*

at the vertical axis directly beneath the point of application and decreases in all directions outward from the center of application. As the distance between the plane and the surface increases, the intensity of the load at any point on the plane decreases.

## 9.3.1. General Pressure Distribution

Concentrated and distributed superimposed loads should be considered in the structural design of sewers, especially where the depth of earth cover is less than 8 ft (2.4 m). Where these loads are anticipated, they are added to the predetermined trench load. Superimposed loads are calculated by use of Holl's and Newmark's modifications to Boussinesq's equation (Spangler 1946).

### 9.3.1.1. *Concentrated Loads*

Holl's integration of Boussinesq's solution leads to the following equation for determining loads due to superimposed concentrated load, such as a truck wheel load (Fig. 9-14):

$$\boxed{W_{sc} = C_s PF/L} \qquad (9\text{-}19)$$

where

$W_{sc}$ = the load on the conduit, in lb/ft (kg/m) of length
$P$ = the concentrated load, in lb (kg)
$F$ = the impact factor

TABLE 9-3. Values of Load Coefficientss, $C_s$, for Concentrated and Distributed Superimposed Loads Vertically Centered Over Conduit*

| $\frac{D}{2H}$ or $\frac{B_c}{2H}$ | $\frac{M}{2H}$ or $\frac{L}{2H}$ 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.5 | 0.7 | 0.8 | 0.9 | 1.0 | 1.2 | 1.5 | 2.0 | 5.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.1 | 0.019 | 0.037 | 0.053 | 0.067 | 0.079 | 0.089 | 0.097 | 0.103 | 0.108 | 0.112 | 0.117 | 0.121 | 0.124 | 0.128 |
| 0.2 | 0.037 | 0.072 | 0.103 | 0.131 | 0.155 | 0.174 | 0.189 | 0.202 | 0.211 | 0.219 | 0.229 | 0.238 | 0.244 | 0.248 |
| 0.3 | 0.053 | 0.103 | 0.149 | 0.190 | 0.224 | 0.252 | 0.274 | 0.292 | 0.306 | 0.318 | 0.333 | 0.345 | 0.355 | 0.360 |
| 0.4 | 0.067 | 0.131 | 0.190 | 0.241 | 0.284 | 0.320 | 0.349 | 0.373 | 0.391 | 0.405 | 0.425 | 0.440 | 0.454 | 0.460 |
| 0.5 | 0.079 | 0.155 | 0.224 | 0.284 | 0.336 | 0.379 | 0.414 | 0.441 | 0.463 | 0.481 | 0.505 | 0.525 | 0.540 | 0.548 |
| 0.6 | 0.089 | 0.174 | 0.252 | 0.320 | 0.379 | 0.428 | 0.467 | 0.499 | 0.524 | 0.544 | 0.572 | 0.596 | 0.613 | 0.624 |
| 0.7 | 0.097 | 0.189 | 0.274 | 0.349 | 0.414 | 0.467 | 0.511 | 0.546 | 0.584 | 0.597 | 0.628 | 0.650 | 0.674 | 0.688 |
| 0.8 | 0.103 | 0.202 | 0.292 | 0.373 | 0.441 | 0.499 | 0.546 | 0.584 | 0.615 | 0.639 | 0.674 | 0.703 | 0.725 | 0.740 |
| 0.9 | 0.108 | 0.211 | 0.306 | 0.391 | 0.463 | 0.524 | 0.574 | 0.615 | 0.647 | 0.673 | 0.711 | 0.742 | 0.766 | 0.784 |
| 1.0 | 0.112 | 0.219 | 0.318 | 0.405 | 0.481 | 0.544 | 0.597 | 0.639 | 0.673 | 0.701 | 0.740 | 0.774 | 0.800 | 0.816 |
| 1.2 | 0.117 | 0.229 | 0.333 | 0.425 | 0.505 | 0.572 | 0.628 | 0.674 | 0.711 | 0.740 | 0.783 | 0.820 | 0.849 | 0.868 |
| 1.5 | 0.121 | 0.238 | 0.345 | 0.440 | 0.525 | 0.596 | 0.650 | 0.703 | 0.742 | 0.774 | 0.820 | 0.861 | 0.894 | 0.916 |
| 2.0 | 0.124 | 0.244 | 0.355 | 0.454 | 0.540 | 0.613 | 0.674 | 0.725 | 0.766 | 0.800 | 0.849 | 0.894 | 0.930 | 0.956 |

*Influence coefficients for solution of Holl's and Newmark's integration of the Boussinesq equation for vertical stress.

TABLE 9-4. Impact Factors for Highway Truck Loads

| *H*, Height of Cover | *F*, Impact Factor |
|---|---|
| 0 to 1 ft (0 to 0.30 m) | 1.3 |
| 1 ft, 1 inch to 2 ft (0.31 to 0.61 m) | 1.2 |
| 2 ft, 1 inch to 3 ft (0.62 to 0.91 m) | 1.1 |
| >3 ft (>0.91 m) | 1 |

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As the depth, *H*, increases, the critical loading configuration can be either one HS-20 wheel load, two HS-20 wheel loads in the passing mode, or the alternate load in the passing mode. Since the exact geometric relationship of individual or combinations of surface wheel loads cannot be anticipated, the most critical loading configurations and the outside dimensions of the distributed load areas within the indicated cover depths are summarized in Table 9-5.

### 9.3.1.4. *Railroad Loads*

In determining the live load transmitted to a pipe installed under railroad tracks, the weight on the locomotive driver axles plus the weight of the track structure, including ballast, is considered to be uniformly distributed over an area equal to the length occupied by the drivers multiplied by the length of ties. Typically, tie length is assumed to be 8.5 ft (2.6 m). The American Railway Engineering and Maintenance of Way Association (AREMA) recommends a Cooper E80 loading with axle loads and axle spacing, as shown in Fig. 9-20. In addition, 200 lb/ft (2,900 N/m) should be allowed for the weight of the track structure.

Typically, railroads require an impact factor of 1.75 for depth of cover up to 5 ft (1.5 m). Between 5 and 30 ft (1.5 and 9.1 m), the impact factor is reduced by 0.03 per ft (0.1 per m) of depth. Below a depth of 30 ft (9.1 m), the impact factor is 1.

TABLE 9-5. Critical Loading Configurations

| *H* | *P* | Distributed Load Area |
|---|---|---|
| <1.33 ft (<0.40 m) | 16,000 lb (71,170 N) | $1.67 + 1.75H\ (0.83 + 1.75H)$ |
| 1.33 to 4.1 ft (0.41 to 1.25 m) | 32,000 lb (142,340 N) | $5.67 + 1.75H\ (0.83 + 1.75H)$ |
| >4.1 ft (>1.25 m) | 48,000 lb (213,515 N) | $5.67 + 1.75H\ (4.83 + 1.75H)$ |

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uponor

# Sclairpipe®

## VERSATILE HIGH DENSITY POLYETHYLENE PIPE

## Choose the size that's right for you

Sclairpipe is available in standard Dimensional Ratio's (DR's), in sizes ranging from 4″ to 48″ in diameter. Sclairpipe is available in PE 3608 and PE 4710. With the higher allowable stress rating of PE 4710, the pipe wall can be thinner for the same pressure rating (higher DR).

The Dimensional Ratio relates the minimum wall thickness of the pipe to its outside diameter, and is important to define the pressure rating of a particular pipe. The maximum continuous operating pressure stated is based on the allowable hydrostatic design stress of each specific material (per ASTM D3350 and PPI's TR-3), and the pipe wall thickness (DR), at a service temperature of 73.4°F.

**Uponor, Sclairpipe Product Range, IPS Size, PE3608**

| | PE3608 | | | DR32.5 (50 psi) | | | DR26 (64 psi) | | | DR21 (80 psi) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nominal Pipe Size | Minimum Outside Diameter *(inches)* | Maximum Outside Diameter *(inches)* | Average Outside Diameter *(inches)* | Average Inside Diameter *(inches)* | Minimum Wall Thickness *(inches)* | Average Weight *(lbs/ft)* | Average Inside Diameter *(inches)* | Minimum Wall Thickness *(inches)* | Average Weight *(lbs/ft)* | Average Inside Diameter *(inches)* | Minimum Wall Thickness *(inches)* | Average Weight *(lbs/ft)* |
| 4 | 4.48 | 4.52 | 4.50 | 4.21 | 0.138 | 0.83 | 4.13 | 0.173 | 1.03 | 4.05 | 0.214 | 1.26 |
| 5 | 5.54 | 5.59 | 5.56 | 5.20 | 0.171 | 1.27 | 5.11 | 0.214 | 1.57 | 5.00 | 0.265 | 1.93 |
| 6 | 6.60 | 6.65 | 6.63 | 6.19 | 0.204 | 1.80 | 6.08 | 0.255 | 2.23 | 5.96 | 0.315 | 2.73 |
| 7 | 7.09 | 7.16 | 7.13 | 6.66 | 0.219 | 2.08 | 6.54 | 0.274 | 2.58 | 6.41 | 0.339 | 3.16 |
| 8 | 8.59 | 8.66 | 8.63 | 8.06 | 0.265 | 3.05 | 7.92 | 0.332 | 3.78 | 7.75 | 0.411 | 4.63 |
| 10 | 10.70 | 10.80 | 10.75 | 10.05 | 0.331 | 4.74 | 9.87 | 0.413 | 5.87 | 9.66 | 0.512 | 7.19 |
| 12 | 12.69 | 12.81 | 12.75 | 11.92 | 0.392 | 6.66 | 11.71 | 0.490 | 8.26 | 11.46 | 0.607 | 10.12 |
| 13 | 13.31 | 13.44 | 13.38 | 12.50 | 0.412 | 7.33 | 12.28 | 0.514 | 9.09 | 12.02 | 0.637 | 11.14 |
| 14 | 13.94 | 14.06 | 14.00 | 13.09 | 0.431 | 8.03 | 12.86 | 0.538 | 9.95 | 12.59 | 0.667 | 12.20 |
| 16 | 15.93 | 16.07 | 16.00 | 14.96 | 0.492 | 10.49 | 14.70 | 0.615 | 13.00 | 14.38 | 0.762 | 15.94 |
| 18 | 17.92 | 18.08 | 18.00 | 16.83 | 0.554 | 13.28 | 16.53 | 0.692 | 16.46 | 16.18 | 0.857 | 20.17 |
| 20 | 19.91 | 20.09 | 20.00 | 18.70 | 0.615 | 16.39 | 18.37 | 0.769 | 20.32 | 17.98 | 0.952 | 24.90 |
| 22 | 21.90 | 22.10 | 22.00 | 20.56 | 0.677 | 19.83 | 20.21 | 0.846 | 24.58 | 19.78 | 1.048 | 30.13 |
| 24 | 23.89 | 24.11 | 24.00 | 22.43 | 0.738 | 23.60 | 22.04 | 0.923 | 29.25 | 21.58 | 1.143 | 35.85 |
| 26 | 25.88 | 26.12 | 26.00 | 24.30 | 0.800 | 27.70 | 23.88 | 1.000 | 34.33 | 23.38 | 1.238 | 42.08 |
| 28 | 27.87 | 28.13 | 28.00 | 26.17 | 0.862 | 32.13 | 25.72 | 1.077 | 39.82 | 25.17 | 1.333 | 48.80 |
| 30 | 29.87 | 30.14 | 30.00 | 28.04 | 0.923 | 36.88 | 27.55 | 1.154 | 45.71 | 26.97 | 1.429 | 56.02 |
| 32 | 31.86 | 32.14 | 32.00 | 29.91 | 0.985 | 41.96 | 29.39 | 1.231 | 52.01 | 28.77 | 1.524 | 63.74 |
| 36 | 35.84 | 36.16 | 36.00 | 33.65 | 1.108 | 53.11 | 33.06 | 1.385 | 65.82 | 32.37 | 1.714 | 80.67 |
| 40 | 39.82 | 40.18 | 40.00 | 37.39 | 1.231 | 65.56 | 36.74 | 1.538 | 81.26 | 35.96 | 1.905 | 99.59 |
| 42 | 41.81 | 42.19 | 42.00 | 39.26 | 1.292 | 72.28 | 38.58 | 1.615 | 89.59 | 37.76 | 2.000 | 109.80 |
| 48 | 47.78 | 48.22 | 48.00 | 44.87 | 1.477 | 94.41 | 44.09 | 1.846 | 117.02 | 43.15 | 2.286 | 143.42 |

Pipe dimensions are in accordance with ASTM F714 and AWWA C906
Pressure Ratings are for water at 73.4 deg F.
Some of the pipe sizes and DR's above are available only on request. Check with your representative for availability.
Other dimensions and DR's not listed may be available upon special request.
All dimensions are in inches unless otherwise noted.
Weights are calculated by the methodology established in PPI's TR-7 and are applicable to PE 3608.

The standard stocked length of Sclairpipe pipe is 50 feet, in sizes above 4″ in diameter with longer lengths available on request.

**Please visit our web site (www.uponor.ca) and use our online design tools to determine the pipe size best suited to your specific application.**

| DR17 (100 psi) | | | DR13.5 (128 psi) | | | DR11 (160 psi) | | | DR9 (200 psi) | | | DR7.3 (254 psi) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average Inside Diameter *(inches)* | Minimum Wall Thickness *(inches)* | Average Weight *(lbs/ft)* | Average Inside Diameter *(inches)* | Minimum Wall Thickness *(inches)* | Average Weight *(lbs/ft)* | Average Inside Diameter *(inches)* | Minimum Wall Thickness *(inches)* | Average Weight *(lbs/ft)* | Average Inside Diameter *(inches)* | Minimum Wall Thickness *(inches)* | Average Weight *(lbs/ft)* | Average Inside Diameter *(inches)* | Minimum Wall Thickness *(inches)* | Average Weight *(lbs/ft)* |
| 3.94 | 0.265 | 1.54 | 3.79 | 0.333 | 1.90 | 3.63 | 0.409 | 2.29 | 3.44 | 0.500 | 2.73 | 3.19 | 0.616 | 3.26 |
| 4.87 | 0.327 | 2.35 | 4.69 | 0.412 | 2.91 | 4.49 | 0.506 | 3.50 | 4.25 | 0.618 | 4.18 | 3.95 | 0.762 | 4.99 |
| 5.80 | 0.390 | 3.33 | 5.58 | 0.491 | 4.12 | 5.35 | 0.602 | 4.96 | 5.06 | 0.736 | 5.92 | 4.70 | 0.908 | 7.08 |
| 6.24 | 0.419 | 3.85 | 6.01 | 0.528 | 4.77 | 5.75 | 0.648 | 5.74 | 5.45 | 0.792 | 6.85 | 5.06 | 0.976 | 8.18 |
| 7.55 | 0.507 | 5.65 | 7.27 | 0.639 | 6.99 | 6.96 | 0.784 | 8.41 | 6.59 | 0.958 | 10.04 | 6.12 | 1.182 | 11.99 |
| 9.41 | 0.632 | 8.77 | 9.06 | 0.796 | 10.86 | 8.68 | 0.977 | 13.07 | 8.22 | 1.194 | 15.59 | 7.63 | 1.473 | 18.63 |
| 11.16 | 0.750 | 12.34 | 10.75 | 0.944 | 15.28 | 10.29 | 1.159 | 18.38 | 9.75 | 1.417 | 21.94 | 9.05 | 1.747 | 26.21 |
| 11.71 | 0.787 | 13.58 | 11.27 | 0.991 | 16.81 | 10.80 | 1.216 | 20.23 | 10.22 | 1.486 | 24.14 | 9.49 | 1.832 | 28.84 |
| 12.25 | 0.824 | 14.88 | 11.80 | 1.037 | 18.42 | 11.30 | 1.273 | 22.17 | 10.70 | 1.556 | 26.45 | 9.93 | 1.918 | 31.60 |
| 14.00 | 0.941 | 19.44 | 13.49 | 1.185 | 24.06 | 12.92 | 1.455 | 28.95 | 12.23 | 1.778 | 34.55 | 11.35 | 2.192 | 41.27 |
| 15.76 | 1.059 | 24.60 | 15.17 | 1.333 | 30.45 | 14.53 | 1.636 | 36.64 | 13.76 | 2.000 | 43.72 | 12.77 | 2.466 | 52.23 |
| 17.51 | 1.176 | 30.37 | 16.86 | 1.481 | 37.59 | 16.15 | 1.818 | 45.24 | 15.29 | 2.222 | 53.98 | 14.19 | 2.740 | 64.48 |
| 19.26 | 1.294 | 36.75 | 18.55 | 1.630 | 45.48 | 17.76 | 2.000 | 54.74 | 16.82 | 2.444 | 65.31 | 15.61 | 3.014 | 78.02 |
| 21.01 | 1.412 | 43.74 | 20.23 | 1.778 | 54.13 | 19.37 | 2.182 | 65.14 | 18.35 | 2.667 | 77.73 | 17.03 | 3.288 | 92.85 |
| 22.76 | 1.529 | 51.33 | 21.92 | 1.926 | 63.52 | 20.99 | 2.364 | 76.45 | 19.88 | 2.889 | 91.22 | 18.45 | 3.562 | 108.97 |
| 24.51 | 1.647 | 59.53 | 23.60 | 2.074 | 73.67 | 22.60 | 2.545 | 88.66 | 21.40 | 3.111 | 105.80 | 19.87 | 3.836 | 126.38 |
| 26.26 | 1.765 | 68.34 | 25.29 | 2.222 | 84.57 | 24.22 | 2.727 | 101.78 | 22.93 | 3.333 | 121.45 | | | |
| 28.01 | 1.882 | 77.75 | 26.97 | 2.370 | 96.22 | 25.83 | 2.909 | 115.80 | 24.46 | 3.556 | 138.19 | | | |
| 31.51 | 2.118 | 98.41 | 30.35 | 2.667 | 121.78 | 29.06 | 3.273 | 146.57 | | | | | | |
| 35.01 | 2.353 | 121.49 | 33.72 | 2.963 | 150.35 | 32.29 | 3.636 | 180.95 | | | | | | |
| 36.76 | 2.471 | 133.94 | 35.40 | 3.111 | 165.76 | 33.91 | 3.818 | 199.49 | | | | | | |
| 42.01 | 2.824 | 174.94 | 40.46 | 3.556 | 216.50 | | | | | | | | | |

Sclair IPS Cut Sheet_PE3608_r201407

- All dimensions are in inches unless otherwise specified.
- Pressure ratings are based on load durations of 50 years at a service temperature of 73.4F. The HDS (pipe wall allowable stress) for PE 3608 and PE 4710 are 800 psi and 1,000 psi respectively.
- Dimensions and tolerances per ASTM F714. Pipe weights calculated using PPI TR-7 using PE3608 density of 0.953 gm/cc and 0.958 gm/cc for PE4710 materials.
- The ASTM D3350 cell classifications conform to the requirements of the applicable pipe specification (ASTM F714, AWWA C906, etc.).
- Contact Uponor Infra for sizes, DR's and DIPS offering not shown.

**Uponor Infra Ltd.**
6507 Mississauga Rd.
Mississauga ON  L5N 1A6
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Tel: 1-866-594- 7473
Fax: (905)-858-0208
Web: www.uponor.ca
E-mail: nainfra-sales@uponor.com

uponor

# 836K

## Landfill Compactor

### Engine

| | | |
|---|---|---|
| Engine Model | Cat® C18 ACERT™ | |
| Emissions | Meets U.S. EPA Tier 4 Final/EU Stage IV/ Korea Tier 4 Final emission standards or meets U.S. EPA Tier 3/EU Stage IIIA equivalent emission standards | |
| Rated Power (Lab) | 414 kW | 555 hp |
| Rated Power (Net ISO 14396) | 412 kW | 553 hp |
| Gross (SAE J1349) | 419 kW | 562 hp |

### Operating Specifications

| | | |
|---|---|---|
| Maximum Operating Weight (Tier 4 Final/Stage IV/Korea Tier 4 Final) – Multiple Blade and Wheel Offerings | 55 927 kg | 123,319 lb |
| Maximum Operating Weight (Tier 3/Stage IIIA equivalent) – Multiple Blade and Wheel Offerings | 55 617 kg | 122,615 lb |

# Lower your operating cost with industry leading efficiency.

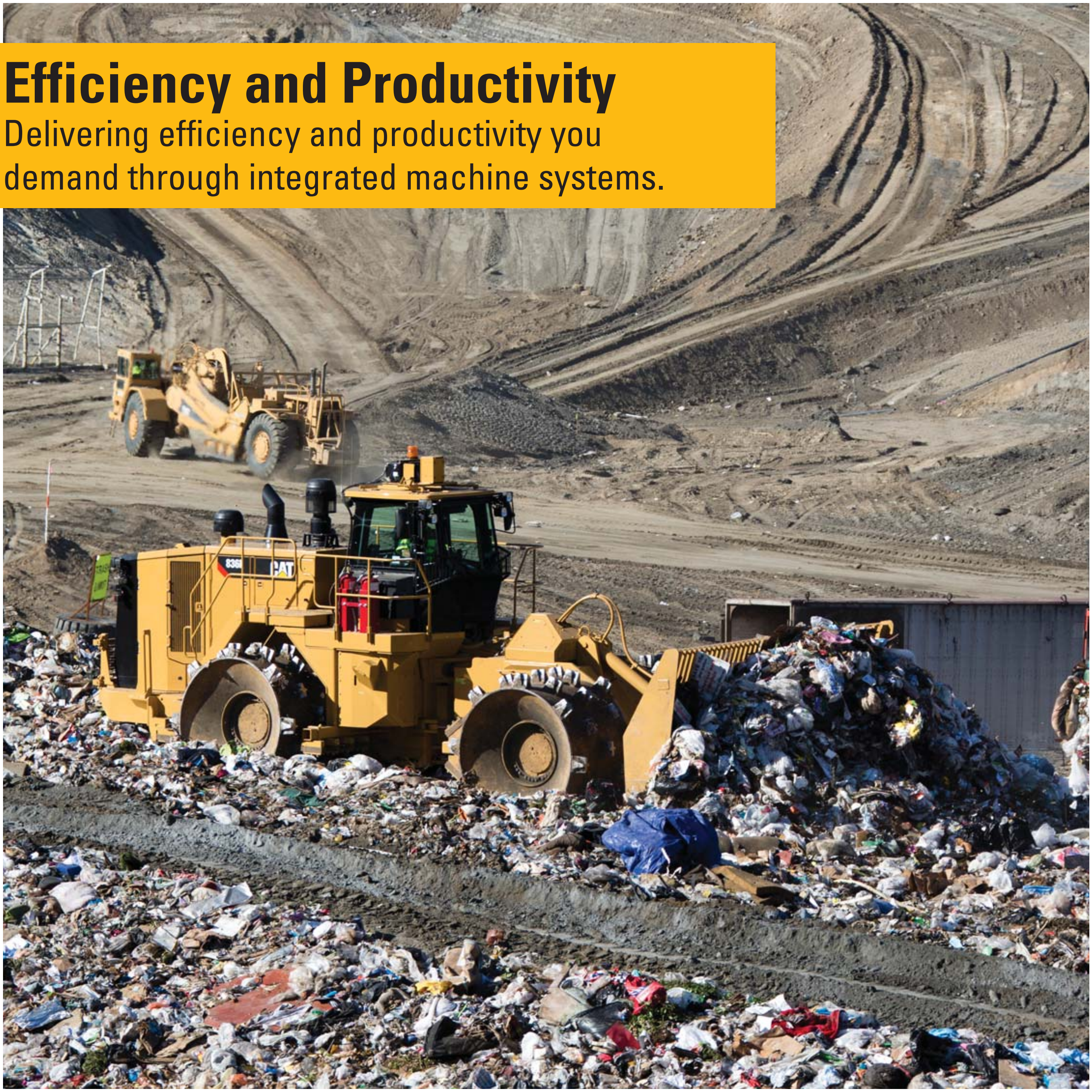
## Contents

**Cat Landfill Compactors are designed with durability built in, ensuring maximum availability through multiple life cycles. With optimized performance and simplified serviceability, our machines allow you to operate more efficiently and safely.**

**Introduced in 1993, the 836 has been the industry leader for over 20 years. Focused on helping our customers succeed, we have continued to build upon each new series. The 836K continues our legacy of reliability, performance, safety, operator comfort, serviceability, and efficiency.**

# Efficiency and Productivity

## Delivering efficiency and productivity you demand through integrated machine systems.



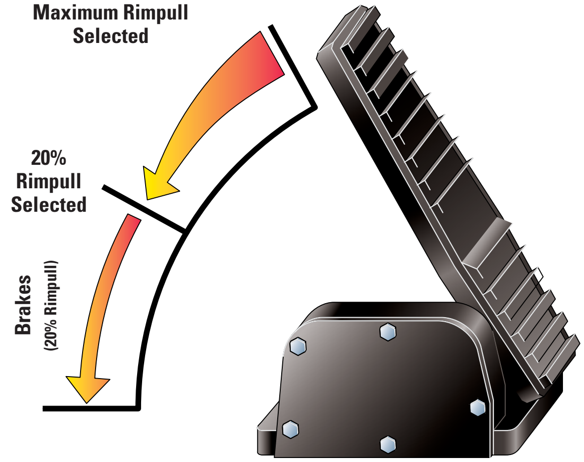
### Improved Hydraulic Efficiency

Efficiency at your landfill is critical for your business. Improved hydraulic efficiency is achieved with new flow sharing implement and steering variable displacement load sensing piston pumps. Since hydraulic flow is now on demand, you will see improved fuel efficiency.

## Impeller Clutch Torque Converter (ICTC)

Lower your cost per ton utilizing advanced ICTC

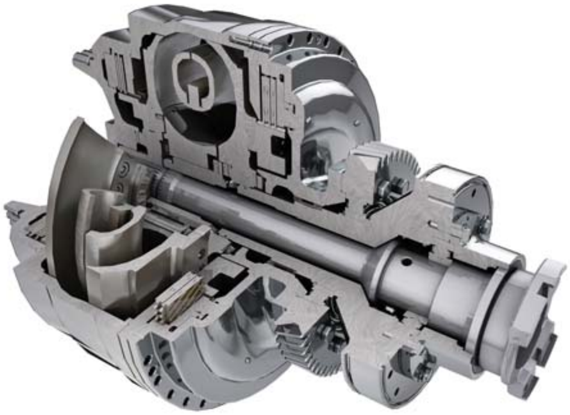
- Reduce wheel slippage and tip wear by modulating rimpull from 100 to 20 percent while depressing left pedal. After 20 percent rimpull is achieved the left pedal applies the brake.
- Reduce the potential for wheel slippage without reducing hydraulic efficiency.
- Improve fuel efficiency in certain applications with our lock-up clutch torque converter providing direct drive.



## Steering and Transmission Integrated Control System (STIC™)

Experience maximum responsiveness and control with STIC that combines directional selection, gear selection and steering into a single lever.

- Simple side-to-side motion turns machine right or left, minimizing operator movements.
- Easy to operate finger controlled gear selection.
- Smoother, faster cycles help reduce operator fatigue through the use of low effort integrated controls.



## Steering System

Confident machine operation starts with precise machine control enabled by the 836K's load sensing hydraulic steering system.

- Increase efficiency with our variable displacement piston pumps.
- Achieve precise positioning for easy steering in tight areas with 43 degrees each way of steering articulation.
- Enhance operator comfort with integrated steering and transmission control functions.

## Electro Hydraulic Controls

Operators increase productivity with our responsive implements feature.

- Operate comfortably through electronically controlled hydraulic cylinder stops.
- Handle easy-to-use soft detent controls.
- Conveniently set automatic implement kickouts from inside the cab.

# Structures

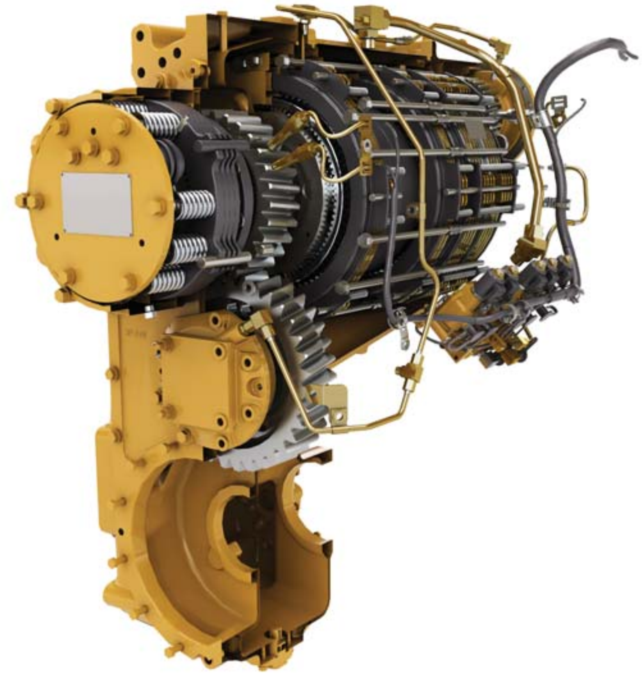
Best built for the toughest conditions.

### Robust Structures

Your bottom line is improved by highly durable structures that achieve multiple life cycles and withstand the toughest loading conditions.

- Full box-section rear frame resists torsional shock and twisting forces.
- Heavy-duty steering cylinder mounts efficiently transmit steering loads into the frame.
- Axle mounting has been optimized for increased structural integrity.
- Lower hitch pin, frame plate, and bearing size have been increased for longer life.

We know the harsh environment your machines encounter at the working face of your landfill on a daily basis. This is why the 836K is specifically designed and made with purpose built structures to remain safe and durable for the long run.



## Cat Planetary Powershift Transmission

Building your success begins with a best-in-class transmission.

- Consistent, smooth shifting and efficiency through integrated electronic controls that utilize Advanced Productivity Electronic Control Strategy (APECS).
- Long life and reliability through heat treat gear and metallurgy.
- Two forward and two reverse speeds to match your application.

## Cat C18 ACERT Engine

The Cat C18 ACERT engine is built and tested to meet your most demanding applications. Two engine options are available that meet Tier 4 Final/Stage IV/Korea Tier 4 Final emission standards or Tier 3/Stage IIIA equivalent emission standards.

- Fully integrated electronic engine controls works in concert with the entire machine to make your fuel go farther.
- Use less fuel idling with Engine Idle Shutdown.
- Maximized durability with Delayed Engine Shutdown.

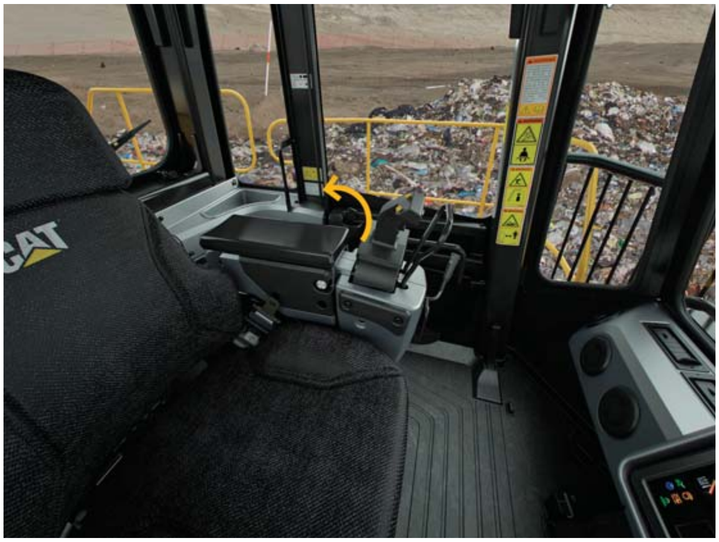
# Power Train

## Operate more efficiently with improved power and control.

### Cat Torque Converter with Lock-up Clutch

- Eliminates TC losses while lowering system heat.
- Improves travel speeds.
- Transfers more power to the ground and optimizes fuel efficiency in all applications.

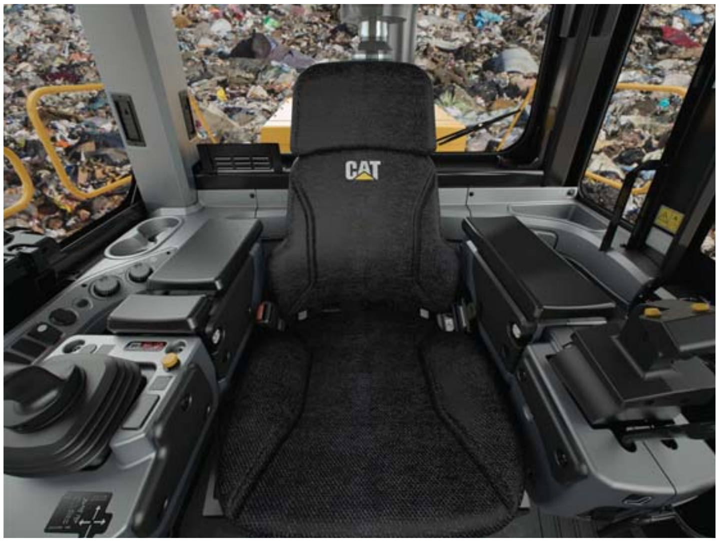
# Your operators can work more efficiently and stay comfortable with our customer-inspired cab features.



## Entry and Exit

Enter and exit the cab easily and safely with these newly designed, ergonomic features.

- Fold up STIC steer/armrest.
- Reduced access stairway angles.
- Standard stairway lighting.



## Cat Comfort Series III Seat

Enhance comfort and help reduce operator fatigue with Cat Comfort Series III seat.

- Mid back design and extra thick, contoured cushions.
- Air suspension system.
- Easy-to-reach seat levers and controls for six way adjustments.
- Seat-mounted implement pod and STIC steer that moves with the seat.
- 76 mm (3 in) wide retractable seat belt.

## Control Panel

Ergonomic placement of switches and information display keep your operators comfortable all day every day.

- Large backlit membrane switches feature LED activation indicators.
- Switches feature ISO symbols for quick function identification.
- Two position rocker switch activates the electro hydraulic park brake.

# Operator Station

Best-in-class operator comfort and ergonomics.

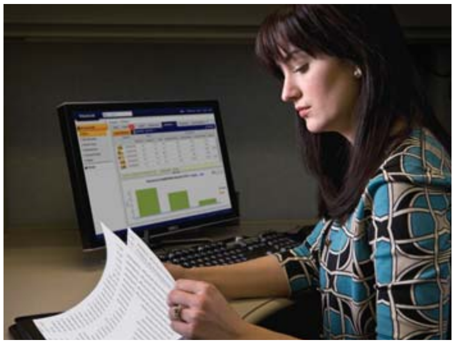
### Environment

Your operator's productivity is enhanced with our clean, comfortable cab environment.

- Experience reduced vibrations from isolation cab mounts and seat air suspension.
- Maintain desired cab temperature with automatic temperature controls.
- Pressurized cab with filtered air.
- Reduced sound levels.
- Convenient floor storage tray/lunch box.

# Integrated Technologies

Monitor, manage, and enhance your job site operations.



Cat Connect makes smart use of technology and services to improve your job site efficiency. Using the data from technology-equipped machines, you'll get more information and insight into your equipment and operations than ever before.

Cat Connect technologies offer improvements in these key areas:

EQUIPMENT MANAGEMENT

**Equipment Management** – increase uptime and reduce operating costs.

PRODUCTIVITY

**Productivity** – monitor production and manage job site efficiency.

SAFETY

**Safety** – enhance job site awareness to keep your people and equipment safe.

## LINK Technologies

LINK technologies wirelessly connect you to your equipment, giving you valuable insight into how your machine or fleet is performing so you can make timely, fact-based decisions that can boost job site efficiency and productivity.

### Product Link™/VisionLink®

Product Link is deeply integrated into your machine, giving you access to timely information like machine location, hours, fuel usage, idle time and event codes via the online VisionLink user interface to help you effectively manage your fleet and lower operating costs.

VIMS™ data, like events, histograms, and historical trends, can be downloaded for analysis, giving you the information you need to proactively maintain fleet health and optimize performance and uptime.

## DETECT Technologies

DETECT technologies help keep people and equipment safe by enhancing operator awareness of the work area around working equipment and by monitoring and reporting unsafe conditions, like avoidance zones.

### Rear Vision Camera

The rear vision camera greatly enhances visibility behind the machine to help the operator work more productively. Work with greater confidence and at peak potential while keeping people and assets safe.

## COMPACT Technologies

COMPACT technologies combine advanced compaction measurement, in-cab guidance, and reporting capabilities to help you consistently meet compaction targets fast, uniformly, in fewer passes – saving on fuel and rework.

### AccuGrade™ Compaction Control

The dealer-installed AccuGrade system uses the Cat Compaction Algorithm to measure effective compaction value and deliver real-time 3D pass mapping guidance to the cab, indicating where to work and when layers are compacted to optimum density. Pass mapping helps eliminate voids, optimize cell space, and document results. VisionLink 3D Project Monitoring provides landfill managers with detailed compaction analysis to more effectively monitor and manage their operation.

# Serviceability

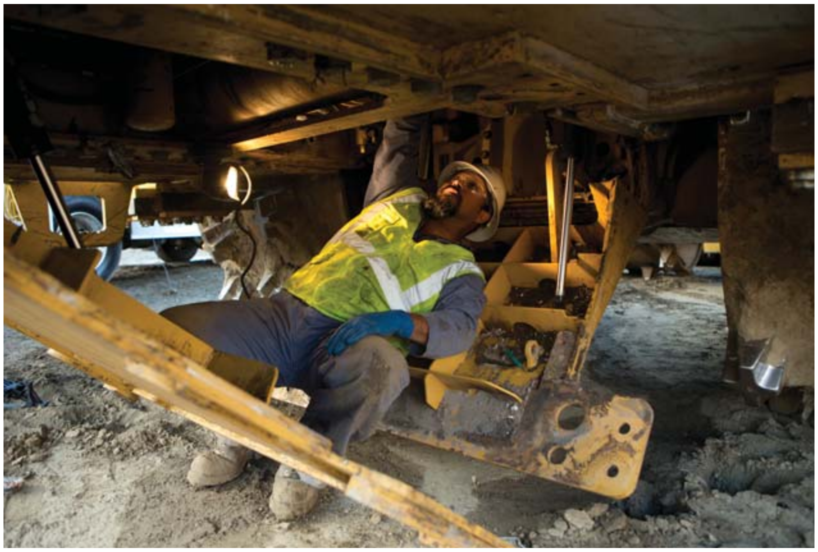
Enabling high uptime by reducing your service time.

**We can help you succeed by ensuring your 836K has design features to reduce your downtime.**

- Ground level swing-out reversing fan for quick inspection and easy cleanout.
- Safe and convenient service with ground level or platform access and grouped service points.
- Swing-out doors on both sides of the engine compartment provide easy access to important daily service checks.
- Ecology drains for ease of service and prevention of spills.
- Reduce downtime with VIMS system notifications so your operators and technicians can resolve any problems before failure.
- Quick visual inspection and minimize fluid contamination with sight gauges.
- Pressurized, temperature controlled engine compartment prevents small debris from entering and prevents extreme temperatures.

# Customer Support

Your Cat dealers know how to keep your machines productive.



### Legendary Cat Dealer Support

A valued partner, your Cat dealer is available whenever you need them.

- Preventive maintenance programs and guaranteed maintenance contracts.
- Best-in-class parts availability.
- Improve your efficiency with operator training.
- Genuine Cat Remanufactured parts.

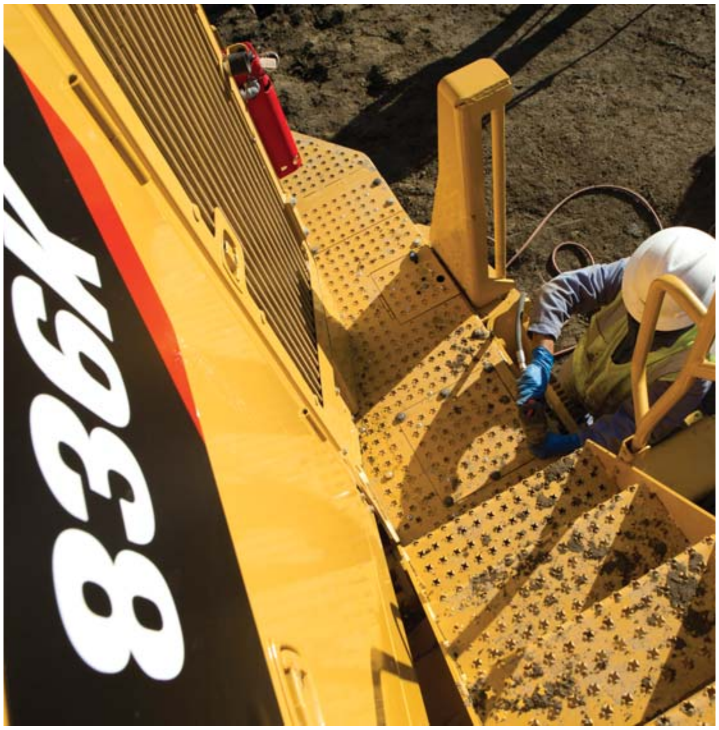
# Safety

Making your safety our priority.

We are constantly improving our products in an effort to provide a safe work environment for the operator and those who work on your job site.

## Machine Access

- Left and right hand removable or optional swing-out stairs with 45 degree angle enhance safety for operators getting on and off the 836K.
- Continuous walkway with non-skid surfaces are designed into the service areas.
- Maintain three points of contact at all times through ground level or platform accessible service areas.



## Visibility

- Optional heated mirrors ensure enhanced visibility for safe operation.
- Standard Cat Vision with in-cab monitor increase operator awareness around the machine.
- Optional LED lights provide excellent workspace visibility.
- Optional cab mounted LED warning beacons.

## Operator Environment

- Reduced vibrations to the operator with isolated cab mounts and seat mounted implement and steering controls.
- Low interior sound levels.
- Pressurized cab with filtered air.
- Standard 76 mm (3 in) seat belts on the operator seat.

# Sustainability

## Stewards of the environment.

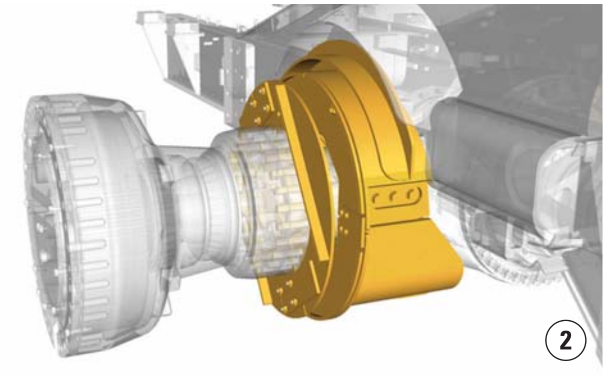
### Protecting the Environment

Environmental responsibility is designed and built into our 836K's features.

- Burns less fuel than the previous model.
- Engine Idle Shutdown can help you save fuel by avoiding unnecessary idling.
- Built for multiple lives, the Cat 836K is one of the most rebuilt products. To assist with maximizing machine life, Caterpillar provides a number of sustainable options such as our Reman and Certified Rebuild programs. In these programs, reused or remanufactured components can deliver cost savings of 40 to 70 percent, which lowers operating cost while benefiting the environment.
- Caterpillar offers retrofit packages to bring new features to older machines, maximizing your resource. And, when you go through the Cat Certified Rebuild program, these retrofit kits are part of the rebuild process.

# Waste Protection

## Maximize uptime, long life – it's what you expect from your bottom line.



### Guarding

Working in the toughest application, the purpose built 836K Landfill Compactor has specialized waste guarding to protect key components and systems from damage, debris, chemicals, premature wear, or wrapping of the material around components. This additional guarding includes:

- **Engine and Power Train Guards** – Hydraulically actuated guards help prevent trash build-up and shield components.
- **Front Frame Guards** – Front frame guards prevent trash build-up inside the frame. This guard further protects components and hydraulic lines.
- **Axle Wrapping and Seal Guarding** – The guarding prevents material from wrapping and binding around the axles, as well as assist in ease of cleaning.
- **Major System Guarding and Sight Gauges** – The hydraulic tank, the hydraulic system oil tube, and transmission oil tube are guarded to resist damage from debris. The sight gauges for the hydraulic and transmission are easily visible from ground level. The fuel tank is positioned away from the debris in the front frame and is easily accessed.
- **Air Inlet Screen** – The vertically corrugated, fine mesh, air inlet screen helps reduce trash from entering the radiator area and allows for debris to fall off.
- **Striker Bars and Optional Cleaner Fingers** – Striker bars are located in front of and behind the rear wheels and behind the front wheels. Striker bars help to keep wheels free of debris to assist the wheel step tips in maintaining good traction. In cohesive material or severe packing conditions, optional cleaner fingers are available to further assist in keeping the wheel step tips clean.
- **Extended Roof** – An oversized roof extends past the cab doors and windows to minimize debris build up.

*1) Engine and Power Train Guards 2) Axle Guards*
*3) Air Inlet Screen 4) Striker Bars/Cleaner Fingers*

# Wheels and Tips

More options to fit your operation.

### New Long Life Paddle and Plus Design Compactor Tips

Providing up to 40% longer life than previous offering.

Designed specifically to compliment Cat machines.

Improving machine performance!
- Longer wear life
- Maintaining traction

Four new wheel and tip configurations are available to meet your particular application:

1) **Paddle Tip** – High performance and less fuel burn with more traction and less weight.

2) **Plus Tip** – Traditional design for increased side slope stability.

3) **Combination Tip** – Both paddle and plus tips to give high performance with side slope stability.

4) **Diamond Tip** – Longest life tip on the market with reputation of reliability that is world class in the waste tip industry.

①

②

③

④

# Operating Costs

## Save time and money by working smart.

Data from customer machines show Cat landfill compactors are among the most fuel efficient machines in the industry. Several features contribute to this excellent fuel efficiency:

- **Positive Flow Control Hydraulics** – Provides only the hydraulic flow required by the implement and steering systems for improved fuel efficiency and greater rimpull.
- **ACERT Engine** – Advanced engine controls maximizes power and efficiency.
- **Engine Idle Shutdown** – Automatic engine and electrical system shutdown conserves fuel.
- **Lockup Torque Converter** – Transfers more power to the ground and optimizes fuel efficiency in all applications.
- **Advanced Productivity Electronic Control Strategy (APECS)** – All new APECS transmission controls provides greater momentum on grades and fuel savings by carrying that momentum through the shift points.
- **AccuGrade Compaction Control uses the Cat Compaction** – Algorithm to help you consistently meet compaction targets fast, uniformly, in fewer passes – saving on fuel and rework.

Machine configuration, operator technique, and job site layout can impact fuel consumption.

- **Machine Configuration** – Select the correct blade and wheel configuration based on your individual application.

# 836K Landfill Compactor Specifications

## Engine

| | | |
|---|---|---|
| Engine Model | C18 ACERT | |
| Emissions | Tier 4 Final/Stage IV/ Korea Tier 4 Final or Tier 3/Stage IIIA equivalent | |
| Rated Power (Lab) | 414 kW | 555 hp |
| Rated Power (Net ISO 14396) | 412 kW | 553 hp |
| Gross (SAE J1349) | 419 kW | 562 hp |
| Net Power – SAE J1349 | | |
| Direct Drive – Gross Power | 370 kW | 496 hp |
| Direct Drive – Torque Rise | 52% | |
| Converter Drive – Gross Power | 370 kW | 496 hp |
| Converter Drive – Torque Rise | 52% | |
| Maximum Gross Torque @ 1,300 rpm | 3085 N·m | 2,275 lbf-ft |
| Maximum Altitude without Derating | 2286 m | 7,500 ft |
| Bore | 145 mm | 5.71 in |
| Stroke | 183 mm | 7.2 in |
| Displacement | 18.1 L | 1,104.5 in³ |
| High Idle Speed | 2,120 rpm | |
| Low Idle Speed | 750 rpm | |

## Operating Specifications

| | | |
|---|---|---|
| Operating Weight with Full Tank Capacities and U-blade (Tier 4 Final/ Stage IV/Korea Tier 4 Final) | 55 927 kg | 123,319 lb |
| Operating Weight with Full Tank Capacities and U-blade (Tier 3/ Stage IIIA equivalent) | 55 617 kg | 122,615 lb |

## Transmission

| | | |
|---|---|---|
| Transmission Type | Planetary – Powershift – ECPC | |
| Travel Speeds | | |
| Forward – Converter 1st | 6.2 km/h | 3.9 mph |
| Forward – Lockup 1st | 6.5 km/h | 4 mph |
| Forward – Converter 2nd | 10.9 km/h | 6.8 mph |
| Forward – Lockup 2nd | 11.7 km/h | 7.3 mph |
| Reverse – Converter 1st | 6.5 km/h | 4 mph |
| Reverse – Lockup 1st | 6.9 km/h | 4.3 mph |
| Reverse – Converter 2nd | 10.4 km/h | 6.5 mph |
| Reverse – Lockup 2nd | 12.3 km/h | 7.6 mph |

## Hydraulic System

| | | |
|---|---|---|
| Hydraulic System | Flow Sharing Implement | |
| Maximum Supply Pressure | 32 000 kPa | 4,640 psi |
| Main Relief Pressure | 24 100 kPa | 3,495 psi |
| Pump Flow at 2,006 rpm | 250 L/min | 66 gal/min |
| Steering System | Double Acting – End Mounted | |
| Bore | 127 mm | 5 in |
| Stroke | 740 mm | 29.1 in |
| Vehicle Articulation Angle | 86° | |
| Lift System | Double Acting Cylinder | |
| Bore | 137.9 mm | 5.5 in |
| Stroke | 1021 mm | 40.2 in |

## Service Refill Capacities

| | | |
|---|---|---|
| Fuel Tank | 793 L | 209 gal |
| Cooling System | 107 L | 28 gal |
| Crankcase | 60 L | 16 gal |
| Diesel Engine Fluid Tank (Tier 4 Final/ Stage IV/Korea Tier 4 Final) | 32.8 L | 9 gal |
| Transmission | 120 L | 32 gal |
| Differentials and Final Drives – Front | 186 L | 49 gal |
| Differentials and Final Drives – Rear | 190 L | 50 gal |
| Hydraulic System (tank only) | 240 L | 63 gal |

- All non-road Tier 4 Final/Stage IV diesel engines are required to use:
  - Ultra Low Sulfur Diesel (ULSD) fuels containing 15 ppm (mg/kg) sulfur or less. Biodiesel blends up to B20 are acceptable when blended with 15 ppm (mg/kg) sulfur or less ULSD and when the biodiesel feedstock meets ASTM D7467 specifications.
  - Cat DEO-ULS™ or oils that meet the Cat ECF-3, API CJ-4, and ACEA E9 specifications are required.

## Axles

| | |
|---|---|
| Front | Planetary – Fixed |
| Rear | Planetary – Oscillating |
| Oscillation Angle | 13° |

## Brakes

| | |
|---|---|
| Control System | Full Hydraulic Split Circuit |
| Parking Brake | Spring Applied, Hydraulic Released |

## Cab

| | Standard | Suppression |
|---|---|---|
| Interior Sound Level | 72 dB(A) | 71 dB(A) |
| Exterior Sound Level | 111 dB(A) | 109 dB(A) |

## Hydraulic System – Steering

| | | |
|---|---|---|
| Steering System – Circuit | Steering Double Acting – End Mounted | |
| Steering System – Pump | Piston – Variable Displacement | |
| Maximum Flow @ × rpm | 52 L/min @ 2,006 rpm | |
| Steering Pressure Limited | 24 100 kPa | 3,495 psi |
| Total Steering Angle | 86 degrees | |

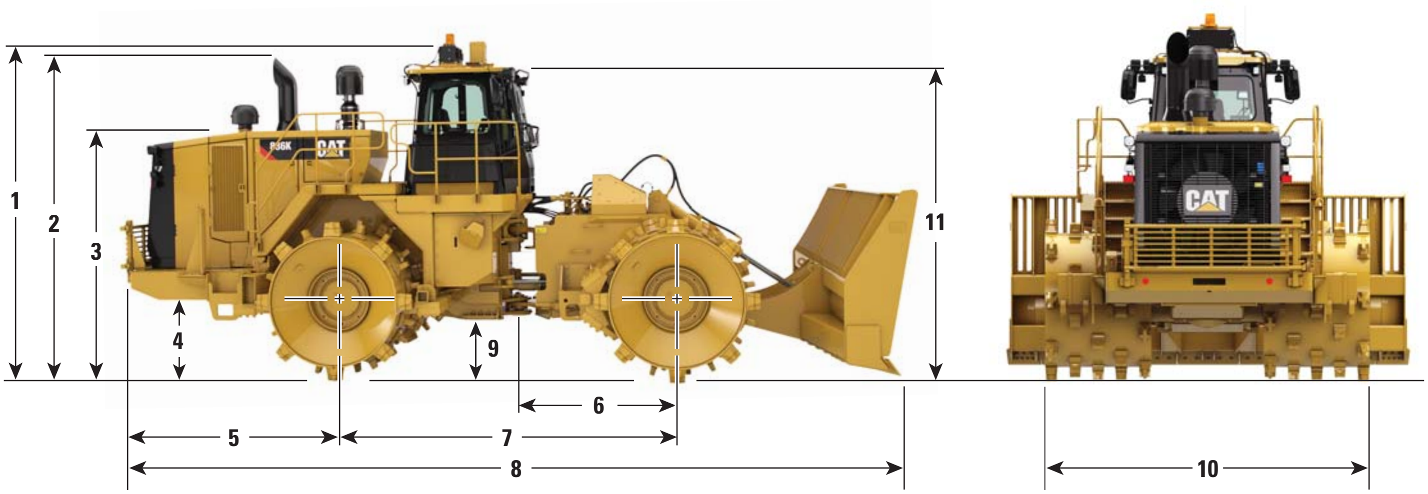
## Wheels and Tips

| | | |
|---|---|---|
| Drum Width | 1400 mm | 4 ft 8 in |
| Drum Diameter | 1770 mm | 5 ft 10 in |
| Diameter with Tips | 2125 mm | 7 ft 0 in |
| Tips per Wheel | 40 | |

# 836K Landfill Compactor Specifications

## Dimensions

All dimensions are approximate.



| | | | |
|---|---|---|---|
| **1** | Height to Top of Cab with A/C | 4655 mm | 15 ft 3 in |
| **2** | Height to Top of Exhaust Pipe | 4608 mm | 15 ft 1 in |
| **3** | Height to Top of Hood | 3421 mm | 11 ft 3 in |
| **4** | Ground Clearance to Bumper | 1029 mm | 3 ft 5 in |
| **5** | Center Line of Rear Axle to Edge of Counterweight | 3187 mm | 10 ft 5 in |
| **6** | Hitch to Center Line of Front Axle | 2275 mm | 7 ft 6 in |
| **7** | Wheelbase | 4550 mm | 14 ft 11 in |
| **8** | Length with Blade on Ground (straight blade) | 10 182 mm | 33 ft 5 in |
| **9** | Ground Clearance | 632 mm | 2 ft 1 in |
| **10** | Width over Wheels | 4280 mm | 14 ft 1 in |
| **11** | Height to ROPS/Canopy | 4284 mm | 14 ft 1 in |
| | Height to Top of Cab with Strobe | 4845 mm | 15 ft 11 in |
| Turning Radius – Inside of Wheels | | 3635 mm | 11 ft 11 in |

## Blade Selection

| | Straight Blade | | Semi U-blade | | U-blade | |
|---|---|---|---|---|---|---|
| Width – Moldboard Length | 4990 mm | 16 ft 4 in | 5238 mm | 17 ft 2 in | 5172 mm | 17 ft |
| Width Over End Bits | 5193 mm | 17 ft | 5311 mm | 17 ft 5 in | 5258 mm | 17 ft 3 in |
| Height with Cutting Edge and Screen | 2236 mm | 7 ft 4 in | 2215 mm | 7 ft 3 in | 2210 mm | 7 ft 3 in |
| Height with Cutting Edge, No Screen | 1217 mm | 4 ft | 1253 mm | 4 ft 1 in | 1255 mm | 4 ft 1 in |
| Maximum Depth of Cut | 364 mm | 1 ft 2 in | 362 mm | 1 ft 2 in | 934 mm | 3 ft 1 in |
| Maximum Lift above Ground | 1730 mm | 5 ft 8 in | 1735 mm | 5 ft 8 in | 1198 mm | 3 ft 11 in |
| **Cutting Edges, Reversible** | | | | | | |
| Length, Each End Section (3 edges) | 1408.2 mm | 4 ft 7 in | 816.6 mm | 2 ft 8 in | 2 @ 779.1 mm and 1 @ 856 mm | 2 @ 2 ft 7 in and 1 @ 2 ft 10 in |
| Length, Each End Section (2 edges) | NA | | 988 mm | 3 ft 3 in | 1094.4 mm | 3 ft 7 in |
| Width × Thickness | 254 mm × 25 mm | 10 in × 1 in | 254 mm × 25 mm | 10 in × 1 in | 254 mm × 25 mm | 10 in × 1 in |
| **End Bits (2), Self-sharpening** | | | | | | |
| Length, Each | 472 mm | 1 ft 7 in | 472 mm | 1 ft 7 in | 472 mm | 1 ft 7 in |
| Width × Thickness | 254 mm × 25 mm | 10 in × 1 in | 254 mm × 25 mm | 10 in × 1 in | 254 mm × 25 mm | 10 in × 1 in |
| Capacity, Rated | 19.3 $m^3$ | 25.9 $yd^3$ | 22.4 $m^3$ | 29.3 $yd^3$ | 25.5 $m^3$ | 33.6 $yd^3$ |
| Turning Diameter, Outside Corner of Blade at 43° ART | 8737 mm | 28 ft 8 in | 8823 mm | 28 ft 11 in | 8795 mm | 28 ft 10 in |
| Overall Machine Length | 10 182 mm | 33 ft 5 in | 10 379 mm | 34 ft 1 in | 10 272 mm | 33 ft 8 in |

# 836K Standard Equipment

## Standard Equipment

Standard equipment may vary. Consult your Cat dealer for details.

### POWER TRAIN

- Advanced Productivity Electronic Control Shifting (APECS)
- Air to air aftercooler
- Brakes, fully hydraulic, enclosed, wet multiple disc brakes
- Cat Clean Emission Module, insulated (Tier 4 Final/Stage IV/Korea Tier 4 Final)
- Electro hydraulic parking brake
- Engine, Cat C18 with ACERT Technology
  - Tier 4 Final/Stage IV/Korea Tier 4 Final
  - Tier 3/Stage IIIA equivalent
- Fuel priming pump, electric
- Fuel to air cooler
- Ground level engine shutoff
- Guard (3 piece) transmission
- Heat shield, turbo and exhaust manifold
- Hydraulically driven demand fan
- Integrated braking
- Radiator, Aluminum Modular Radiator (AMR)
- Separated cooling system
- Starting aid (ether) automatic
- Throttle lock
- Torque converter with lockup clutch (LUC)
- Turbine precleaner, engine air intake
- Transmission, planetary, with 2F/2R speed range control
- Underhood ventilation system

### ELECTRICAL

- Alarm, back-up
- Alternator, 150 amp
- Batteries, maintenance-free (4-1,000 CCA)
- Converter, 10-15 amp, 24V to 12V
- Lighting system, halogen (front and rear)
- Lighting, access stairway
- Starter, electric (heavy duty)
- Starter lockout (ground level)
- Starting receptacle for emergency start
- Transmission lockout (ground level)

### OPERATOR ENVIRONMENT

- Air conditioner
- Cab, sound-suppressed and pressurized
- Internal four-post rollover protective structure (ROPS/FOPS)
- Radio ready for (entertainment) includes antenna, speakers and converter (12V, 10-15 amp) 12V power port for mobile phone or laptop connection
- Camera, rear vision
- Coat and hard hat hooks
- Flip-up armrest
- Heater and defroster
- Horn, electric
- Hydraulic controls (floor mounted)
- Implement hydraulic lockout
- Laminated glass
- Light, (dome) cab
- Lunchbox and beverage holders
- Instrumentation, Gauges
  - DEF fluid level (Tier 4 Final/Stage IV)
  - Hydraulic oil temperature
  - Speedometer/tachometer
  - Torque converter temperature
- Instrumentation, Warning Indicators
  - Action alert system, three category
  - Axle/brake oil temp, front
  - Brake oil pressure
  - Electrical system, low voltage
  - Engine failure malfunction alert and action lamp
- Mirrors, rearview (externally mounted)
- Parking brake status
- Radio, CB (ready)
- Seat, Cat Comfort, (cloth) air suspension
- Seat belt, retractable, 76 mm (3") wide
- STIC Control System with steering lock
- Sun visor, front
- Tinted glass
- Transmission gear (indicator)
- Vital Information Management System (VIMS) with graphical information display: external data port, customizable operator profiles
- Wet-arm wipers/washers (front and rear)
- Intermittent wipers (front and rear)

*(continued on next page)*

## Standard Equipment (continued)

Standard equipment may vary. Consult your Cat dealer for details.

### WHEELS

- Wheels, paddle, plus, combination, and diamond wheel configurations

### GUARDS

- Guards, axle (front and rear)
- Guards, cab window
- Guards, crankcase and power train, hydraulically powered
- Guards, rear fan and grill

### BLADES

- Bulldozer arrangement is included in the standard equipment. Bulldozer blades are optional.

### FLUIDS

- Antifreeze, premixed 50% concentration of extended life coolant with freeze protection to –34° C (–29° F)

### OTHER STANDARD EQUIPMENT

- Auto Blade Positioner (ABP)
- Demand fan/swing out (hydraulic reversible)
- Doors, service access locking
- Ecology drains for engine, radiator, hydraulic tank
- Electronic clutch pressure control and remote mounted pressure taps
- Emergency platform egress
- Engine, crankcase, 250 hour interval with CJ-4 oil
- Fuel tank, 793 L (210 gal)
- Hitch, drawbar with pin
- Hoses, Cat XT™
- Hydraulic oil cooler
- Hydraulic, steering and brake filtration/screening system
- Oil sampling valves
- Product Link
- Stairways, fixed-L/R (rear access)
- Steering, load sensing
- Vandalism protection caplocks
- Venturi stack

# 836K Optional Equipment

## Optional Equipment

Optional equipment may vary. Some options may be included/excluded in arrangement packages. Consult your Cat dealer for details.

- 4-Hydraulic belly guard actuators
- Additional starter and batteries
- Cab, rubber mounted glass
- Cleaner finger arrangement
- Fast fill fuel
- Flashing strobe
- Fuel line heater
- Heated and ventilated seat
- Heated mirrors
- High speed oil change
- Dual stage precleaner with dust ejector
- Panoramic mirror
- Premium LED lights
- Radio, AM/FM/CD/MP3
- RESPA cab precleaner
- Seat belt reminder
- Sound suppression
- Swingout stairs
- Various blades
  - Straight blade
  - U-blade
  - Semi U-blade
- Various tip and wheel arrangements
  - Paddle
  - Plus
  - Diamond

# Notes

AEHQ7077-02 (07-2015)
Replaces AEHQ7077-01

# K.3 – Structural Capacity of the Leachate Collection System

**Client:** **Zion Landfill, Inc.**
**Project:** **Zion Landfill – Site 2 North Expansion**
**Project #:** **631020105**
**Calculated By:** **SJW** **Date:** **05/2022**
**Checked By:** **DAM** **Date:** **05/2022**

**TITLE:** **STRUCTURAL CAPACITY OF THE LEACHATE COLLECTION SYSTEM**

---

## Problem Statement

Determine if the leachate collection pipes underlying the vertical and horizontal expansions possess sufficient strength to support the overlying landfill materials, in accordance with 35 Ill. Admin. Code Section 811.308 (e), considering the following failure modes:

1. Wall crushing
2. Wall buckling

## Given

- ☐ Calculation in Appendix K.2 Loads on the Leachate Collection System.
- ☐ The safety factor against wall crushing is determined by the following formula (see WL Plastics *WL PipeCalcTM Supplement*, Equation 24 and 25).

$$P_T = P_E + P_L \text{ (Equation 24)}$$

$$N_c = \frac{460{,}800}{P_T \times DR} \text{ (Equation 25)}$$

Where:
$N_c$ = safety factor against wall crushing
$P_T$ = total load pressure at pipe crown (psf) = $P_E + P_L$
$P_E$ = overburden pressure at pipe crown (psf) = wH
w = material density (pcf)
H = height of material above the pipe crown (ft)
$P_L$ = live load pressure at pipe crown = 0
DR = SDR = Standard dimensional ratio
= (pipe outer diameter)/(pipe wall thickness)

☐ The safety factor against wall buckling is determined by the following formula (see WL Plastics *WL PipeCalcTM Supplement*, Equation 26-29)

$$N_B = \frac{144P_{WC}}{P_T} \text{ (Equation 26)}$$

Where:

$N_B$ = safety factor against wall buckling
$P_{wc}$= constrained buckling pressure (lb/in$^2$)

$$P_{WC} = 5.65 * \sqrt{\frac{RB'E'E}{12(SDR-1)^3}} \text{ (Equation 27)}$$

$$R = 1\text{-}0.33\frac{H'}{H} \text{ (Equation 28)}$$

R = reduction factor for buoyancy
H’ = height of leachate above pipe (ft)
H = material cover above pipe (ft)

$$B' = \frac{1}{1+10.87312^{(-0.065H)}} \text{ (Equation 29)}$$

B’= elastic support factor
E’= modulus of soil reaction (lb/in$^2$)
E= modulus of elasticity for the pipe (lb/in$^2$)
DR = SDR = Standard dimensional ratio
= (pipe outer diameter)/(pipe wall thickness)
$P_T$ = total load pressure at pipe crown (psf)

☐ Leachate collection system pipes underlying the vertical expansion are all 6-inch Standard Dimension Ratio (SDR) 17 HDPE pipe.

☐ All leachate collection pipes within the horizontal expansion will be 6-inch SDR-17 HDPE pipe.

☐ The maximum waste thickness in the horizontal expansion area is 196 feet. The maximum waste thickness in the vertical expansion area is 207 feet. Due to the similarity in waste thickness, all calculations conservatively assume that a 207-ft waste column is acting on the underlying leachate pipes.

☐ Maximum material height (H) = 213 ft. (reference Appendix K.2 calculations)

☐ Height of leachate above pipe (H’) = 1 ft.

☐ The overburden overlying the pipe crowns ($P_E$) = 16,306.5 psf (reference Appendix K.2 calculations)

- ☐ E’ = 3,000 psi (see WL Plastics *WL PipeCalcTM Supplement*, Table 10)
- ☐ E = 12,200 psi for leachate temperatures at 140°F for 30-year closure period (interpolation from information provided in the WL Plastics *WL PipeCalcTM Supplement*, Table 17)

**Calculations**

*Wall Crushing*

6-inch SDR-17 Pipe

Calculate the safety factor against wall crushing for the 6-inch, SDR-17 HDPE pipe:

$$P_T = P_E + P_L = 16{,}306.5\ psf + 0 = 16{,}306.5\ psf$$

$$N_c = \frac{460{,}800}{P_T \times SDR} = \frac{460{,}800}{(16{,}306.5\ \text{psf})(17)} = \mathbf{1.6}$$

*Wall Buckling*

6-inch SDR-17 Pipe

Calculate the safety factor against wall buckling for the 6-inch, SDR-17 HDPE pipe:

$$R = 1\text{-}0.33\left(\frac{H'}{H}\right) = 1\text{-}0.33\left(\frac{1\ \text{ft}}{213\ \text{ft}}\right) = 0.998$$

$$B' = \frac{1}{1+10.87312^{-0.065H}} = \frac{1}{1+10.87312^{-(0.065\ \text{x}\ 213\ \text{ft.})}} = 1.00$$

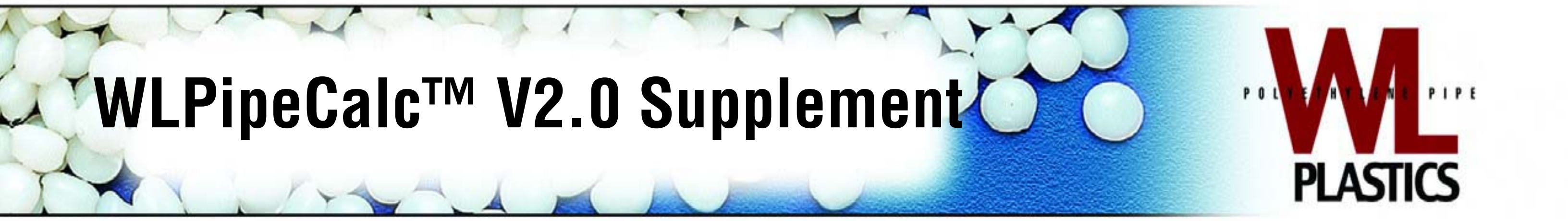
$$P_{WC} = 5.65\sqrt{\frac{RB'E'E}{12(SDR-1)^3}} = 5.65\sqrt{\frac{(0.998)(1.00)(3{,}000\ \text{psi})(12{,}200\ \text{psi})}{12(17-1)^3}} = 154.1\ \text{psi}$$

$$N_B = \frac{144P_{WC}}{P_T} = \frac{(144)(154.1\ \text{psi})}{16{,}306.5\ \text{psf}} = \mathbf{1.3}$$

## Results

The existing and proposed leachate collection pipe will possess sufficient strength to support the overlying landfill, as shown by the calculated factors of safety against pipe wall buckling and pipe wall crushing for the leachate pipes.

| Leachate Pipe Factors of Safety | |
|---|---|
| **Pipe Failure Mode** | **SDR-17 Pipe** |
| Wall Crushing | 1.6 |
| Wall Buckling | 1.3 |



# WLPipeCalc™ V2.0 Supplement

## WLPipeCalc™ V2.0 Supplement – Equations & Information

### *Contents*

### *Notice*

*The WLPipeCalc™ CD-ROM and this supplement are intended for use as piping system guides. These publications should not be used in place of a professional engineer's judgment or advice and they are not intended as installation instructions. The information in or generated by the WLPipeCalc™ CD-ROM and this supplement does not constitute a guarantee or warranty for piping installations and cannot be guaranteed because the conditions of use are beyond our control. The user of the information assumes all risk associated with its use. WL Plastics Corporation has made every reasonable effort to ensure accuracy, but the information in or generated by the WLPipeCalc™ CD-ROM and this supplement may not be complete, especially for special or unusual applications. Changes to the WLPipeCalc™ CD-ROM and this supplement may occur from time to time without notice. Contact WL Plastics Corporation to determine if you have the most current edition.*

The WLPipeCalc™ CD-ROM allows the user to enter values for variables and determine a result using the equations in the CD-ROM publication. This publication, WL120, provides equations used for WLPipeCalc™ CD-ROM calculation screens, and related information.

Other equations and methods for determining piping system design may be applicable. As part of piping system design, the user should determine the design equations and methods that are appropriate for the intended use.

### *1 – Pipe Pressure Rating*

See publications WL102, WL104 and WL118, and "Working Pressure Rating for Water" for additional information.

$$PR = \frac{2\,HDB\, f_T\ f_E}{(DR - 1)} \tag{1}$$

Where

PR = pressure rating, psi.
HDB = hydrostatic design basis at 73°F (Table 1)
$f_T$ = operating temperature multiplier (Table 2)
$f_E$ = environmental design factor (table 3)
DR = pipe dimension ratio

$$DR = \frac{D}{t} \tag{2}$$

D = pipe outside diameter, in (WL102; WL104)
t = pipe minimum wall thickness, in

**Table 1 HDB – WL Plastics PE3408 HDPE**

| | *HDB at 73°F* | *HDB at 140°F* |
|---|---|---|
| WL Plastics PE3408 | 1600 psi | 800 psi |

**Table 2 Operating Temperature Multiplier, $f_T$**

| *Maximum Operating Temperature* |  | *Multiplier, $f_T$* |
|---|---|---|
| *°F* | *°C* |  |
| $\le$ 40* | $\le$ 4 | 1.3 |
| > 40 $\le$ 60* | > 4 $\le$ 16 | 1.1 |
| > 60 $\le$ 80 | > 16 $\le$ 27 | 1.0 |
| > 80 $\le$ 90 | > 27 $\le$ 32 | 0.9 |
| > 90 $\le$ 100 | > 32 $\le$ 38 | 0.8 |
| > 100 $\le$ 110 | > 38 $\le$ 43 | 0.71 |
| > 110 $\le$ 120 | > 43 $\le$ 49 | 0.64 |
| > 120 $\le$ 130 | > 49 $\le$ 54 | 0.57 |
| > 130 $\le$ 140 | > 54 $\le$ 60 | 0.50 |

* For water distribution and transmission applications, multipliers for 60°F (16°C) and lower temperatures are not used.

**Table 3 Environmental Design Factor, $f_E$**

| *Factor, $f_E$* | *Environmental and Applications Conditions,* |
|---|---|
| 0.50* | Liquids that are chemically benign to polyethylene such as potable and process water, municipal sewage, wastewater, reclaimed water, salt water, brine solutions, glycol/antifreeze solutions, alcohol; Buried pipes for gases that are chemically benign to polyethylene such as dry natural gas (in Class 1 or 2 locations where Federal Regulations (49 CFR Part 192) do not limit pressure), methane, propane, butane, carbon dioxide, hydrogen sulfide. |
| 0.32 | Buried pipes for compressed air at ambient temperature; Buried pipes for fuel gases such as natural gas, LP gas, propane, butane in distribution systems and Class 3 or 4 locations where Federal Regulations limit pipe pressure to the lesser of 100 psi or the design pressure rating. |
| 0.25 | Permeating or solvating liquids in the pipe or the surrounding soil such as gasoline, fuel oil, kerosene, crude oil, diesel fuel, liquid hydrocarbon fuels, vegetable and mineral oils. |

* The maximum design factor, 0.50, is a cumulative factor based on variability in materials, testing and processing, handling and installation abuse, and variability in operating conditions. It is widely accepted for thermoplastic pressure pipe design in North America.

## 2 – Hazen-Williams Pressure Water Flow

Hazen and Williams developed an empirical formula for friction (head) loss for water flow at 60° F that can be applied to liquids having a kinematic viscosity of 1.130 centistokes (0.00001211 $ft^2$/sec), or 31.5 SSU. Some error can occur at other temperatures because the viscosity of water varies with temperature,

Hazen-Williams formula for friction (head) loss in feet:

$$h_f = \frac{0.002083\,L}{d^{4.8655}}\left(\frac{100\,Q}{C}\right)^{1.85} \qquad (3)$$

Hazen-Williams formula for friction (head) loss in psi:

$$p_f = \frac{0.0009015\,L}{d^{4.8655}}\left(\frac{100\,Q}{C}\right)^{1.85} \qquad (4)$$

Where

$h_f$ = friction (head) loss, ft
L = pipe length, ft
Q = flow, gal/min
d = pipe inside diameter, in (WL102; WL104)
C = Hazen-Williams Friction Factor, dimensionless
$p_f$ = friction (head) loss, lb/in$^2$

**Table 4 Hazen-Williams Friction Factor, C**

| *Pipe Material* | *Values for C* |  |  |
|---|---|---|---|
|  | *Range High / Low* | *Average Value* | *Typical Design Value* |
| Butt fused polyethylene pipe with internal beads | 160 / 130 | 155 | 150 |
| Cement or mastic lined iron or steel pipe | 160 / 130 | 148 | 140 |
| Copper, brass, lead, tin or glass pipe or tubing | 150 / 120 | 140 | 130 |
| Wood stave | 145 / 110 | 120 | 110 |
| Welded and seamless steel | 150 / 80 | 130 | 100 |
| Cast and ductile iron | 150 / 80 | 130 | 100 |
| Concrete | 152 / 85 | 120 | 100 |
| Corrugated steel | – | 60 | 60 |

Full Pipe Flow Velocity

Water flow velocity in a full, circular pipe:

$$V = 0.40853\frac{Q}{d^2} \qquad (5)$$

Where

V = water flow velocity, ft/sec
Q = flow, gal/min
d = pipe inside diameter, in (WL102; WL104)

## 3 – Manning Gravity Water Flow

The Manning equation is limited to water or liquids with a kinematic viscosity equal to water. A derived version of the Manning equation for circular pipes flowing full or half full is:

$$Q = 0.275\frac{d^{8/3}S^{1/2}}{n} \qquad (6)$$

or

$$Q_{CFS} = \left(6.136 \times 10^{-4}\right)\frac{d^{8/3}S^{1/2}}{n} \qquad (7)$$

Where

$Q$ = flow, gal/min
$Q_{CFS}$ = flow, ft$^3$/sec
$d$ = pipe inside diameter, in (WL102; WL104)
$S$ = hydraulic slope, ft/ft

$$S = \frac{h_1 - h_2}{L} \qquad (8)$$

$h_1$ = upstream pipe elevation, ft
$h_2$ = downstream pipe elevation, ft
$n$ = roughness coefficient, dimensionless

**Table 5 Manning Equation n Values**

| *Surface* | *n, range* | *n, typical design* |
|---|---|---|
| Polyethylene pipe | 0.008 – 0.011 | 0.009 |
| Uncoated cast or ductile iron pipe | 0.012 – 0.015 | 0.013 |
| Corrugated steel pipe | 0.021 – 0.030 | 0.024 |
| Concrete pipe | 0.012 – 0.016 | 0.015 |
| Vitrified clay pipe | 0.011 – 0.017 | 0.013 |
| Brick and cement mortar sewers | 0.012 – 0.017 | 0.015 |
| Wood stave | 0.010 – 0.013 | 0.011 |
| Rubble masonry | 0.017 – 0.030 | 0.021 |

Circular pipes will carry more liquid when slightly less than full compared to completely full because there is a slight reduction in flow area compared to a significant reduction in the wetted surface of the pipe. Maximum flow occurs at about 93% of full pipe flow, and maximum velocity at about 78% of full pipe flow.

## *4 – Low Pressure Gas Flow*

***Caution – To minimize the risk of mechanical damage, pressure gas piping is buried, installed at heights and in areas where moving equipment cannot contact or damage piping, and encased in shatter resistant materials. Pressure gas piping is restrained to prevent movement in case of mechanical damage.***

Where inlet and outlet gas pressures are less than 1 psig (27.7 in $H_2O$) the Mueller low pressure gas flow equation may be used.

$$Q_h = \frac{2971 d^{2.725}}{S_g^{\,0.425}}\left(\frac{h_1 - h_2}{L}\right)^{0.575} \qquad (9)$$

Where

$S_g$ = gas specific gravity (Table 6)
$h_1$ = inlet pressure, in $H_2O$
$h_2$ = outlet pressure, in $H_2O$
$L$ = pipe length, ft
$d$ = pipe inside diameter, in (WL102; WL104)

**Table 6 Approximate Specific Gravity (14.7 psi & 68°F)**

| *Gas* | *Specific Gravity, $S_g$* |
|---|---|
| Acetylene (ethylene), $C_2H_2$ | 0.907 |
| Air | 1.000 |
| Ammonia, $NH_3$ | 0.596 |
| Argon, A | 1.379 |
| Butane, $C_4H_{10}$ | 2.067 |
| Carbon Dioxide, $CO_2$ | 1.529 |
| Carbon Monoxide, CO | 0.967 |
| Ethane, $C_2H_6$ | 1.049 |
| Ethylene, $C_2H_4$ | 0.975 |
| Helium, He | 0.138 |
| Hydrogen Chloride, HCl | 1.286 |
| Hydrogen, H | 0.070 |
| Hydrogen Sulfide, $H_2S$ | 1.190 |
| Methane, $CH_4$ | 0.554 |
| Methyl Chloride, $CH_3Cl$ | 1.785 |
| Natural Gas | 0.667 |
| Nitric Oxide, NO | 1.037 |
| Nitrogen, $N_2$ | 0.967 |
| Nitrous Oxide, $N_2O$ | 1.530 |
| Oxygen, $O_2$ | 1.105 |
| Propane, $C_3H_8$ | 1.562 |
| Propene (Propylene), $C_3H_6$ | 1.451 |
| Sulfur Dioxide, $SO_2$ | 2.264 |
| Landfill Gas (approx. value) | 1.00 |
| Carbureted Water Gas | 0.63 |
| Coal Gas | 0.42 |
| Coke-Oven Gas | 0.44 |
| Refinery Oil Gas | 0.99 |
| "Wet" Gas (approximate value) | 0.75 |

## *5 – Working Pressure Rating for Water*

Working Pressure Rating (WPR) for water at ≤ 80°F (≤ 27°C) has application pressure components for steady long-term internal pressure and momentary surge pressure from sudden water velocity change. WPR application pressure components are compared to pipe capabilities, pressure class, PC, which includes allowances for recurring or occasional surge, $P_{RS}$ or $P_{OS}$.

The pipe's capacity for internal water pressure at ≤ 80°F is its pressure class, PC. PC includes components for long-term steady pressure and momentary pressure surge.

$$PC_S = \frac{2\,HDB\,f_E}{(DR-1)} \qquad (10)$$

Where

$PC_S$ = Steady pressure for water at ≤ 80°F, psi
HDB = hydrostatic design basis, psi
= 1600 psi
$f_E$ = environmental design factor for water
= 0.50
DR = pipe dimension ratio

The pipe's allowance for momentary surge pressure is for either recurring or occasional surge pressure, and it is applied above the steady pressure. Recurring surge pressures occur frequently and are inherent in system design and operation. The recurring surge pressure allowance is:

$$P_{RS} = 0.5\,PC \qquad (11)$$

Where

$P_{RS}$ = Recurring surge pressure allowance, psi

Occasional surge pressures are caused by emergency operations. The occasional surge pressure allowance is:

$$P_{OS} = 1.0\,PC \qquad (12)$$

Where

$P_{OS}$ = Occasional surge pressure allowance, psi

The maximum pressure in the pipe depends on the operating condition. For steady pressure conditions, the surge allowance is not used. For a momentary surge event, the maximum pressure is the steady pressure plus the applicable surge allowance.

For steady pressure conditions:

$$PC = PC_S \qquad (13)$$

For a momentary recurring surge event:

$$PC = PC_S + P_{RS} \qquad (14)$$

For a momentary occasional surge event:

$$PC = PC_S + P_{OS} \qquad (15)$$

Application requirements are determined using working pressure rating, WPR, which has steady pressure and surge pressure components. The steady internal water pressure component, working pressure, WP, is determined by the designer, who also determines if the potential for surge pressure is recurring or occasional.

Surge pressure magnitude is dependent on sudden velocity change.

$$P_S = a\left(\frac{\Delta v}{2.31g}\right) \qquad (16)$$

Where

$P_S$ = Surge pressure, psi
a = Surge pressure wave velocity (celerity), ft/sec

$$a = \frac{4660}{\sqrt{1+\frac{K}{E_d}(DR-2)}} \qquad (17)$$

K = bulk modulus of water, psi
= 300,000 psi
$E_d$ = Dynamic instantaneous effective modulus of pipe material, psi
= 150,000 psi
DR = Pipe dimension ratio
Δv = Sudden velocity change*, ft/sec
g = gravitational acceleration, ft/sec$^2$
= 32.2 ft/sec$^2$

* Pressure surge does not occur unless the sudden velocity change occurs within the Critical Time

$$Critical\,Time, \sec = \frac{2L}{a} \qquad (18)$$

Where

L = Pipe length, ft

WLPipeCalc assumes Δv occurs within the Critical Time, but does not calculate Critical Time.

WLPipeCalc calculates celerity within the surge pressure calculation, but not as a separate value.

WLPipeCalc determines the sustained pressure and surge pressure components of WPR separately using the following relationships.

During steady pressure operation, WP never exceeds WPR and never exceeds $PC_S$ for steady pressure conditions (Equation 13).

$$WP \le WPR \le PC_S \qquad (19)$$

During a momentary surge event, the maximum pressure in the pipe, WPR, never exceeds PC plus the applicable surge allowance (Equations 14 or 15).

$$WP + P_s \le WPR \le PC_S + P_{RS} \qquad (20)$$

or

$$WP + P_S \le WPR \le PC_S + P_{OS} \qquad (21)$$

If the potential for surge pressure, $P_S$, exceeds the surge pressure allowance, $P_{OS}$ or $P_{RS}$, allowable steady pressure, WP is reduced and the difference allocated to surge pressure so that Equations 19, 20 and 21 are maintained. Surge pressure allowance is never applied to steady pressure.

WLPipeCalc determines WPR in terms of its steady pressure and surge pressure components. A negative steady pressure value indicates an unsuitable application.

## *6 – Buried Polyethylene Pipe*

For typical burial cover depths of 1½ pipe diameters (minimum 4 ft (1.9 m)) to approximately 50 ft (23.6 m), static earthloads and surface live loads on buried (constrained) pipe can result in pipe wall crushing, pipe wall buckling, and pipe deflection. Static (prism) loads and live loads are compared to the pipe's resistance properties. Safety factors against compressive crushing and wall buckling are calculated. Deflection is controlled by installation quality and embedment material quality. Long-term and short-term percent deflections are calculated for comparison to industry standard deflection criteria.

Prism Load Static Soil Pressure:

$$P_E = w\,H \qquad (22)$$

Where

$P_E$ = soil pressure at pipe crown, lb/ft$^2$
w = soil density, lb/ft$^3$
H = height of soil above pipe crown, ft

**Table 7 Densities of Typical Soils**

| *Type of Soil* | *Dry Density, lb/ft$^3$* | *Saturated Density, lb.ft$^3$* |
|---|---|---|
| Organic silts, clays | 31-94 | 81-112 |
| Crushed rock | 94-125 | 119-137 |
| Glacial tills | 106-144 | 131-150 |
| Silts; clays | 37-112 | 87-131 |
| Sands; gravels | 93-114 | 118-150 |

Saturated soil has greater density because of the liquid it contains; however, the effective unit weight of flooded soil is reduced by groundwater floatation of soil particles. If appropriate, soil density should be adjusted to compensate for flooding conditions.

Live Load Pressure:,

Live load pressure results from intermittently applied loads on the surface such as from various kinds of traffic. Live loads may be applied directly to the surface or through rigid pavement. AISI H20 and HS20 truck and semi-trailer truck live loads simulate a 20-ton truck through 12-in thick rigid pavement and include a 1.5 impact factor.

**Table 8 H20 & HS20 Highway Live Load**

| *Height Above Pipe Crown, ft* | *Live Load, lb/ft$^2$* |
|---|---|
| 1 | 1800 |
| 2 | 800 |
| 3 | 600 |
| 4 | 400 |
| 5 | 250 |
| 6 | 200 |
| 7 | 175 |
| 8 | 100 |

Live load pressure without pavement, such as for heavy off-highway vehicles on unpaved surfaces, are determined using the Boussinesq method.

$$P_L = 1.5\,\frac{I_I\,W_L\,H^3}{\pi\left(X^2 + H^2\right)^{2.5}} \qquad (23)$$

Where

$P_L$ = live load pressure at pipe crown, lb/ft$^2$
$I_I$ = impact factor (2.0 through 4.5 or higher)
$W_L$ = wheel load, lb
H = vertical distance from pipe crown to wheel load application surface, ft
X = horizontal distance from center of pipe crown to center of wheel load, ft

Railroad live loads are typically described using AISI Cooper E80 values which are applied as three, 80,000 lb loads over three, 2ft x 8 ft areas spaced 5 ft apart.

**Table 9 E80 Cooper Railroad Live Loading**

| *Height Above Pipe Crown, ft* | *Live Load, lb/ft²* |
|---|---|
| 2 | 3800 |
| 5 | 2400 |
| 8 | 1600 |
| 10 | 1100 |
| 12 | 800 |
| 15 | 600 |
| 20 | 300 |
| 30 | 100 |

Live loads may be determined using other appropriate methods.

Total Load Pressure:

$$P_T = P_E + P_L \qquad (24)$$

Where

$P_T$ = total load pressure at pipe crown, lb/ft²

Wall Crushing Resistance:

$$N_C = \frac{460800}{P_T\,DR} \qquad (25)$$

Where

$N_C$ = safety factor against wall crushing

Wall Buckling Resistance

$$N_B = \frac{144\,P_{WC}}{P_T} \qquad (26)$$

Where

$N_B$ = safety factor against wall buckling

$$P_{WC} = 5.65\sqrt{'\frac{R\,B'E'E}{12\left(DR-1\right)^3}} \qquad (27)$$

Where

$P_{WC}$ = constrained buckling pressure, psi

R = reduction factor for buoyancy

$$R = 1 - 0.33\frac{H'}{H} \qquad (28)$$

H' = height of groundwater above pipe, ft

H = soil cover above pipe, ft

B' = elastic support factor

$$B' = \frac{1}{1 + 10.87312^{(-0.065\,H)}} \qquad (29)$$

E' = modulus of soil reaction, psi (Table 10)

E = modulus of elasticity, psi (Table 17)

= 28,200 psi for long-term at 73°F

= 110,000 psi for short-term at 73°F

**Table 10 Modulus of Soil Reaction, E'**

| *Degree of Bedding Compaction,* | *Soil Type Pipe Bedding Material (Unified Classification System[a])*<br>A | <br>B | <br>C | <br>D | <br>E |
|---|---|---|---|---|---|
| | *Average Value for E', psi (MPa)* | | | | |
| *Dumped* | 1000<br>(6.89) | 200<br>(1.38) | 100<br>(0.69) | 50<br>(0.34) | |
| *Slight, <85% Proctor, 40% Relative Density* | 3000<br>(20.68) | 1000<br>(6.89) | 400<br>(2.76) | 200<br>(1.38) | No data available; consult a competent soils engineer; otherwise use E'= 0 |
| *Moderate, 85-95% Proctor, 40-70% Relative Density* | 3000<br>(20.68) | 2000<br>(13.79) | 1000<br>(6.89) | 400<br>(2.76) | |
| *High, >95% Proctor, >70% Relative Density* | 3000<br>(20.68) | 3000<br>(20.68 | 2000<br>(13.79) | 1000<br>(6.89) | |

A - Crushed rock

B – Coarse grained soils; little or no fines GW, GP, SW, SP[c] contains less than 12% fines

C – Fine grained soils (LL<50); soils with medium to no plasticity, CL, ML, ML-CL, with less than 25% coarse grained particles. Coarse grained soils with fines GM, GC, SM, SC contains more than 12% fines

D – Fine grained soils (LL<50); soils with medium to no plasticity, CL, ML, ML-CL, with less than 25% coarse grained particles

E – Fine-grained soils (LL[b]>50) Soils with medium to high plasticity, CH, MH, CH-MH

Note – Standard Proctors in accordance with ASTM D 698 are used with this table. Values applicable only for fills less than 50 ft (15 m). Table does not include a safety factor. For use in predicting initial deflections only; appropriate Deflection Lag Factor must be applied for long-term deflections

[a] ASTM D2487; USBR E-3. [b] LL = liquid limit [c] Or any borderline soil beginning with one of these symbols (i.e., GM-GC, GC-SC).

Percent Deflection

$$\left(\frac{\Delta X}{D_M}\right) = \frac{P_T}{144}\left(\frac{K\,D_L}{\frac{2E}{3}\left(\frac{1}{DR-1}\right)^3 + 0.061\,E'}\right)100 \qquad (30)$$

Where

$\Delta X$ = horizontal deflection, in

$D_M$ = pipe mean diameter, in

$\left(\frac{\Delta X}{D_M}\right)$ = percent deflection

$$D_M = D\left(1 - \frac{1.06}{DR}\right) \tag{31}$$

D = pipe outside diameter, in (WL102; WL104)
K = bedding factor (typically 0.1)
$D_L$ = deflection lag factor (Table 11)

**Table 11 Deflection Lag Factor**

| $D_L$ | Typical Value |
|---|---|
| 1.0 | Minimum value for use only with granular backfill and if the full soil prism load is assumed to act on the pipe. |
| 1.5 | Minimum value for use with granular backfill and assumed trench loadings |
| 2.5 | Minimum value for use with CL, ML backfills, for conditions where the backfill can become saturated, etc. |

Safe deflection for non-pressure PE3408 piping generally depends on ring bending wall strain, which is typically limited to 8%.

$$\left(\frac{\Delta X}{D_M}\right) \le \frac{\varepsilon\left(DR - 1.06\right)}{1.06\, f_D} \tag{32}$$

Where

ε = wall strain percent
$\le$ 8.0% for non-pressure PE3408
$f_D$ = deformation shape factor
= 6.0 for typical non-elliptical pipe deformation

Wall strain in pressurized PE3408 pipes is more complex because internal pressure increases wall strain.

**Table 12 Safe % Deflection for PE3408 Pressure Pipe**

| Safe % Deflection | DR |
|---|---|
| 2.5 | $\le$ 9 |
| 3.0 | 11 |
| 4.0 | 13.5 |
| 5.0 | 17 |
| 6.0 | 21 |
| 7.0 | 26 |
| 8.5 | 32.5 |

## *7 – Submerged Pipe Ballast*

Ballast weights are attached to or placed over the pipe for submergence. Ballast weights are typically bottom heavy and shaped to prevent pipe rolling. Design incorporates pipe and ballast weight and displacement, the fluids inside and outside the pipe, and environmental conditions.

$$V_P = \frac{\pi D^2}{576} \tag{33}$$

Where

$V_P$ = displaced volume of pipe, $ft^3/ft$
π = Pi (approximately 3.1416)
D = pipe outside diameter, in (WL102; WL104)

$$B_P = V_P\, K\, \omega_{LO} \tag{34}$$

Where

$B_P$ = pipe displacement uplift force, lb/ft
K = submerged environment factor
$\omega_{LO}$ = specific weight of liquid outside pipe, $lb/ft^3$

**Table 13 Submerged Environment Factor**

| Submerged Environment | Factor, K |
|---|---|
| Significant tidal flows, roving currents, stream currents | 1.5 |
| Low tidal flows or slow moving stream , river, lake or pond currents | 1.3 |
| Neutral buoyancy condition | 1.0 |

**Table 14 Specific Weights at 60°F (15°C)**

| Fluid | Specific Weight, ω, $lb/ft^3$ |
|---|---|
| Air and other gases | 0.0 |
| Fresh water | 62.4 |
| Seawater | 64.0 |
| Gasoline | 42.5 |
| Kerosene | 50.2 |
| Crude oil | 53.1 |
| Brine, 6% NaCl | 65.1 |
| Brine, 24% NaCl | 73.8 |
| Brine, 12% CaCl | 69.0 |
| Brine, 30% CaCl | 80.4 |
| Concrete | 110 to 150 |
| Steel | 490 |
| Brick | 112 – 137 |
| Sand, Gravel | 100 – 109 |
| Cast iron | 440 – 480 |
| Brass | 511 – 536 |
| Bronze | 548 |

$$V_B = \frac{\pi d^2}{576} \tag{35}$$

Where

$V_B$ = pipe ID volume, $ft^3/ft$
d = inside diameter of pipe, in (WL102; WL104)

$$B_N = V_B\ \omega_{LI} + w_P \tag{36}$$

Where

$B_N$ = submergence force of pipe and contents, lb/ft
$\omega_{LI}$ = pipe contents specific weight, lb/ft$^3$
$w_P$ = weight of pipe, lb/ft (WL102 or WL104)

$$W_{BS} = B_P - B_N \tag{37}$$

Where

$W_{BS}$ = required weight for submerged ballast, lb/ft

$$W_{BD} = \frac{W_{BS}\ \omega_B\ L}{(\omega_B - \omega_{LO})} \tag{38}$$

Where

$W_{BD}$ = dry weight of individual blast weights, lb
$\omega_B$ = ballast material specific weight, lb/ft$^3$
L = distance between ballast weights, ft

The distance between ballast weights should not exceed 15 ft (7 m) to minimize pipe bending stresses during installation.

## *8 – Length Change with Temperature Change*

Unconstrained pipe will increase in length with temperature increase. Unconstrained applications include floating pipes. To a lesser degree, suspended and surface pipelines, and loose fitting pipes within casings (sliplining) are nearly unconstrained as surface friction acts against thermal expansion movement.

Unconstrained length change:

$$\Delta L = 12\, L\, \alpha\, \Delta T \tag{39}$$

Where

$\Delta L$ = length change, in
L = pipe length, ft
$\alpha$ = coefficient of linear thermal expansion, in/in/°F
= $0.8 \times 10^{-4}$ in/in/°F (WL106)
$\Delta T$ = temperature change, °F

## *9 – Groundwater Flotation*

Flotation should be considered where empty or partially full pipelines buried at depths less than 1½ pipe diameters can encounter high groundwater or flooding conditions. Embedment soil particles immersed in liquid are buoyed, reducing embedment and backfill earthload on the pipe. Liquid in the pipe adds weight to counter buoyant groundwater lifting force. A concrete cap, concrete anti-flotation anchors, soil stabilization, or other anchoring measures may be used to prevent groundwater flotation.

Groundwater flotation does not occur if:

$$F_B \le F_D \tag{40}$$

Where

$F_B$ = groundwater buoyant force, lb/ft

$$F_B = \frac{\pi\, \omega_G\, D^2}{48} \tag{41}$$

$\omega_G$ = groundwater specific weight, lb/ft$^3$ (Table 8)
$\pi$ = pi, approximately 3.1416
D = pipe outside diameter, in (WL102; WL104)
$F_D$ = downforce on pipe, lb/ft

$$F_D = w_P + W_F + W_D + W_{LI} \tag{42}$$

$w_P$ = weight of pipe, lb/ft (WL102 or WL104)
$W_F$ = flooded soil weight, lb/ft

$$W_f = (\omega_D - \omega_G)\frac{D}{12}\left(H_f + \frac{D(4-\pi)}{1152}\right) \tag{43}$$

$\omega_D$ = dry soil specific weight, lb/ft$^3$
$H_f$ = flooded soil height above pipe, ft
$W_D$ = dry soil weight, lb/ft

$$W_D = \omega_D \frac{D}{12}(H - H') \tag{44}$$

H = soil cover above pipe, ft
H' = height of groundwater above pipe, ft
$W_{LI}$ = liquid inside pipe weight, lb/ft

For empty pipe,

$$W_{LI} = 0 \tag{45}$$

For half-full pipe,

$$W_{LI} = \omega_{LI} \frac{\pi d^2}{96} \tag{46}$$

For full pipe,

$$W_{LI} = \omega_{LI} \frac{\pi d^2}{48} \tag{47}$$

d = inside diameter of pipe, in (WL102; WL104)
$\omega_{LI}$ = pipe contents specific weight, lb/ft$^3$

$$N = \frac{F_D}{F_B} \tag{48}$$

N = safety factor

## 10 – ATL for Pull-In Installation

During pull-in installation, a tensile load on the pipe greater than the Allowable Tensile Load, ATL, for the pipe can permanently damage the pipe. Tensile pull-in loads at or below the ATL will not damage the pipe. During pull-in installation, both ends of the pull should be monitored for continuous movement, and if pull-in equipment can apply tensile loads exceeding the ATL, a “weak-link” or breakaway device should be installed where the pipe attaches to pulling equipment. The ATL calculation is based on ASTM F1804.

$$ATL = f_y\, f_t\, T_y\, \pi D^2 \left(\frac{1}{DR} - \frac{1}{DR^2}\right) \tag{49}$$

Where

ATL = Allowable Tensile Load, lb
$f_y$ = tensile yield design (safety) factor
= 0.4
$f_t$ = time under tension design (safety) factor.

**Table 15 Time under Tension Factor, $f_t$**

| *Time under tension* | *$f_t$* |
|---|---|
| Up to 1 hour | 1.00 |
| 1 to 12 hours | 0.95 |
| 12 to 24 hours | 0.91 |

$T_y$ = nominal pipe material tensile yield strength, psi
= 3200 psi for PE3408 pipe at 60-80°F (15-27°C)

Tensile yield strength will vary with temperature, and should be adjusted for the pipe temperature at the time of installation. Black PE3408 pipe in the summer sun can reach temperatures of 140°F (60°C). To obtain the pipe installation temperature pipe material yield strength, multiply the nominal yield strength by the appropriate temperature multiplier from Table 2.

$$T_{y-Install} = f_T\, T_y \tag{50}$$

Where

$T_{y\text{-INSTALL}}$= pipe material yield strength for pipe temperature at time of installation, psi
$f_T$ = temperature multiplier (Table 2)

## 11 – Minimum Field Bending Radius

Field bending radius depends on pipe diameter, wall thickness (DR) and whether or not fittings are or will be present in the bend. The minimum diameter of a pipe loop is twice the minimum field bending radius.

$$R_F = \frac{D}{12} f_R \tag{51}$$

Where

$R_F$ = minimum field bending radius, ft
D = pipe outside diameter, in (WL102; WL104)
$f_R$ = bending radius factor

**Table 16 Bending Radius Factor, $f_R$**

| *Pipe DR* | *Bending Radius Factor, $f_R$* |
|---|---|
| ≤ 9 | 20 |
| > 9 ≤ 13.5 | 25 |
| > 13.5 ≤ 21 | 27 |
| > 21 | 30 |
| Fitting in bend | 100 |

## 12 – High Pressure Gas Flow

***Caution – To minimize the risk of mechanical damage, pressure gas piping is buried, installed at heights and in areas where moving equipment cannot contact or damage piping, and encased in shatter resistant materials. Pressure gas piping is restrained to prevent movement in case of mechanical damage.***

The Mueller equation for gas pressures greater than 1 psig has been modified for gauge pressure rather than absolute pressure for inlet and outlet pressures.

$$Q_h = \frac{2826\, d^{2.725}}{S_g^{\;0.425}} \left(\frac{(p_1 + 14.7)^2 - (p_2 + 14.7)^2}{L}\right)^{0.575} \tag{52}$$

Where

$Q_h$ = flow, standard ft$^3$/hour
$S_g$ = gas specific gravity
$p_1$ = inlet pressure, lb/in$^2$
$p_2$ = outlet pressure, lb/in$^2$
L = pipe length, ft
d = pipe inside diameter, in (WL102; WL104)

## 13 – Above Grade Pipe Support

At a minimum, above grade pipe supports should cradle the bottom third of the pipe, and be one-half pipe diameter long. Long-term vertical deflection between supports should not exceed 1-in (25 mm).

$$L_S = \frac{1}{12}\left(\frac{4608\,E\,I\,y_s}{5\left(w_p + w_{LI}\right)}\right)^{0.25} \tag{53}$$

$$y_S = \frac{5\left(w_P + w_{LI}\right)\left(12L_S\right)^4}{4608\,E\,I} \tag{54}$$

$L_S$ = support spacing, ft
$y_S$ = vertical deflection at center of span, in
E = modulus of elasticity, psi (Table 10)
= 28,200 psi for long-term at 73°F
I = moment of inertia, $in^4$

$$I = \frac{\pi\left(D^4 - d^4\right)}{64} \tag{55}$$

D = pipe outside diameter, in (WL102; WL104)
d = pipe inside diameter, in (WL102; WL104)
$w_P$ = weight of pipe, lb/ft (WL102 or WL104)
$w_{LI}$ = liquid inside pipe weight, lb/ft

For empty pipe,

$$w_{LI} = 0 \tag{56}$$

For half-full pipe,

$$w_{LI} = \omega_{LI}\frac{\pi d^2}{1152} \tag{57}$$

For full pipe,

$$w_{LI} = \omega_{LI}\frac{\pi d^2}{576} \tag{58}$$

$\omega_{LI}$ = pipe contents specific weight, $lb/ft^3$

## 14 – External Pressure/Vacuum Resistance

Circumferentially applied external pressure or internal vacuum or a combination of external pressure and vacuum will attempt to flatten the pipe. Freestanding pipe such as pipe in surface, sliplining and submerged applications is not supported by embedment or other external confinement that can significantly enhance resistance to flattening from external pressure. The resistance of freestanding pipe to flattening from external pressure depends on wall thickness (pipe DR), elastic properties (time and temperature dependent elastic modulus and Poisson's ratio), and roundness.

$$P_{CR} = \frac{2\,E\,f_O}{\left(1-\mu^2\right)}\left(\frac{1}{DR-1}\right)^3 \tag{59}$$

Where

$P_{CR}$ = flattening resistance limit, psi
E = modulus of elasticity, psi
μ = Poisson's Ratio
= 0.35 for short-term stress
= 0.45 for long-term stress
$f_O$ = roundness factor
DR = pipe dimension ratio,

$$P_{AL} = \frac{P_{CR}}{N} \tag{60}$$

$P_{AL}$ = safe external pressure, psi
N = safety factor (typically ≥ 2)

**Table 17 Modulus of Elasticity for PE3408**

| Temperature, °F (°C) | *Modulus of Elasticity for Load Time, kpsi (MPa)* | | | | | | |
|---|---|---|---|---|---|---|---|
| | Short-term | 10 h | 100 h | 1000 h | 1 y | 10 y | 50 y |
| -20 (-29) | 300.0<br>(2069) | 140.8<br>(971) | 125.4<br>(865) | 107.0<br>(738) | 93.0<br>(641) | 77.4<br>(534) | 69.1<br>(476) |
| 0 (-18) | 260.0<br>(1793) | 122.0<br>(841) | 108.7<br>(749) | 92.8<br>(640) | 80.6<br>(556) | 67.1<br>(463) | 59.9<br>(413) |
| 40 (4) | 170.0<br>(1172) | 79.8<br>(550) | 71.0<br>(490) | 60.7<br>(419) | 52.7<br>(363) | 43.9<br>(303) | 39.1<br>(270) |
| 60 (16) | 130.0<br>(896) | 61.0<br>(421) | 54.3<br>(374) | 46.4<br>(320) | 40.3<br>(278) | 33.5<br>(231) | 29.9<br>(206) |
| 73 (23) | 110.0<br>(758 | 57.5<br>(396 | 51.2<br>((353) | 43.7<br>(301) | 38.0<br>(262) | 31.6<br>(218) | 28.2<br>(194) |
| 100 (38) | 100.0<br>(690) | 46.9<br>(323) | 41.8<br>(288) | 35.7<br>(246) | 31.0<br>(214) | 25.8<br>(178) | 23.0<br>(159 |
| 120 (49) | 65.0<br>(448) | 30.5<br>(210) | 27.2<br>(188) | 23.2<br>(160) | 20.2<br>(139) | 16.8<br>(116) | 15.0<br>(103) |
| 140 (60) | 50.0<br>(345) | 23.5<br>(162) | 20.9<br>(144) | 17.8<br>(123) | 15.5<br>(107) | 12.9<br>(89) | 11.5<br>(79) |

**Table 18 Roundness Factor, $f_o$**

| *% Deflection* | *$f_o$* | *% Deflection* | *$f_o$* |
|---|---|---|---|
| 0 | 1.00 | 6 | 0.52 |
| 1 | 0.92 | 7 | 0.48 |
| 2 | 0.88 | 8 | 0.42 |
| 3 | 0.78 | 9 | 0.39 |
| 4 | 0.70 | ≤ 10 | 0.36 |
| 5 | 0.62 | | |

## 15 – Thermal Contraction Tensile Load

During temperature decrease, straight, unconstrained pipe on a "frictionless" surface that is anchored at both ends, will apply a tensile load against the anchored ends.

$$F = E\,\alpha\,\Delta T\,\pi\,D^2\left(\frac{1}{(0.944\,DR)} - \frac{1}{(0.944\,DR)^2}\right) \qquad (61)$$

Where

$F$ = tensile load, lb
$E$ = modulus of elasticity, psi (Table 17)
$\alpha$ = coefficient of linear thermal expansion, in/in/°F
= $0.8 \times 10^{-4}$ in/in/°F (WL106)
$\Delta T$ = temperature change, °F
$D$ = pipe outside diameter, in (WL102; WL104)
$DR$ = dimension ratio

## 16 – Poisson Pullback Force

When a tensile force is applied to a ductile material, it extends in the direction of pull, and dimensions at right angles to the direction of pull decrease. When PE pipe is pressurized, it expands slightly, and its length decreases slightly. The ratio of dimensional increase to decrease is the Poisson ratio.

Pressurized PE pipe expands slightly in the hoop direction, and if unrestrained, it decreases slightly in length. When restrained, a longitudinal pullback force develops along the length of the pipe. Joints in the system must withstand the Poisson pull back force or disjoining can occur. Pullback force varies with the duration of internal pressure because the Poisson ratio varies for short-term or long-term load (stress).

$$F_P = P\,(DR - 1)\,\mu\,\frac{\pi}{8}\left(D^2 - d^2\right) \qquad (62)$$

Where

$F_P$ = Pullback force, lb
$P$ = Internal pressure, psi
$DR$ = pipe dimension ratio, dimensionless
$\mu$ = Poisson Ratio
= 0.35 for short-term stress
= 0.45 for long-term stress
$D$ = pipe outside diameter, in (WL102; WL104)
$d$ = pipe inside diameter, in (WL102; WL104)

Poisson pullback force results from steady pressure (long-term Poisson ratio applied), during pressure leak testing (short-term-Poisson ratio applied), and during a surge pressure event (long-term Poisson ratio applied to steady pressure and short-term Poisson ratio applied to surge pressure).

## 17 – End Anchor Load, Temperature Increase

During temperature increase, end anchored, constrained pipe will apply a compressive load against the end anchors. If the distance between pipe constraints is greater than the critical distance, $L_C$, the pipe will deflect laterally between constraints and the compressive load, $P_T$, against the anchors will not exceed the critical compressive load, $P_C$.

$$L_c = \frac{1}{12}\sqrt{\frac{\pi^3\,E\left(D^4 - d^4\right)}{64\,P_C}} \qquad (63)$$

$$P_C = S_C\,\frac{\pi}{4}\left(D^2 - d^2\right) \qquad (64)$$

$$P_T = E\,\alpha\,\Delta T\,\frac{\pi}{4}\left(D^2 - d^2\right) \qquad (65)$$

$$SF = \frac{P_C}{P_T} \qquad (66)$$

$$y = 12\,L\sqrt{\frac{\alpha\,\Delta T}{2}} \qquad (67)$$

Where

$L_C$ = critical distance between constraints, ft
$E$ = elastic modulus, psi (Table 17)
$D$ = pipe outside diameter, in (WL102; WL104)
$d$ = pipe inside diameter, in (WL102; WL104)
$S_C$ = compressive strength, psi (Table 19)
$P_C$ = critical compressive load, lb
$P_T$ = for $L < L_C$, thrust force at end anchors, lb
$L$ = distance between pipe constraints, ft
$SF$ = compressive load safety factor
$\alpha$ = coefficient of linear thermal expansion, in/in/°F
= $0.8 \times 10^{-4}$ in/in/°F (WL106)
$\Delta T$ = temperature change, °F
$y$ = for $L > L_C$, maximum lateral deflection at L/2, in

**Table 19 Approximate Compressive Strength at 73°F**

| *Load Duration* | *Compressive Strength, $S_C$, psi* |
|---|---|
| short term | 1800 |
| 1 day | 1600 |
| 1 month | 850 |

## *18 – Trench Width*

For conventional excavation, the trench needs to be wide enough to properly place embedment below the pipe springline. Minimum trench width for up to three parallel pipes in a common trench is determined using:

$$B_d = C_1 + D_1 + [C_1 \text{ or } C_2] + D_2 + [C_2 \text{ or } C_3] + D_3 + C_3 \quad (68)$$

Where

$B_d$ = minimum trench width, in
$D_x$ = outside diameter of pipe 1, 2, or 3, in
$C_x$ = clearance between pipes for larger pipe, or between pipe and trench wall, in

**Table 20 Trench Clearance**

| Pipe Outside Diameter, D, in | Clearance between pipes for the larger pipe, or between pipe and trench wall, C, in |
|---|---|
| <3 | 5 |
| 3 ≤ 16 | 6 |
| > 16 ≤ 34 | 9 |
| > 34 ≤ 54 | 12 |

## *19 – Pipe Volume*

$$V = 0.0408\, d^2 L \quad (69)$$

Where

V = pipe volume, U.S. gal
d = pipe inside diameter, in (WL102; WL104)
L = length of pipe, ft

## *20 – Temperature Conversion*

Converting temperatures on Fahrenheit and Celsius (Centigrade) temperature scales:

$$C = (F - 32)\frac{5}{9} \quad (70)$$

$$F = \frac{9}{5}C + 32 \quad (71)$$

Where

C = degrees Celsius
F = degrees Fahrenheit

Example: A temperature of 73° on the Fahrenheit scale is equal to a temperature of 23° on the Celsius (Centigrade) scale.

Converting degrees on Fahrenheit and Celsius temperature scales:

$$C = F\frac{5}{9} \quad (72)$$

$$F = \frac{9}{5}C \quad (73)$$

Where

C = degrees Celsius
F = degrees Fahrenheit

Example: A temperature change of 20°F is equal to a temperature change of 11.1°C.

## *21 – HDPE Thermal Properties*

**Table 21 HDPE Thermal Properties**

| *Property* | *Typical Value* |
|---|---|
| R, Thermal Resistance (1" thickness) | 0.28 (hr-ft$^2$-°F)/Btu |
| $C_T$, Thermal Conductance (1" thickness) | 3.50 Btu/(h-ft$^2$-°F) |
| K, Thermal Conductivity (ASTM C177) | 3.50 Btu/(h-ft$^2$-°F-/in) |

$$R = \frac{1}{C_T} \quad (74)$$

$$R = \frac{t}{k} \quad (75)$$

$$C_T = \frac{k}{t} \quad (76)$$

Where

R = Thermal resistance, (hr-ft$^2$-°F)/Btu
$C_T$ = Thermal conductance, Btu/(h-ft$^2$-°F)
t = thickness, in
k = thermal conductivity, Btu/(h-ft$^2$-°F-/in

# K.4 – Ring Deflection of the Leachate Collection Pipe

APTIM

**Client:** Zion Landfill, Inc.
**Project:** Zion Landfill – Site 2 North Expansion
**Project #:** 631020105
**Calculated By:** SJW **Date:** 05/2022
**Checked By:** DAM **Date:** 05/2022

# TITLE: RING DEFLECTION OF THE LEACHATE COLLECTION PIPE

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## Problem Statement

Determine the ring deflection of the leachate collection pipe to demonstrate that an adequate cross-sectional area is capable of being maintained to allow cleaning in accordance with 35 Ill. Admin. Code 811.308 (c).

## Given

- ☐ HDPE Pipe design guidelines in WL Plastics *WL PipeCalcTM Supplement*.
- ☐ Leachate collection system design contained in Section 2.3 of this Application.
- ☐ Leachate design details, contained in the Design Drawings.
- ☐ Geotechnical Analysis Report, **Appendix J**.

## Assumptions

- ☐ Pipe deflection may be determined with a variation of the Modified Iowa formula shown below (see WL Plastics *WL PipeCalcTM Supplement*, Equation 30)

$$\text{Percent Deflection} = \frac{P_T}{144}\left(\frac{K \times D_L}{\frac{2E}{3}\left(\frac{1}{SDR-1}\right)^3 + 0.061E'}\right) \times 100\% \text{ (Equation 30)}$$

Where:
$P_T$ = total load pressure at pipe crown (psf)
K = bedding factor
$D_L$ = deflection lag factor
E’ = modulus of soil reaction (psi)
E = modulus of elasticity for the pipe (psi)
SDR = standard dimension ratio

- ☐ One pipe type is analyzed in this calculation. The type and total load pressure includes:
  - ☐ 6-inch SDR-17 Pipe: $P_T$ = 16,306.5 psf (see Appendix K.3)
- ☐ The following parameters are used to calculate the percent deflection:
  - ☐ $D_L$ = 1.0 (see WL Plastics *WL PipeCalcTM Supplement*, Table 11)
  - ☐ K = 0.1 (see WL Plastics *WL PipeCalcTM Supplement*, Equation 30)
  - ☐ E’ = 3,000 $lb/in^2$ (see Appendix K.3 calculations)
  - ☐ E = 12,200 $lb/in^2$ (see Appendix K.3 calculations)
- ☐ Table 11 of the WL Plastics *WL PipeCalcTM Supplement*, which states that long-term deflection is typically limited to 8% for non-pressure piping.

**TITLE:** **RING DEFLECTION OF THE LEACHATE COLLECTION PIPE**

## Calculations

The maximum pipe deflection is incurred with the maximum loading on the pipe. Maximum loading occurs when the landfill is fully constructed and final grades are achieved. Therefore, the pipe deflection calculations will account for the calculated loads for final buildout conditions for the vertical and horizontal expansion.

<u>6-inch SDR-17 Pipe</u>

$$\text{Percent Deflection} = \frac{P_T}{144}\left(\frac{K \times D_L}{\frac{2E}{3}\left(\frac{1}{\text{SDR-1}}\right)^3 + 0.061E'}\right) \times 100\%$$

$$\text{Percent Deflection} = \frac{16{,}306.5\ \text{psf}}{144}\left(\frac{(0.1) \times (1.0)}{\frac{(2)(12{,}200\ \text{psi})}{3}\left(\frac{1}{17\text{-}1}\right)^3 + (0.061)(3{,}000\ \text{psi})}\right) \times 100\% = \mathbf{6.1\% < 8\%}$$

## Results

The calculated ring deflection represents the worst-case loading conditions at the landfill. The calculated maximum percent ring deflection is less than 8.0% for all pipes, as recommended in WL Plastics *WL PipeCalcTM Supplement*. Therefore, the pipe design is appropriate for the anticipated loading conditions with regard to ring deflection and is capable of being maintained to allow cleaning of the piping.

Railroad live loads are typically described using AISI Cooper E80 values which are applied as three, 80,000 lb loads over three, 2ft x 8 ft areas spaced 5 ft apart.

**Table 9 E80 Cooper Railroad Live Loading**

| *Height Above Pipe Crown, ft* | *Live Load, lb/ft²* |
|---|---|
| 2 | 3800 |
| 5 | 2400 |
| 8 | 1600 |
| 10 | 1100 |
| 12 | 800 |
| 15 | 600 |
| 20 | 300 |
| 30 | 100 |

Live loads may be determined using other appropriate methods.

Total Load Pressure:

$$P_T = P_E + P_L \tag{24}$$

Where

$P_T$ = total load pressure at pipe crown, lb/ft²

Wall Crushing Resistance:

$$N_C = \frac{460800}{P_T\, DR} \tag{25}$$

Where

$N_C$ = safety factor against wall crushing

Wall Buckling Resistance

$$N_B = \frac{144\, P_{WC}}{P_T} \tag{26}$$

Where

$N_B$ = safety factor against wall buckling

$$P_{WC} = 5.65\sqrt{\frac{R\, B'\, E'\, E}{12\left(DR-1\right)^3}} \tag{27}$$

Where

$P_{WC}$ = constrained buckling pressure, psi
R = reduction factor for buoyancy

$$R = 1 - 0.33\frac{H'}{H} \tag{28}$$

H' = height of groundwater above pipe, ft
H = soil cover above pipe, ft
B' = elastic support factor

$$B' = \frac{1}{1 + 10.87312^{\left(-0.065\, H\right)}} \tag{29}$$

E' = modulus of soil reaction, psi (Table 10)
E = modulus of elasticity, psi (Table 17)
= 28,200 psi for long-term at 73°F
= 110,000 psi for short-term at 73°F

**Table 10 Modulus of Soil Reaction, E'**

| *Degree of Bedding Compaction,* | *Soil Type Pipe Bedding Material (Unified Classification System[a])* | | | | |
|---|---|---|---|---|---|
| | A | B | C | D | E |
| | *Average Value for E', psi (MPa)* | | | | |
| *Dumped* | 1000<br>(6.89) | 200<br>(1.38) | 100<br>(0.69) | 50<br>(0.34) | No data available; consult a competent soils engineer; otherwise use E'= 0 |
| *Slight, <85% Proctor, 40% Relative Density* | 3000<br>(20.68) | 1000<br>(6.89) | 400<br>(2.76) | 200<br>(1.38) | |
| *Moderate, 85-95% Proctor, 40-70% Relative Density* | 3000<br>(20.68) | 2000<br>(13.79) | 1000<br>(6.89) | 400<br>(2.76) | |
| *High, >95% Proctor, >70% Relative Density* | 3000<br>(20.68) | 3000<br>(20.68 | 2000<br>(13.79) | 1000<br>(6.89) | |

A - Crushed rock

B – Coarse grained soils; little or no fines GW, GP, SW, SP[c] contains less than 12% fines

C – Fine grained soils (LL<50); soils with medium to no plasticity, CL, ML, ML-CL, with less than 25% coarse grained particles. Coarse grained soils with fines GM, GC, SM, SC contains more than 12% fines

D – Fine grained soils (LL<50); soils with medium to no plasticity, CL, ML, ML-CL, with less than 25% coarse grained particles

E – Fine-grained soils (LL[b]>50) Soils with medium to high plasticity, CH, MH, CH-MH

Note – Standard Proctors in accordance with ASTM D 698 are used with this table. Values applicable only for fills less than 50 ft (15 m). Table does not include a safety factor. For use in predicting initial deflections only; appropriate Deflection Lag Factor must be applied for long-term deflections

[a] ASTM D2487; USBR E-3. [b] LL = liquid limit [c] Or any borderline soil beginning with one of these symbols (i.e., GM-GC, GC-SC).

Percent Deflection

$$\left(\frac{\Delta X}{D_M}\right) = \frac{P_T}{144}\left(\frac{K\, D_L}{\frac{2E}{3}\left(\frac{1}{DR-1}\right)^3 + 0.061\, E'}\right)100 \tag{30}$$

Where

ΔX = horizontal deflection, in
$D_M$ = pipe mean diameter, in

$\left(\frac{\Delta X}{D_M}\right)$ = percent deflection

$$D_M = D\left(1 - \frac{1.06}{DR}\right) \tag{31}$$

D = pipe outside diameter, in (WL102; WL104)
K = bedding factor (typically 0.1)
$D_L$ = deflection lag factor (Table 11)

**Table 11 Deflection Lag Factor**

| $D_L$ | Typical Value |
|---|---|
| 1.0 | Minimum value for use only with granular backfill and if the full soil prism load is assumed to act on the pipe. |
| 1.5 | Minimum value for use with granular backfill and assumed trench loadings |
| 2.5 | Minimum value for use with CL, ML backfills, for conditions where the backfill can become saturated, etc. |

Safe deflection for non-pressure PE3408 piping generally depends on ring bending wall strain, which is typically limited to 8%.

$$\left(\frac{\Delta X}{D_M}\right) \le \frac{\varepsilon\left(DR - 1.06\right)}{1.06\, f_D} \tag{32}$$

Where

ε = wall strain percent
≤ 8.0% for non-pressure PE3408
$f_D$ = deformation shape factor
= 6.0 for typical non-elliptical pipe deformation

Wall strain in pressurized PE3408 pipes is more complex because internal pressure increases wall strain.

**Table 12 Safe % Deflection for PE3408 Pressure Pipe**

| Safe % Deflection | DR |
|---|---|
| 2.5 | $\le 9$ |
| 3.0 | 11 |
| 4.0 | 13.5 |
| 5.0 | 17 |
| 6.0 | 21 |
| 7.0 | 26 |
| 8.5 | 32.5 |

## 7 – Submerged Pipe Ballast

Ballast weights are attached to or placed over the pipe for submergence. Ballast weights are typically bottom heavy and shaped to prevent pipe rolling. Design incorporates pipe and ballast weight and displacement, the fluids inside and outside the pipe, and environmental conditions.

$$V_P = \frac{\pi D^2}{576} \tag{33}$$

Where

$V_P$ = displaced volume of pipe, $ft^3/ft$
π = Pi (approximately 3.1416)
D = pipe outside diameter, in (WL102; WL104)

$$B_P = V_P\, K\, \omega_{LO} \tag{34}$$

Where

$B_P$ = pipe displacement uplift force, lb/ft
K = submerged environment factor
$\omega_{LO}$ = specific weight of liquid outside pipe, $lb/ft^3$

**Table 13 Submerged Environment Factor**

| Submerged Environment | Factor, K |
|---|---|
| Significant tidal flows, roving currents, stream currents | 1.5 |
| Low tidal flows or slow moving stream , river, lake or pond currents | 1.3 |
| Neutral buoyancy condition | 1.0 |

**Table 14 Specific Weights at 60°F (15°C)**

| Fluid | Specific Weight, ω, $lb/ft^3$ |
|---|---|
| Air and other gases | 0.0 |
| Fresh water | 62.4 |
| Seawater | 64.0 |
| Gasoline | 42.5 |
| Kerosene | 50.2 |
| Crude oil | 53.1 |
| Brine, 6% NaCl | 65.1 |
| Brine, 24% NaCl | 73.8 |
| Brine, 12% CaCl | 69.0 |
| Brine, 30% CaCl | 80.4 |
| Concrete | 110 to 150 |
| Steel | 490 |
| Brick | 112 – 137 |
| Sand, Gravel | 100 – 109 |
| Cast iron | 440 – 480 |
| Brass | 511 – 536 |
| Bronze | 548 |

$$V_B = \frac{\pi d^2}{576} \tag{35}$$

Where

$V_B$ = pipe ID volume, $ft^3/ft$
d = inside diameter of pipe, in (WL102; WL104)

# K.5 – Groundwater Seepage

**Client:** Zion Landfill, Inc.
**Project:** Zion Landfill – Site 2 North Expansion
**Project #:** 631020105
**Calculated By:** SJW **Date:** 05/2022
**Checked By:** DAM **Date:** 05/2022

**TITLE:** **GROUNDWATER SEEPAGE QUANTITIES**

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## Problem Statement

Calculate the inward groundwater seepage rate through the landfill composite liner system.

## Given

- ☐ Design specifications for existing landfill liner system and proposed expansion landfill liner system.
- ☐ Hydrogeology described in Section 2.2 and the Geologic Drawings in this Application.
- ☐ The HELP Model User's Guide for Version 3 (1994), Table 4 – *Default Soil, Waste, Geosynthetic Characteristics,* and Section 4.6.3 – *Layer Types*

## Assumptions

- ☐ The piezometric surface is conservatively assumed to be at ground level, resulting in a maximum inward gradient of 55 feet.
- ☐ Minimum low permeable earth liner thickness = 5 ft
- ☐ Maximum hydraulic conductivity of low permeable earth liner = 1 x $10^{-7}$ cm/sec = 3.3 x $10^{-9}$ ft/sec (Title 35 Illinois Administrative Code Section 811.306 (d)(2)).
- ☐ HDPE geomembrane liner thickness = 60 mil. = 0.06 in = 0.005 ft
- ☐ Saturated HDPE geomembrane hydraulic conductivity = 2.0 x $10^{-13}$ cm/sec = 6.56 x $10^{-15}$ ft/sec (HELP Model User's Guide, Table 4)
- ☐ Assume that leachate does not accumulate in granular drainage blanket. This will result in an increase in infiltration into the landfill and increase the rate of groundwater seepage.
- ☐ Assume that 0.05% of the HDPE geomembrane liner is flawed. However, a Construction Quality Assurance (CQA) program has been developed for the proposed expansion area to ensure proper installation of the geomembrane liner and cover.
- ☐ Darcy's Law for Groundwater Flow is used to determine the rate of groundwater infiltration:

$$Q=K\ i\ A;$$

Where:
$Q$ = Rate of groundwater seepage ($ft^3$/sec)
$K$ = Hydraulic conductivity (ft/sec)
$i$ = Hydraulic gradient (ft/ft)
$A$ = Area ($ft^2$)

## Calculations

Calculate equivalent hydraulic conductivity ($K_{eq}$) assuming:

$K_{eq(1)}$ = Liner design does not include an HDPE geomembrane liner
$K_{eq(2)}$ = Liner design does include an HDPE geomembrane liner

$K_{eq(1)}$ = Maximum hydraulic conductivity of the low permeable earth liner
= 1 x $10^{-7}$ cm/sec = 3.3 x $10^{-9}$ ft/sec

For $K_{eq(2)}$, a weighted average is used to determine the combined hydraulic conductivity of the low permeable earth liner and HDPE geomembrane liner.

$$K_{eq(2)}=\frac{H_{HDPE}+H_{liner}}{\left(\frac{H_{HDPE}}{K_{HDPE}}\right)+\left(\frac{H_{liner}}{K_{liner}}\right)}=\frac{0.005\text{ ft}+5\text{ ft}}{\left(\frac{0.005\text{ ft.}}{6.56\times10^{-15}\text{ft/sec}}\right)+\left(\frac{5\text{ ft}}{3.3\times10^{-9}\text{ft/sec}}\right)}=6.55\times10^{-12}\text{ ft/sec}$$

*Rate of Seepage*

Groundwater seepage was calculated per unit area, therefore, Darcy's Law for groundwater flow is considered for one unit of area, so the following equation is derived:

| | |
|---|---|
| (1) Q = KiA | Divide equation (1) by one unit of area to arrive at equation (2); |
| (2) Q = Ki | Where "i" is equal to the quotient of the head difference between the maximum piezometric surface elevation and average liner elevation, and the thickness of the pervious media (H). The calculation conservatively assumes a piezometric surface at ground level, resulting in a maximum of 55 feet of head on the liner. This derivation gives the following equation for groundwater seepage rate per unit area: |

Without an HDPE Geomembrane Liner:

$$Q_1=\frac{K_{eq(1)}}{H}(\text{maximum potentiometric head})$$

$$=\frac{3.3\times10^{-9}\text{ ft/sec}}{5\text{ ft}}(55\text{ ft})$$

$$=3.63\times10^{-8}\text{ ft/sec}\left(\frac{3600\text{ sec}}{\text{hr}}\right)\left(\frac{24\text{ hrs}}{\text{day}}\right)\left(\frac{365\text{ days}}{\text{year}}\right)$$

$Q_1$= **1.14 ft / year**

Including an HDPE Geomembrane Liner (Composite Liner System):

$$Q_2 = \frac{K_{eq(2)}}{H}(\text{maximum potentiometric head})$$

$$= \frac{6.55 \times 10^{-12}\ \text{ft/sec}}{(5\ \text{ft.} + 0.005\ \text{ft})}(55\ \text{ft})$$

$$= 7.20 \times 10^{-11}\ \text{ft/sec}\left(\frac{3600\ \text{sec}}{\text{hr}}\right)\left(\frac{24\ \text{hrs}}{\text{day}}\right)\left(\frac{365\ \text{days}}{\text{year}}\right)$$

$$Q_2 = \mathbf{0.00227\ ft\ /year}$$

Weighted to Reflect an HDPE Geomembrane Liner with Flaws:

Rate of seepage is calculated assuming that 0.05% of the HDPE geomembrane liner is flawed.

$$Q_s = (0.05\%)(Q_1) + (99.95\%)(Q_2)$$

$$= (0.0005)(1.14\ \text{ft/year}) + (0.9995)(0.00227\ \text{ft/year})$$

$$Q_s = \mathbf{0.0028\ ft/yr}$$

## Results

The estimated quantity of leachate derived from groundwater seepage per unit area of a composite liner system is **0.0028 ft/year** (**0.034 in/year**).

# K.6 – HELP Model Analysis

APTIM

**Client:** **Zion Landfill, Inc.**
**Project:** **Zion Landfill – Site 2 North Expansion**
**Project #:** **631020105**
**Calculated By:** **SJW** **Date:** **05/2022**
**Checked By:** **DAM** **Date:** **05/2022**

**TITLE:** **HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE (HELP) MODEL ANALYSIS**

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## Problem Statement

Determine the maximum leachate generation rate and head that will occur under three different time periods:

1. Operational Period
   This analysis is completed to identify the maximum leachate generation rate during the operational (waste filling) period and to demonstrate that the leachate head will be less than one foot. Two operational conditions are evaluated: leachate generation and head occurring after placing the first waste lift and the last waste lift of a cell.

2. 30 –Year Post-Closure Care Period
   This analysis is completed to identify the maximum leachate generation rate during the post-closure care period and to demonstrate that the leachate head will be less than one foot. Steady state conditions are used per Title 35 Illinois Administrative Code (IAC) 811.307 (b)(2)(A) and (b)(2)(B).

3. 70-years After the Post-Closure Care Period
   This analysis is completed to identify the maximum leachate head that will occur during the 70 years after the post-closure period to ensure that the groundwater impact evaluation modeling is based on conservative assumptions.

The leachate head evaluation is completed using Hydrologic Evaluation of Landfill Performance (HELP) Version 3.07 modeling software developed by the United States Environmental Protection Agency.

## Given

1. Hydrologic Evaluation of Landfill Performance (HELP) Version 3.07 User's Guide for Version 3 (Pertinent pages attached).

2. Illinois State Climatologist Map of Average Wind Speed for Illinois (https://stateclimatologist.web.illinois.edu/wind-speeds/)

3. Illinois State Climatologist Data for Waukegan, Illinois (Station 119029) (https://stateclimatologist.web.illinois.edu/data/illinois-climate-summaries/waukegan-station-119029/)

**Client:** Zion Landfill, Inc.
**Project:** Zion Landfill – Site 2 North Expansion
**Project #:** 631020105
**Calculated By:** SJW **Date:** 05/2022
**Checked By:** DAM **Date:** 05/2022

**TITLE:** **HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE (HELP) MODEL ANALYSIS**

## Assumptions

General model assumptions that apply to all modeled scenarios are presented below. Additional model-specific assumptions are provided in subsequent text and identified in the attached **Model Assumption Tables**.

### General Model Assumptions (All Models)

1. The geomembrane within the final cover and bottom liner were conservatively modeled with pinhole defects, increasing the potential for leachate accumulation. The following HELP model characteristics were applied to the final cover and bottom liner layers:

   Pinhole density = 1 hole per acre;
   Installation defects = 10 holes per acre;
   Placement Quality = 4 (Poor).

2. Subsurface infiltration due to groundwater seepage into the liner is considered as a contributing source for leachate generation based on the "Groundwater Seepage" calculation in this appendix. The subsurface infiltration rate is assumed to be 0.0028 feet/year (0.034 inches/year).

3. A cover slope of 10% is assumed, which represents the minimum design slope of the final landform.

4. The hydraulic conductivity of the layers are based on default saturated hydraulic conductivities specified in Table 4 of the Hydrologic Evaluation of Landfill Performance, User's Guide for Version 3, with the following exceptions, which are based on the proposed design:

   a. The re-compacted soil liner of the final cover is modeled with an assumed saturated hydraulic conductivity of $1 \times 10^{-5}$ cm/sec.

   b. The drainage material of the leachate collection layer is modeled with an assumed saturated hydraulic conductivity of $1 \times 10^{-1}$ cm/sec.

5. Geotextiles within the design are not modeled per HELP Model User's guide procedures.

6. The HELP Model does not include a geocomposite layer. However, HELP Default Texture No. 20, "Drainage Net," adequately characterizes the drainage net component of the geocomposite. This also provides a more conservative estimate regarding rainfall infiltration through the final cover system and is consistent with Assumption 5.

7. The drainage length along the leachate drainage layer to a collection pipe is 155 feet at a 2% slope.

8. An average wind speed of 9 miles per hour is interpolated from the Illinois State Climatologist Office map of Average Wind Speed for Illinois. The map presents annual averages based on data collected from 1991-2000.

9. Solar Radiation Data was synthetically generated by HELP using the latitude of the site (42.49 degrees).

10. Mean temperature, precipitation, and growing season data was obtained from the Illinois State Climatologist Office. The data was recorded from 1971 through 2000 in Waukegan, Illinois, located approximately 9 miles south of the proposed expansion.

    The growing season was determined to be April 29th (Day 120) to October 15th (Day 289). **Table 1** provides mean temperature and precipitation values by month.

**Table 1: Mean Temperature and Precipitation Values, 1971-2000**
**Waukegan, IL**

| Month | Temperature (°F) | Precipitation (inches) |
|---|---|---|
| January | 20.3 | 1.60 |
| February | 24.8 | 1.40 |
| March | 34.5 | 2.15 |
| April | 45.1 | 3.73 |
| May | 56.3 | 3.44 |
| June | 66.2 | 3.62 |
| July | 71.5 | 3.49 |
| August | 70.3 | 4.22 |
| September | 62.8 | 3.40 |
| October | 51.3 | 2.42 |
| November | 38.6 | 2.57 |
| December | 26.1 | 2.05 |
| **Annual** | **47.3** | **34.09** |

11. Multiple parameters specified below are based on recommended default values provided in HELP. The data is selected by identifying the closest HELP data station to the facility. For the Zion Landfill, information is based on Milwaukee, Wisconsin.

    a. Evaporative Zone Depth:
        i. 8-inches for Bare Soils (Operational Model).
        ii. 20-inches for Fair Stand of Grass (Post-Closure Models)

    b. Leaf Area Index
        i. 0.0 for Bare Soils (Operational Model).
        ii. 2.0 for Fair Stand of Grass (Post-Closure Models)

    c. Relative Humidity:
        i. 1st Quarter: 72.0%
        ii. 2nd Quarter: 70.0%
        iii. 3rd Quarter: 74.0%
        iv. 4th Quarter: 75.0%

## Model 1A: Operational Conditions Model – First Waste Lift

1. This model is evaluated assuming that 15 feet of waste has been placed (typical first lift thickness). This is a worst-case assumption because the thin waste column thickness is limited in its ability to absorb rainwater prior to reaching field capacity and releasing leachate.

2. The model is run for one year, which is significantly greater than the time period required to install the first lift.

3. This model conservatively assumes that the first waste lift has an initial moisture content of 24.6%. Per the Hydrologic Evaluation of Landfill Performance, User's Guide for Version 3, the moisture content of municipal solid waste when it is received at the landfill ranges between 8% and 20%. Field capacity, which represents the maximum storage content that a waste can hold against gravity drainage, for municipal solid waste is 29.2% (see User's Guide). This model conservatively assumes that by the time the first waste lift has been installed, it has reached initial moisture content of 24.6%, which is the midpoint between 20% and 29.2%.

4. The model is run assuming that leachate is removed from the leachate collection layer for treatment, which represents how the landfill will be operated. The drainage layer of the leachate collection layer is set to HELP Layer Type 2 (Collection Layer).

5. This model assumes that a 6-inch soil layer is used as daily cover. The material is not vegetated, resulting in "bare ground" conditions (maximum leaf area index of 0.0).

6. The SCS curve number for the daily cover was determined by HELP to be 95.3 based on the following assumptions:

    a. 10% slope length (slope of plateau area)
    b. 240 feet slope distance (maximum distance along plateau)
    c. Bare Soil (No Vegetation)
    d. Soil Texture 12 (Si-CL infiltration layer).

7. No runoff will occur from the daily cover soils (0.0% runoff in model).

Model 1B: Operational Conditions Model – Final Waste Lift

1. This model is evaluated assuming that the entire waste column has been installed, but final cover has not yet been installed. The waste mass is divided into two layers:

    a. 195 feet of waste with an initial moisture content of 29.2% (field capacity). This represents thirteen (13) 15-foot thick waste lifts.

    b. 12 feet of waste with an initial moisture content of 24.6%. This represents the final 12-foot lift to achieve the final waste grades at the thickest waste column (207 ft) of the expansion (see Model 1A Assumption 3 for explanation of value).

2. The model is run for one year, which is significantly greater than the time period required to install the final lift.

3. The model is run assuming that leachate is removed from the leachate collection layer for treatment, which represents how the landfill will be operated. The drainage layer of the leachate collection layer is set to HELP Layer Type 2 (Collection Layer).

4. This model assumes that a 6-inch soil layer is used as daily cover. The material is not vegetated, resulting in "bare ground" conditions (maximum leaf area index of 0.0).

5. No runoff will occur from the daily cover soils (0.0% runoff in model).

6. The SCS curve number for the daily cover was determined by HELP to be 95.3 based on the following assumptions:

    e. 10% slope length (slope of plateau area)
    f. 240 feet slope distance (maximum distance along plateau)
    g. Bare Soil (No Vegetation)
    h. Soil Texture 12 (Si-CL infiltration layer).

## Model 2: Post-Closure Care Period (30 Years After Closure)

1. The model is run for thirty years, representing the 30-year post-closure care period.
2. The model is run assuming that leachate is removed from the leachate collection layer for treatment, which represents how the landfill will be operated. The drainage layer of the leachate collection layer is set to HELP Layer Type 2 (Collection Layer).
3. This model is evaluated assuming that final cover is in place.
4. This model is evaluated assuming a 207 foot high column of waste has been installed, which represents the maximum waste column thickness of the proposed expansion.
5. The re-compacted final cover soil liner is modeled with an assumed hydraulic conductivity of $1x10^{-5}$ cm/sec.
6. The evaporative zone depth was selected to be twenty inches, which is the HELP default for a fair stand of grass for Milwaukee, Wisconsin.
7. The SCS curve number of 80.4 was determined by HELP based on the following assumptions:
   a. 10% slope length (slope of plateau area)
   b. 240 feet slope distance (maximum distance along plateau)
   c. Fair stand of grass
   d. Soil Texture 8 (ML infiltration layer).
8. All runoff may occur from final cover soils (100% runoff).
9. The model assumes steady-state conditions, as determined by HELP. Under this modeling option, the HELP program estimates values near steady-state and then runs one year of initialization to refine the estimates before starting the simulation. The soil water contents at the end of this year of initialization are taken as the initial values for the simulation period. The program then runs the complete simulation, starting again from the beginning of the first year of data. The results for the initialization period are not reported.

Model 3: 70 Years After Post-Closure Care Period (Years 31-100)

1. The model is run for seventy years to capture the entire modeled timeframe of the groundwater impact evaluation. The groundwater impact evaluation considers a 100-year period after closure of the landfill.
2. The model is run assuming that leachate is NOT removed from the leachate collection layer for treatment. The drainage layer of the leachate collection layer is set to HELP Layer Type 1 (Vertical Percolation Layer).
3. This model is evaluated assuming that final cover is in place.
4. This model is evaluated assuming a 207 foot high column of waste has been installed, which represents the maximum waste column thickness of the proposed expansion.
5. The re-compacted final cover soil liner is modeled with an assumed hydraulic conductivity of $1x10^{-5}$ cm/sec.
6. The SCS curve number of 80.4 was determined by HELP based on the following assumptions:
   a. 10% slope length (slope of plateau area)
   b. 240 feet slope distance (maximum distance along plateau)
   c. Fair stand of grass
   d. Soil Texture 8 (ML infiltration layer).
7. All runoff may occur from final cover soils (100% runoff).
8. The model assumes steady-state conditions, as determined by HELP. Under this modeling option, the HELP program estimates values near steady-state and then runs one year of initialization to refine the estimates before starting the simulation. The soil water contents at the end of this year of initialization are taken as the initial values for the simulation period. The program then runs the complete simulation, starting again from the beginning of the first year of data. The results for the initialization period are not reported.

## Calculations

Please see the attached Model Assumption Tables for detailed assumptions for each modeled layer. Model results for each scenario are also attached to this calculation. The leachate head evaluation is completed using Hydrologic Evaluation of Landfill Performance (HELP) Version 3.07 modeling software developed by the United States Environmental Protection Agency. HELP model results are generated on a per-acre basis, allowing the designer to extrapolate the results based on actual acreages of open and closed areas of the landfill.

APTIM

**Client:** **Zion Landfill, Inc.**
**Project:** **Zion Landfill – Site 2 North Expansion**
**Project #:** **631020105**
**Calculated By:** **SJW** **Date:** **05/2022**
**Checked By:** **DAM** **Date:** **05/2022**

**TITLE: HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE (HELP) MODEL ANALYSIS**

The leachate generation rate is reported in the HELP model results in inches/time/acre. The amount of time is equal to the model run time. Conversion of the results to gallons/day/acre are calculated below.

Model 1A: Operational Conditions Model – First Lift

Highest Average Monthly Leachate Generation Rate = 1.989 in./time/acre

$$\left(\frac{1.989\text{ in.}}{\text{year}}\right)\left(\frac{1\text{ ft.}}{12\text{ in.}}\right)\left(\frac{43{,}560\text{ ft.}^2}{1\text{ acre}}\right)\left(\frac{7.48\text{ gal}}{1\text{ ft.}^2}\right) = 1{,}742\text{ gal/day/acre}$$

Model 1B: Operational Conditions Model – Last Lift

Highest Average Monthly Leachate Generation Rate = 0.6796 in./time/acre

$$\left(\frac{0.6796\text{ in.}}{\text{year}}\right)\left(\frac{1\text{ ft.}}{12\text{ in.}}\right)\left(\frac{43{,}560\text{ ft.}^2}{1\text{ acre}}\right)\left(\frac{7.48\text{ gal}}{1\text{ ft.}^2}\right) = 595\text{ gal/day/acre}$$

Model 2: Post-Closure Care Period (30 Years After Closure)

Highest Average Monthly Leachate Generation Rate = .0034 in./time/acre

$$\left(\frac{0.0034\text{ in.}}{30\text{ years}}\right)\left(\frac{1\text{ ft.}}{12\text{ in.}}\right)\left(\frac{43{,}560\text{ ft.}^2}{1\text{ acre}}\right)\left(\frac{7.48\text{ gal}}{1\text{ ft.}^2}\right) = 3.0\text{ gal/day/acre}$$

## Results

The peak daily leachate head is reported below to show that the maximum leachate head is less than 12 inches, demonstrating compliance with 35 Ill. Admin. Code 811.307(b)(1). Leachate generation rates are reported below for the month when the highest leachate generation rate occurs. Although 35 Ill. Admin. Code 811.307(b)(2) requires the leachate collection system to be designed to operate during the month when the highest average monthly precipitation occurs, it is more conservative to design the leachate collection system to operate during the month when the highest average leachate generation rate occurs. Highest average monthly leachate generation rates and peak daily leachate head values will be used to evaluate the leachate collection system in subsequent calculations to ensure that the system design is adequate to handle the highest expected leachate volumes.

**HELP Model Results**

| Model | Highest Average Monthly Leachate Generation Rate (gallons/day/acre) | Peak Daily Leachate Head (inches) |
|---|---|---|
| Model 1A: Operational Conditions Model – First Waste Lift | 1,742 | 2.7 |
| Model 1B: Operational Conditions Model – Final Waste Lift | 595 | 1.3 |
| Model 2: Post-Closure Care Period (30 Years After Closure) | 3.0 | 0.0 |
| Model 3: 70 Years After Post-Closure Care Period (Years 31-100)[1] | – | 7.9 |

Note:

1. No leachate generation rate is reported for Model 3 because the model assumes that no leachate is collected from the landfill for treatment.

## MODEL 1A: OPERATIONAL PERIOD - INITIAL LIFT
## HELP MODEL LAYER INPUT VALUES

| Landfill Design Component | Landfill Design Component Sublayer | Help Model Layer Identifier | Assumption Parameter | Assumption Value |
|---|---|---|---|---|
| **Operational Soils** | **Daily Cover[1,2]** | **1** | Thickness: | 6 inches |
| | | | SCS Curve Number: | 95.3[2] |
| | | | HELP Layer Type: | 1 (Vertical Percolation Layer) |
| | | | HELP Texture Default Number: | 12 |
| **Municipal Solid Waste** | **Municipal Waste[3]** | **2** | Thickness: | 180 inches (15 foot lift) |
| | | | Initial Moisture Content[3]: | 24.60% |
| | | | HELP Layer Type: | 1 (Vertical Percolation Layer) |
| | | | HELP Texture Default Number: | 18 |
| **Leachate Collection System on Landfill Floor** | **6 oz/$yd^2$ Nonwoven Geotextile (Filter)[5]** | **NA (HELP Model Does Not Consider Geotextiles)** | NA | NA |
| | **Drainage Material (Coarse Aggregate)[4,6]** | **3** | Thickness: | 12 inches |
| | | | Modeled Hydraulic Conductivity[4]: | $1 \times 10^{-1}$ cm/sec |
| | | | HELP Layer Type[6]: | 2 (Leachate Collection Layer) |
| | | | HELP Texture Default Number: | 5 |
| | **8 oz/$yd^2$ Nonwoven Geotextile (Cushion)[5]** | **NA (HELP Model Does Not Consider Geotextiles)** | NA | NA |
| **Composite Base Liner System** | **60-mil HDPE Textured Geomembrane** | **4** | Thickness: | 0.06 inches |
| | | | HELP Layer Type: | 4 (Geomembrane Layer) |
| | | | HELP Texture Default Number: | 35 |
| | | | Max. Leachate Flow Length Across Floor to Trench: | 155 feet |
| | | | Drainage Slope Along Max. Leachate Flow Length Across Floor to Trench: | 2.0% |
| | | | Pinhole Density: | 1 hole per acre |
| | | | Installation Defects: | 10 holes per acre |
| | | | Placement Quality: | 4 (Poor) |
| | **Compacted Cohesive Soil** | **5** | Thickness: | 60 inches |
| | | | HELP Layer Type: | 3 (Barrier Soil Layer) |
| | | | HELP Texture Default Number: | 16 |

**Notes:**

1. Daily cover is assumed to be 6-inches of soil.

2. The SCS curve number of 95.1 was determined by HELP based on the following assumptions:
a. 10% slope length
b. 240 feet slope distance
c. Bare soil (no vegetation)
d. Soil Texture 12

3. With the exception of the municipal solid waste, initial moisture contents for all layers are set to HELP model default values specified in Table 4 of the Hydrologic Evaluation of Landfill Performance (HELP) Model User's Guide for Version 3. Per the User's Guide, the maximum expected moisture content of municipal solid waste when it is received at the landfill is 20% and field capacity for municipal solid waste is 29.2%. This model is completed under the conservative assumption that by the time the first waste lift has been installed, the municipal solid waste has reached initial moisture content of 24.6% (midpoint between 20% and 29.2%).

4. With the exception of the leachate collection layer drainage material, the hydraulic conductivity of the layers are based on default saturated hydraulic conductivities specified in Table 4 of the Hydrologic Evaluation of Landfill Performance (HELP) Model User's Guide for Version 3. The drainage material of the leachate collection layer is modeled with an assumed saturated hydraulic conductivity of 1x10-1 cm/sec based on its specified design.

5. Geotextiles within the design are not modeled per HELP Model User's guide procedures.

6. During operations, leachate will be removed from the facility as necessary. As such, the layer is set to a collection layer (Layer Type 2).

# MODEL 1B: OPERATIONAL PERIOD - FINAL LIFT
# HELP MODEL LAYER INPUT VALUES

| Landfill Design Component | Landfill Design Component Sublayer | Help Model Layer Identifier | Assumption Parameter | Assumption Value |
|---|---|---|---|---|
| **Operational Soils** | **Daily Cover[1,2]** | **1** | Thickness: | 6 inches |
| | | | SCS Curve Number: | 95.3[2] |
| | | | HELP Layer Type: | 1 (Vertical Percolation Layer) |
| | | | HELP Texture Default Number: | 12 |
| **Municipal Solid Waste** | **Municipal Waste Final 12 Foot Lift[3]** | **2** | Thickness: | 144 inches |
| | | | Initial Moisture Content[3]: | 24.60% |
| | | | HELP Layer Type: | 1 (Vertical Percolation Layer) |
| | | | HELP Texture Default Number: | 18 |
| **Municipal Solid Waste** | **Municipal Waste Previously Placed Lifts[3]** | **3** | Thickness: | 2,340 inches (95 feet placed in thirteen 15-foot lifts) |
| | | | HELP Layer Type: | 1 (Vertical Percolation Layer) |
| | | | HELP Texture Default Number: | 18 |
| **Leachate Collection System on Landfill Floor** | **6 $\text{oz/yd}^2$ Nonwoven Geotextile (Filter)[5]** | **NA (HELP Model Does Not Consider Geotextiles)** | NA | NA |
| | **Drainage Material (Coarse Aggregate)[4]** | **4** | Thickness: | 12 inches |
| | | | Modeled Hydraulic Conductivity[4]: | $1 \times 10^{-1}$ cm/sec |
| | | | HELP Layer Type: | 2 (Leachate Collection Layer) |
| | | | HELP Texture Default Number: | 5 |
| | **8 $\text{oz/yd}^2$ Nonwoven Geotextile (Cushion)[5]** | **NA (HELP Model Does Not Consider Geotextiles)** | NA | NA |
| **Composite Base Liner System** | **60-mil HDPE Textured Geomembrane** | **5** | Thickness: | 0.06 inches |
| | | | HELP Layer Type: | 4 (Geomembrane Layer) |
| | | | HELP Texture Default Number: | 35 |
| | | | Max. Leachate Flow Length Across Floor to Trench: | 155 feet |
| | | | Drainage Slope Along Max. Leachate Flow Length Across Floor to Trench: | 2.0% |
| | | | Pinhole Density: | 1 hole per acre |
| | | | Installation Defects: | 10 holes per acre |
| | | | Placement Quality: | 4 (Poor) |
| | **Compacted Cohesive Soil** | **6** | Thickness: | 60 inches |
| | | | HELP Layer Type: | 3 (Barrier Soil Layer) |
| | | | HELP Texture Default Number: | 16 |

**Notes:**

1. Daily cover is assumed to be 6-inches of soil.

2. The SCS curve number of 95.1 was determined by HELP based on the following assumptions:
a. 10% slope length
b. 240 feet slope distance
c. Bare soil (no vegetation)
d. Soil Texture 12

3. With the exception of the municipal solid waste, initial moisture contents for all layers are set to HELP model default values specified in Table 4 of the Hydrologic Evaluation of Landfill Performance (HELP) Model User's Guide for Version 3. Per the User's Guide, the maximum expected moisture content of municipal solid waste when it is received at the landfill is 20% and field capacity for municipal solid waste is 29.2%. This model is completed under the conservative assumption that by the time the first waste lift has been installed, the municipal solid waste has reached initial moisture content of 24.6% (midpoint between 20% and 29.2%).

4. With the exception of the leachate collection layer drainage material, the hydraulic conductivity of the layers are based on default saturated hydraulic conductivities specified in Table 4 of the Hydrologic Evaluation of Landfill Performance (HELP) Model User's Guide for Version 3. The drainage material of the leachate collection layer is modeled with an assumed saturated hydraulic conductivity of 1x10-1 cm/sec based on its specified design.

5. Geotextiles within the design are not modeled per HELP Model User's guide procedures.

6. During operations, leachate will be removed from the facility as necessary. As such, the layer is set to a collection layer (Layer Type 2).

## MODEL 2: 30-YEAR POST CLOSURE CARE PERIOD
## HELP MODEL LAYER INPUT VALUES

| Landfill Design Component | Landfill Design Component Sublayer | Help Model Layer Identifier | Assumption Parameter | Assumption Value |
|---|---|---|---|---|
| Final Cover | Vegetated Cover Soils[1] | 1 | Thickness: | 6 inches |
| | | | SCS Curve Number[1]: | 80.4 |
| | | | HELP Layer Type: | 1 (Vertical Percolation Layer) |
| | | | HELP Texture Default Number: | 8 |
| | Protective Cover | 2 | Thickness: | 30 inches |
| | | | HELP Layer Type: | 1 (Vertical Percolation Layer) |
| | | | HELP Texture Default Number: | 12 |
| | Double Sided Geocomposite[2,4] | 3 | Thickness: | 0.2 inches |
| | | | HELP Layer Type: | 2 (Lateral Drainage Layer) |
| | | | HELP Texture Default Number[2]: | 20[2] |
| | 40 mil LLPDE Geomembrane Liner | 4 | Thickness: | 0.04 inches |
| | | | HELP Layer Type: | 4 (Geomembrane Layer) |
| | | | HELP Texture Default Number: | 36 |
| | | | Pinhole Density: | 1 hole per acre |
| | | | Installation Defects: | 10 holes per acre |
| | | | Placement Quality: | 4 (Poor) |
| | Recompacted Soil Liner[3] | 5 | Thickness: | 24 inches |
| | | | Modeled Hydraulic Conductivity[3]: | $1 \times 10^{-5}$ cm/sec |
| | | | HELP Layer Type: | 3 (Barrier Soil Layer) |
| | | | HELP Texture Default Number: | 16 |
| Municipal Solid Waste | Municipal Waste | 6 | Thickness: | 2,484 inches |
| | | | HELP Layer Type: | 1 (Vertical Percolation Layer) |
| | | | HELP Texture Default Number: | 18 |
| Leachate Collection System on Landfill Floor | 6 oz/$yd^2$ Nonwoven Geotextile (Filter)[4] | NA (HELP Model Does Not Consider Geotextiles) | NA | NA |
| | Drainage Material (Coarse Aggregate)[3,6] | 7 | Thickness: | 12 inches |
| | | | Modeled Hydraulic Conductivity[3]: | $1 \times 10^{-1}$ cm/sec |
| | | | HELP Layer Type[6]: | 2 (Leachate Collection Layer) |
| | | | HELP Texture Default Number: | 5 |
| | 8 oz/$yd^2$ Nonwoven Geotextile (Cushion)[4] | NA (HELP Model Does Not Consider Geotextiles) | NA | NA |
| Composite Base Liner System | 60-mil HDPE Textured Geomembrane | 8 | Thickness: | 0.06 inches |
| | | | HELP Layer Type: | 4 (Geomembrane Layer) |
| | | | HELP Texture Default Number: | 35 |
| | | | Max. Leachate Flow Length Across Floor to | 155 feet |
| | | | Drainage Slope Along Max. Leachate Flow Length Across Floor to Trench: | 2.0% |
| | | | Pinhole Density: | 1 hole per acre |
| | | | Installation Defects: | 10 holes per acre |
| | | | Placement Quality: | 4 (Poor) |
| | Compacted Cohesive Soil | 9 | Thickness: | 60 inches |
| | | | HELP Layer Type: | 3 (Barrier Soil Layer) |
| | | | HELP Texture Default Number: | 16 |

**Notes:**

1. The SCS curve number of 80.4 was determined by HELP based on the following assumptions:
a. 10% slope length
b. 240 feet slope distance
c. Fair stand of Grass
d. Soil Texture 8

2. The HELP Model does not include a geocomposite layer option. However, the HELP Default Texture No. 20, "Drainage Net," adequately characterizes the drainage net component of the geocomposite.

3. The hydraulic conductivity of the soils layers are based on default saturated hydraulic conductivities specified in Table 4 of the Hydrologic Evaluation of Landfill Performance, User's Guide for Version 3, with the exceptions of the re-compacted soil liner of the final cover and the drainage material of the leachate collection system. The re-compacted soil liner is modeled with an assumed hydraulic conductivity of 1x10-5 cm/sec, per the proposed design. The drainage material of the leachate collection layer is modeled with an assumed saturated hydraulic conductivity of 1x10-1 cm/sec based on its specified design.

4. Initial moisture contents for soil layers are based on steady state modeling method of HELP. Under this modeling option, the HELP program estimates values near steady-state and then runs one year of initialization to refine the estimates before starting the simulation. The soil water contents at the end of this year of initialization are taken as the initial values for the simulation period. The program then runs the complete simulation, starting again from the beginning of the first year of data. The results for the initialization period are not reported.

5. Geotextiles within the design are not modeled per HELP Model User's guide procedures.

6. During the 30 year post-closure period, leachate will be removed from the landfill as necessary. As such, the layer is set to a collection layer (Layer Type 2).

## MODEL 3: 70-YEARS AFTER POST CLOSURE CARE PERIOD
## HELP MODEL LAYER INPUT VALUES

| Landfill Design Component | Landfill Design Component Sublayer | Help Model Layer Identifier | Assumption Parameter | Assumption Value |
|---|---|---|---|---|
| **Final Cover** | **Vegetated Cover Soils[1]** | **1** | Thickness: | 6 inches |
| | | | SCS Curve Number[1]: | 80.4 |
| | | | HELP Layer Type: | 1 (Vertical Percolation Layer) |
| | | | HELP Texture Default Number: | 8 |
| | **Protective Cover** | **2** | Thickness: | 30 inches |
| | | | HELP Layer Type: | 1 (Vertical Percolation Layer) |
| | | | HELP Texture Default Number: | 12 |
| | **Double Sided Geocomposite[2,4]** | **3** | Thickness: | 0.2 inches |
| | | | HELP Layer Type: | 2 (Lateral Drainage Layer) |
| | | | HELP Texture Default Number[2]: | 20[2] |
| | **40 mil LLPDE Geomembrane Liner** | **4** | Thickness: | 0.04 inches |
| | | | HELP Layer Type: | 4 (Geomembrane Layer) |
| | | | HELP Texture Default Number: | 36 |
| | | | Pinhole Density: | 1 hole per acre |
| | | | Installation Defects: | 10 holes per acre |
| | | | Placement Quality: | 4 (Poor) |
| | **Recompacted Soil Liner[3]** | **5** | Thickness: | 24 inches |
| | | | Modeled Hydraulic Conductivity[3]: | $1 \times 10^{-5}$ cm/sec |
| | | | HELP Layer Type: | 3 (Barrier Soil Layer) |
| | | | HELP Texture Default Number: | 16 |
| **Municipal Solid Waste** | **Municipal Waste** | **6** | Thickness: | 2,484 inches |
| | | | HELP Layer Type: | 1 (Vertical Percolation Layer) |
| | | | HELP Texture Default Number: | 18 |
| **Leachate Collection System on Landfill Floor** | **6 oz/$yd^2$ Nonwoven Geotextile (Filter)[4]** | **NA (HELP Model Does Not Consider Geotextiles)** | NA | NA |
| | **Drainage Material (Coarse Aggregate)[3,6]** | **7** | Thickness: | 12 inches |
| | | | Modeled Hydraulic Conductivity[3]: | $1 \times 10^{-1}$ cm/sec |
| | | | HELP Layer Type[6]: | 1 (Vertical Percolation Layer) |
| | | | HELP Texture Default Number: | 5 |
| | **8 oz/$yd^2$ Nonwoven Geotextile (Cushion)[4]** | **NA (HELP Model Does Not Consider Geotextiles)** | NA | NA |
| **Composite Base Liner System** | **60-mil HDPE Textured Geomembrane** | **8** | Thickness: | 0.06 inches |
| | | | HELP Layer Type: | 4 (Geomembrane Layer) |
| | | | HELP Texture Default Number: | 35 |
| | | | Max. Leachate Flow Length Across Floor to | 155 feet |
| | | | Drainage Slope Along Max. Leachate Flow Length Across Floor to Trench: | 2.0% |
| | | | Pinhole Density: | 1 hole per acre |
| | | | Installation Defects: | 10 holes per acre |
| | | | Placement Quality: | 4 (Poor) |
| | **Compacted Cohesive Soil** | **9** | Thickness: | 60 inches |
| | | | HELP Layer Type: | 3 (Barrier Soil Layer) |
| | | | HELP Texture Default Number: | 16 |

**Notes:**

1. The SCS curve number of 80.4 was determined by HELP based on the following assumptions:
a. 10% slope length
b. 240 feet slope distance
c. Fair stand of Grass
d. Soil Texture 8

2. The HELP Model does not include a geocomposite layer option. However, the HELP Default Texture No. 20, “Drainage Net,” adequately characterizes the drainage net component of the geocomposite.

3. The hydraulic conductivity of the soils layers are based on default saturated hydraulic conductivities specified in Table 4 of the Hydrologic Evaluation of Landfill Performance, User’s Guide for Version 3, with the exceptions of the re-compacted soil liner of the final cover and the drainage material of the leachate collection system. The re-compacted soil liner is modeled with an assumed hydraulic conductivity of 1x10-5 cm/sec, per the proposed design. The drainage material of the leachate collection layer is modeled with an assumed saturated hydraulic conductivity of 1x10-1 cm/sec based on its specified design.

4. Initial moisture contents for soil layers are based on steady state modeling method of HELP. Under this modeling option, the HELP program estimates values near steady-state and then runs one year of initialization to refine the estimates before starting the simulation. The soil water contents at the end of this year of initialization are taken as the initial values for the simulation period. The program then runs the complete simulation, starting again from the beginning of the first year of data. The results for the initialization period are not reported.

5. Geotextiles within the design are not modeled per HELP Model User’s guide procedures.

6. After the post-closure period, leachate will be not be removed from the landfill. As such, the layer is set to a vertical percolation layer (Layer Type 1).

```
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**                                                                  **
**                                                                  **
**          HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE           **
**             HELP MODEL VERSION 3.07  (1 NOVEMBER 1997)           **
**             DEVELOPED BY ENVIRONMENTAL LABORATORY                **
**                USAE WATERWAYS EXPERIMENT STATION                 **
**          FOR USEPA RISK REDUCTION ENGINEERING LABORATORY         **
**                                                                  **
**                                                                  **
**********************************************************************
**********************************************************************


PRECIPITATION DATA FILE:    C:\SOURCE\zion\precip1b.D4
TEMPERATURE DATA FILE:      C:\SOURCE\zion\temp1b.D7
SOLAR RADIATION DATA FILE:  C:\SOURCE\zion\solar1b.D13
EVAPOTRANSPIRATION DATA:    C:\source\zion\evap1b.D11
SOIL AND DESIGN DATA FILE:  C:\source\zion\soilm1a.D10
OUTPUT DATA FILE:           C:\source\zion\outm1a.OUT


TIME:  16:21     DATE:   2/28/2020


**********************************************************************

       TITLE:  ZION LANDFILL SITE 2 NORTH EXPANSION FIRST LIFT

**********************************************************************


     NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER
              WERE SPECIFIED BY THE USER.


                                   LAYER  1
                                   --------

                     TYPE 1 - VERTICAL PERCOLATION LAYER
                         MATERIAL TEXTURE NUMBER  12
           THICKNESS                    =      6.00   INCHES
           POROSITY                     =      0.4710 VOL/VOL
           FIELD CAPACITY               =      0.3420 VOL/VOL
           WILTING POINT                =      0.2100 VOL/VOL
           INITIAL SOIL WATER CONTENT   =      0.3420 VOL/VOL
           EFFECTIVE SAT. HYD. COND.    =  0.419999997000E-04 CM/SEC
```

```
                        LAYER  2
                        --------

          TYPE 1 - VERTICAL PERCOLATION LAYER
              MATERIAL TEXTURE NUMBER  18
THICKNESS                   =    180.00   INCHES
POROSITY                    =      0.6710 VOL/VOL
FIELD CAPACITY              =      0.2920 VOL/VOL
WILTING POINT               =      0.0770 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.2460 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.100000005000E-02 CM/SEC



                        LAYER  3
                        --------

            TYPE 2 - LATERAL DRAINAGE LAYER
              MATERIAL TEXTURE NUMBER   0
THICKNESS                   =     12.00   INCHES
POROSITY                    =      0.4570 VOL/VOL
FIELD CAPACITY              =      0.1310 VOL/VOL
WILTING POINT               =      0.0580 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.1310 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.100000001000      CM/SEC
SLOPE                       =      2.00   PERCENT
DRAINAGE LENGTH             =    155.0    FEET



                        LAYER  4
                        --------

            TYPE 4 - FLEXIBLE MEMBRANE LINER
              MATERIAL TEXTURE NUMBER  35
THICKNESS                   =      0.06   INCHES
POROSITY                    =      0.0000 VOL/VOL
FIELD CAPACITY              =      0.0000 VOL/VOL
WILTING POINT               =      0.0000 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.0000 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.199999996000E-12 CM/SEC
FML PINHOLE DENSITY         =      1.00   HOLES/ACRE
FML INSTALLATION DEFECTS    =     10.00   HOLES/ACRE
FML PLACEMENT QUALITY       =  4 - POOR
```

```
                             LAYER  5
                             --------

                   TYPE 3 - BARRIER SOIL LINER
                   MATERIAL TEXTURE NUMBER  16
    THICKNESS                    =    60.00   INCHES
    POROSITY                     =     0.4270 VOL/VOL
    FIELD CAPACITY               =     0.4180 VOL/VOL
    WILTING POINT                =     0.3670 VOL/VOL
    INITIAL SOIL WATER CONTENT   =     0.4270 VOL/VOL
    EFFECTIVE SAT. HYD. COND.    =  0.100000001000E-06 CM/SEC
    SUBSURFACE INFLOW            =     0.03   INCHES/YR



             GENERAL DESIGN AND EVAPORATIVE ZONE DATA
             ----------------------------------------

  NOTE:  SCS RUNOFF CURVE NUMBER WAS COMPUTED FROM DEFAULT
           SOIL DATA BASE USING SOIL TEXTURE #12 WITH BARE
           GROUND CONDITIONS, A SURFACE SLOPE OF 10.% AND
           A SLOPE LENGTH OF  240. FEET.

 SCS RUNOFF CURVE NUMBER              =    95.30
 FRACTION OF AREA ALLOWING RUNOFF     =     0.0    PERCENT
 AREA PROJECTED ON HORIZONTAL PLANE   =     1.000  ACRES
 EVAPORATIVE ZONE DEPTH               =     8.0    INCHES
 INITIAL WATER IN EVAPORATIVE ZONE    =     2.544  INCHES
 UPPER LIMIT OF EVAPORATIVE STORAGE   =     4.168  INCHES
 LOWER LIMIT OF EVAPORATIVE STORAGE   =     1.414  INCHES
 INITIAL SNOW WATER                   =     0.000  INCHES
 INITIAL WATER IN LAYER MATERIALS     =    73.524  INCHES
 TOTAL INITIAL WATER                  =    73.524  INCHES
 TOTAL SUBSURFACE INFLOW              =     0.03   INCHES/YEAR



              EVAPOTRANSPIRATION AND WEATHER DATA
              -----------------------------------

  NOTE:  EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
           MILWAUKEE             WISCONSIN

      STATION LATITUDE                        =  42.49 DEGREES
      MAXIMUM LEAF AREA INDEX                 =   0.00
      START OF GROWING SEASON (JULIAN DATE)   =    120
```

```
            END OF GROWING SEASON (JULIAN DATE)     =    289
            EVAPORATIVE ZONE DEPTH                 =   8.0  INCHES
            AVERAGE ANNUAL WIND SPEED              =   9.00 MPH
            AVERAGE 1ST QUARTER RELATIVE HUMIDITY  =  72.00 %
            AVERAGE 2ND QUARTER RELATIVE HUMIDITY  =  70.00 %
            AVERAGE 3RD QUARTER RELATIVE HUMIDITY  =  74.00 %
            AVERAGE 4TH QUARTER RELATIVE HUMIDITY  =  75.00 %


        NOTE:  PRECIPITATION DATA WAS SYNTHETICALLY GENERATED USING
                 COEFFICIENTS FOR    MILWAUKEE           WISCONSIN

                 NORMAL MEAN MONTHLY PRECIPITATION (INCHES)

   JAN/JUL     FEB/AUG     MAR/SEP     APR/OCT     MAY/NOV     JUN/DEC
   -------     -------     -------     -------     -------     -------
     1.60        1.40        2.15        3.73        3.44        3.62
     3.49        4.22        3.40        2.42        2.57        2.05


        NOTE:  TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING
                 COEFFICIENTS FOR    MILWAUKEE           WISCONSIN

            NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

   JAN/JUL     FEB/AUG     MAR/SEP     APR/OCT     MAY/NOV     JUN/DEC
   -------     -------     -------     -------     -------     -------
    20.30       24.80       34.50       45.10       56.30       66.20
    71.50       70.30       62.80       51.30       38.60       26.10


   NOTE:  SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING
                 COEFFICIENTS FOR    MILWAUKEE           WISCONSIN
                   AND STATION LATITUDE   =  42.57 DEGREES




*******************************************************************************
     AVERAGE MONTHLY VALUES IN INCHES FOR YEARS     1 THROUGH    1
-------------------------------------------------------------------------------

                     JAN/JUL  FEB/AUG  MAR/SEP  APR/OCT  MAY/NOV  JUN/DEC
                     -------  -------  -------  -------  -------  -------
   PRECIPITATION
```

```
-------------
TOTALS               0.81      1.61      1.52      2.33      2.67      3.47
                     3.48      4.34      4.07      3.29      5.13      1.82

STD. DEVIATIONS      0.00      0.00      0.00      0.00      0.00      0.00
                     0.00      0.00      0.00      0.00      0.00      0.00

RUNOFF
------
TOTALS              0.000     0.000     0.000     0.000     0.000     0.000
                    0.000     0.000     0.000     0.000     0.000     0.000

STD. DEVIATIONS     0.000     0.000     0.000     0.000     0.000     0.000
                    0.000     0.000     0.000     0.000     0.000     0.000

EVAPOTRANSPIRATION
------------------
TOTALS              0.195     0.462     0.637     3.189     1.714     3.805
                    2.486     4.669     2.720     1.829     1.454     0.470

STD. DEVIATIONS     0.000     0.000     0.000     0.000     0.000     0.000
                    0.000     0.000     0.000     0.000     0.000     0.000

SUBSURFACE INFLOW INTO LAYER  5
-------------------------------
TOTALS             0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
                   0.0000    0.0000    0.0000    0.0000    0.0000    0.0000

LATERAL DRAINAGE COLLECTED FROM LAYER  3
----------------------------------------
TOTALS             0.0025    0.0026    0.0029    0.0028    0.0029    0.0028
                   0.0029    0.0029    0.0028    0.0029    0.0079    1.9890

STD. DEVIATIONS    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
                   0.0000    0.0000    0.0000    0.0000    0.0000    0.0000

PERCOLATION/LEAKAGE THROUGH LAYER  5
------------------------------------
TOTALS             0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
                   0.0000    0.0000    0.0000    0.0000    0.0000    0.0000

STD. DEVIATIONS    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
                   0.0000    0.0000    0.0000    0.0000    0.0000    0.0000


----------------------------------------------------------------------
        AVERAGES OF MONTHLY AVERAGED DAILY HEADS (INCHES)
----------------------------------------------------------------------
```

```
   DAILY AVERAGE HEAD ON TOP OF LAYER  4
   -------------------------------------
   AVERAGES        0.0011   0.0013   0.0013   0.0013   0.0013   0.0013
                   0.0013   0.0013   0.0013   0.0013   0.0036   0.8775

   STD. DEVIATIONS 0.0000   0.0000   0.0000   0.0000   0.0000   0.0000
                   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000

 ******************************************************************************


 ******************************************************************************
  AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS    1 THROUGH    1
 ------------------------------------------------------------------------------
                                    INCHES            CU. FEET        PERCENT
                              -------------------  --------------   ----------
  PRECIPITATION                  34.54    (   0.000)     125380.2     100.00

  RUNOFF                          0.000   (  0.0000)          0.00      0.000

  EVAPOTRANSPIRATION             23.632   (  0.0000)      85785.54     68.420

  SUBSURFACE INFLOW INTO         0.00000                     0.000    0.00000
    LAYER  5

  LATERAL DRAINAGE               2.02479 (  0.00000)      7349.990    5.86216
  COLLECTED FROM LAYER  3

  PERCOLATION/LEAKAGE           0.00000 (  0.00000)         0.000    0.00000
  THROUGH LAYER  5

  AVERAGE HEAD ON TOP                    0.074 (    0.000)
    OF LAYER  4

  CHANGE IN WATER STORAGE 8.917   (  0.0000)      32368.13     25.816

 ******************************************************************************
```

```
******************************************************************************
            PEAK DAILY VALUES FOR YEARS     1 THROUGH    1
------------------------------------------------------------------------------
                                                (INCHES)      (CU. FT.)
                                               ----------    -------------
      PRECIPITATION                               1.60          5808.000

      RUNOFF                                      0.000            0.0000

      DRAINAGE COLLECTED FROM LAYER  3           0.11756        426.73547

      PERCOLATION/LEAKAGE THROUGH LAYER  5     0.000000          0.00000

      AVERAGE HEAD ON TOP OF LAYER  4                1.608

      MAXIMUM HEAD ON TOP OF LAYER  4                2.726

      LOCATION OF MAXIMUM HEAD IN LAYER  3
            (DISTANCE FROM DRAIN)                   23.5 FEET

      SNOW WATER                                 1.12          4080.6218


      MAXIMUM VEG. SOIL WATER (VOL/VOL)                      0.5210

      MINIMUM VEG. SOIL WATER (VOL/VOL)                      0.1767

   ***  Maximum heads are computed using McEnroe's equations.  ***

            Reference:  Maximum Saturated Depth over Landfill Liner
                        by Bruce M. McEnroe, University of Kansas
                        ASCE Journal of Environmental Engineering
                        Vol. 119, No. 2, March 1993, pp. 262-270.

******************************************************************************
```

```
**********************************************************************
               FINAL WATER STORAGE AT END OF YEAR     1
----------------------------------------------------------------------
                    LAYER        (INCHES)       (VOL/VOL)
                    -----        --------       ---------
                      1            2.6254         0.4376

                      2           52.4171         0.2912

                      3            1.7783         0.1482

                      4            0.0000         0.0000

                      5           25.6200         0.4270

                  SNOW WATER       0.000

**********************************************************************
**********************************************************************
```

```
**********************************************************************
**********************************************************************
**                                                                  **
**                                                                  **
**            HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE         **
**              HELP MODEL VERSION 3.07  (1 NOVEMBER 1997)          **
**                DEVELOPED BY ENVIRONMENTAL LABORATORY             **
**                  USAE WATERWAYS EXPERIMENT STATION               **
**           FOR USEPA RISK REDUCTION ENGINEERING LABORATORY        **
**                                                                  **
**                                                                  **
**********************************************************************
**********************************************************************


PRECIPITATION DATA FILE:    C:\SOURCE\zion\precip1b.D4
TEMPERATURE DATA FILE:      C:\SOURCE\zion\temp1b.D7
SOLAR RADIATION DATA FILE:  C:\SOURCE\zion\solar1b.D13
EVAPOTRANSPIRATION DATA:    C:\source\zion\evap1b.D11
SOIL AND DESIGN DATA FILE:  C:\source\zion\soilm1b.D10
OUTPUT DATA FILE:           C:\source\zion\outm1b.OUT


TIME:  16:25     DATE:   2/28/2020


**********************************************************************
     TITLE:  ZION LANDFILL SITE 2 NORTH EXPANSION LAST LIFT
**********************************************************************


     NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER
              WERE SPECIFIED BY THE USER.


                                   LAYER  1
                                   --------

                     TYPE 1 - VERTICAL PERCOLATION LAYER
                         MATERIAL TEXTURE NUMBER  12
           THICKNESS                     =      6.00   INCHES
           POROSITY                      =      0.4710 VOL/VOL
           FIELD CAPACITY                =      0.3420 VOL/VOL
           WILTING POINT                 =      0.2100 VOL/VOL
           INITIAL SOIL WATER CONTENT    =      0.3420 VOL/VOL
           EFFECTIVE SAT. HYD. COND.     =  0.419999997000E-04 CM/SEC
```

```
                        LAYER  2
                        --------

          TYPE 1 - VERTICAL PERCOLATION LAYER
              MATERIAL TEXTURE NUMBER  18
THICKNESS                   =    144.00   INCHES
POROSITY                    =      0.6710 VOL/VOL
FIELD CAPACITY              =      0.2920 VOL/VOL
WILTING POINT               =      0.0770 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.2460 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.100000005000E-02 CM/SEC



                        LAYER  3
                        --------

          TYPE 1 - VERTICAL PERCOLATION LAYER
              MATERIAL TEXTURE NUMBER  18
THICKNESS                   =   2340.00   INCHES
POROSITY                    =      0.6710 VOL/VOL
FIELD CAPACITY              =      0.2920 VOL/VOL
WILTING POINT               =      0.0770 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.2920 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.100000005000E-02 CM/SEC



                        LAYER  4
                        --------

            TYPE 2 - LATERAL DRAINAGE LAYER
              MATERIAL TEXTURE NUMBER   0
THICKNESS                   =     12.00   INCHES
POROSITY                    =      0.4570 VOL/VOL
FIELD CAPACITY              =      0.1310 VOL/VOL
WILTING POINT               =      0.0580 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.1310 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.100000001000     CM/SEC
SLOPE                       =      2.00   PERCENT
DRAINAGE LENGTH             =    155.0    FEET
```

```
                          LAYER  5
                          --------

              TYPE 4 - FLEXIBLE MEMBRANE LINER
                MATERIAL TEXTURE NUMBER  35
   THICKNESS                    =      0.06   INCHES
   POROSITY                     =      0.0000 VOL/VOL
   FIELD CAPACITY               =      0.0000 VOL/VOL
   WILTING POINT                =      0.0000 VOL/VOL
   INITIAL SOIL WATER CONTENT   =      0.0000 VOL/VOL
   EFFECTIVE SAT. HYD. COND.    =  0.199999996000E-12 CM/SEC
   FML PINHOLE DENSITY          =      1.00   HOLES/ACRE
   FML INSTALLATION DEFECTS     =     10.00   HOLES/ACRE
   FML PLACEMENT QUALITY        =  4 - POOR


                          LAYER  6
                          --------

                TYPE 3 - BARRIER SOIL LINER
                MATERIAL TEXTURE NUMBER  16
   THICKNESS                    =     60.00   INCHES
   POROSITY                     =      0.4270 VOL/VOL
   FIELD CAPACITY               =      0.4180 VOL/VOL
   WILTING POINT                =      0.3670 VOL/VOL
   INITIAL SOIL WATER CONTENT   =      0.4270 VOL/VOL
   EFFECTIVE SAT. HYD. COND.    =  0.100000001000E-06 CM/SEC
   SUBSURFACE INFLOW            =      0.03   INCHES/YR


          GENERAL DESIGN AND EVAPORATIVE ZONE DATA
          ----------------------------------------

 NOTE:  SCS RUNOFF CURVE NUMBER WAS COMPUTED FROM DEFAULT
          SOIL DATA BASE USING SOIL TEXTURE #12 WITH BARE
          GROUND CONDITIONS, A SURFACE SLOPE OF 10.% AND
          A SLOPE LENGTH OF  240. FEET.

 SCS RUNOFF CURVE NUMBER            =     95.30
 FRACTION OF AREA ALLOWING RUNOFF   =      0.0    PERCENT
 AREA PROJECTED ON HORIZONTAL PLANE =      1.000  ACRES
 EVAPORATIVE ZONE DEPTH             =      8.0    INCHES
 INITIAL WATER IN EVAPORATIVE ZONE  =      2.544  INCHES
 UPPER LIMIT OF EVAPORATIVE STORAGE =      4.168  INCHES
 LOWER LIMIT OF EVAPORATIVE STORAGE =      1.414  INCHES
```

```
          INITIAL SNOW WATER                  =      0.000  INCHES
          INITIAL WATER IN LAYER MATERIALS    =    747.948  INCHES
          TOTAL INITIAL WATER                 =    747.948  INCHES
          TOTAL SUBSURFACE INFLOW             =      0.03   INCHES/YEAR


                      EVAPOTRANSPIRATION AND WEATHER DATA
                      -----------------------------------

           NOTE:  EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
                    MILWAUKEE             WISCONSIN

               STATION LATITUDE                         =  42.49 DEGREES
               MAXIMUM LEAF AREA INDEX                  =   0.00
               START OF GROWING SEASON (JULIAN DATE)    =    120
               END OF GROWING SEASON (JULIAN DATE)      =    289
               EVAPORATIVE ZONE DEPTH                   =   8.0  INCHES
               AVERAGE ANNUAL WIND SPEED                =   9.00 MPH
               AVERAGE 1ST QUARTER RELATIVE HUMIDITY    =  72.00 %
               AVERAGE 2ND QUARTER RELATIVE HUMIDITY    =  70.00 %
               AVERAGE 3RD QUARTER RELATIVE HUMIDITY    =  74.00 %
               AVERAGE 4TH QUARTER RELATIVE HUMIDITY    =  75.00 %


           NOTE:  PRECIPITATION DATA WAS SYNTHETICALLY GENERATED USING
                    COEFFICIENTS FOR    MILWAUKEE          WISCONSIN

                    NORMAL MEAN MONTHLY PRECIPITATION (INCHES)

    JAN/JUL     FEB/AUG     MAR/SEP     APR/OCT     MAY/NOV     JUN/DEC
    -------     -------     -------     -------     -------     -------
     1.60        1.40        2.15        3.73        3.44        3.62
     3.49        4.22        3.40        2.42        2.57        2.05


           NOTE:  TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING
                    COEFFICIENTS FOR    MILWAUKEE          WISCONSIN

               NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

    JAN/JUL     FEB/AUG     MAR/SEP     APR/OCT     MAY/NOV     JUN/DEC
    -------     -------     -------     -------     -------     -------
     20.30       24.80       34.50       45.10       56.30       66.20
     71.50       70.30       62.80       51.30       38.60       26.10
```

```
     NOTE:  SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING
           COEFFICIENTS FOR    MILWAUKEE          WISCONSIN
                AND STATION LATITUDE  =  42.57 DEGREES




**********************************************************************
     AVERAGE MONTHLY VALUES IN INCHES FOR YEARS    1 THROUGH    1
----------------------------------------------------------------------

                  JAN/JUL  FEB/AUG  MAR/SEP  APR/OCT  MAY/NOV  JUN/DEC
                  -------  -------  -------  -------  -------  -------
   PRECIPITATION
   -------------
   TOTALS           0.81     1.61     1.52     2.33     2.67     3.47
                    3.48     4.34     4.07     3.29     5.13     1.82

   STD. DEVIATIONS  0.00     0.00     0.00     0.00     0.00     0.00
                    0.00     0.00     0.00     0.00     0.00     0.00

   RUNOFF
   ------
   TOTALS           0.000    0.000    0.000    0.000    0.000    0.000
                    0.000    0.000    0.000    0.000    0.000    0.000

   STD. DEVIATIONS  0.000    0.000    0.000    0.000    0.000    0.000
                    0.000    0.000    0.000    0.000    0.000    0.000

   EVAPOTRANSPIRATION
   ------------------
   TOTALS           0.195    0.462    0.637    3.189    1.720    3.834
                    2.486    4.649    2.732    1.817    1.454    0.470

   STD. DEVIATIONS  0.000    0.000    0.000    0.000    0.000    0.000
                    0.000    0.000    0.000    0.000    0.000    0.000

   SUBSURFACE INFLOW INTO LAYER   6
   -------------------------------
   TOTALS          0.0000   0.0000   0.0000   0.0000   0.0000   0.0000
                   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000

   LATERAL DRAINAGE COLLECTED FROM LAYER  4
   ----------------------------------------
   TOTALS          0.0025   0.0026   0.0029   0.0028   0.0029   0.0028
                   0.0029   0.0029   0.0028   0.0029   0.3202   0.6796
```

```
   STD. DEVIATIONS 0.0000   0.0000   0.0000   0.0000   0.0000   0.0000
                   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000

   PERCOLATION/LEAKAGE THROUGH LAYER  6
   ------------------------------------
   TOTALS          0.0000   0.0000   0.0000   0.0000   0.0000   0.0000
                   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000

   STD. DEVIATIONS 0.0000   0.0000   0.0000   0.0000   0.0000   0.0000
                   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000


----------------------------------------------------------------------
          AVERAGES OF MONTHLY AVERAGED DAILY HEADS (INCHES)
 ---------------------------------------------------------------------


   DAILY AVERAGE HEAD ON TOP OF LAYER  5
   -------------------------------------
   AVERAGES        0.0011   0.0013   0.0013   0.0013   0.0013   0.0013
                   0.0013   0.0013   0.0013   0.0013   0.1460   0.2998

  STD. DEVIATIONS  0.0000   0.0000   0.0000   0.0000   0.0000   0.0000
                   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000

**********************************************************************


**********************************************************************
 AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS    1 THROUGH    1
----------------------------------------------------------------------
                             INCHES          CU. FEET       PERCENT
                       -------------------  ------------- ---------
  PRECIPITATION          34.54    (   0.000)    125380.2     100.00

  RUNOFF                  0.000   (  0.0000)        0.00       0.000

  EVAPOTRANSPIRATION     23.647   (  0.0000)      85837.82     68.462

  SUBSURFACE INFLOW INTO  0.00000                  0.000     0.00000
    LAYER  6

  LATERAL DRAINAGE        1.02777 (  0.00000)    3730.790    2.97558
  COLLECTED FROM LAYER  4

  PERCOLATION/LEAKAGE    0.00000 (  0.00000)        0.000    0.00000
  THROUGH LAYER  6

  AVERAGE HEAD ON TOP             0.038 (    0.000)
```

```
    OF LAYER  5

  CHANGE IN WATER STORAGE  9.899    (  0.0000)      35934.87     28.661

***********************************************************************
```

```
*******************************************************************************
            PEAK DAILY VALUES FOR YEARS     1 THROUGH    1
-------------------------------------------------------------------------------
                                                (INCHES)      (CU. FT.)
                                               ----------    -------------
      PRECIPITATION                                1.60           5808.000

      RUNOFF                                       0.000             0.0000

      DRAINAGE COLLECTED FROM LAYER  4            0.05069        184.01436

      PERCOLATION/LEAKAGE THROUGH LAYER  6        0.000000          0.00000

      AVERAGE HEAD ON TOP OF LAYER  5                0.693

      MAXIMUM HEAD ON TOP OF LAYER  5                1.260

      LOCATION OF MAXIMUM HEAD IN LAYER  4
            (DISTANCE FROM DRAIN)                   14.0 FEET

      SNOW WATER                                  1.12          4080.6218


      MAXIMUM VEG. SOIL WATER (VOL/VOL)                      0.5210

      MINIMUM VEG. SOIL WATER (VOL/VOL)                      0.1767

   ***  Maximum heads are computed using McEnroe's equations.  ***

            Reference:  Maximum Saturated Depth over Landfill Liner
                        by Bruce M. McEnroe, University of Kansas
                        ASCE Journal of Environmental Engineering
                        Vol. 119, No. 2, March 1993, pp. 262-270.

*******************************************************************************
```

```
**********************************************************************
               FINAL WATER STORAGE AT END OF YEAR    1
----------------------------------------------------------------------
                    LAYER        (INCHES)       (VOL/VOL)
                    -----        --------       ---------
                      1            2.6258         0.4376

                      2           41.9630         0.2914

                      3          686.0509         0.2932

                      4            1.5877         0.1323

                      5            0.0000         0.0000

                      6           25.6200         0.4270

                  SNOW WATER       0.000

***********************************************************************
***********************************************************************
```

```
**********************************************************************
**********************************************************************
**                                                                  **
**                                                                  **
**          HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE           **
**             HELP MODEL VERSION 3.07   (1 NOVEMBER 1997)          **
**              DEVELOPED BY ENVIRONMENTAL LABORATORY               **
**                USAE WATERWAYS EXPERIMENT STATION                 **
**         FOR USEPA RISK REDUCTION ENGINEERING LABORATORY          **
**                                                                  **
**                                                                  **
**********************************************************************
**********************************************************************


 PRECIPITATION DATA FILE:    C:\SOURCE\zion\precip3b.D4
 TEMPERATURE DATA FILE:      C:\SOURCE\zion\temp3b.D7
 SOLAR RADIATION DATA FILE:  C:\SOURCE\zion\solar3b.D13
 EVAPOTRANSPIRATION DATA:    C:\source\zion\evap3b.D11
 SOIL AND DESIGN DATA FILE:  C:\source\zion\soilm2.D10
 OUTPUT DATA FILE:           C:\source\zion\outm2.OUT


 TIME:  16:43     DATE:   2/28/2020


**********************************************************************
     TITLE:  ZION LANDFILL - SITE 2 NORTH EXPANSION PC YEARS 1-30
**********************************************************************


   NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER WERE
          COMPUTED AS NEARLY STEADY-STATE VALUES BY THE PROGRAM.


                                LAYER  1
                                --------

                    TYPE 1 - VERTICAL PERCOLATION LAYER
                        MATERIAL TEXTURE NUMBER   8
           THICKNESS                 =      6.00   INCHES
           POROSITY                  =      0.4630 VOL/VOL
           FIELD CAPACITY            =      0.2320 VOL/VOL
           WILTING POINT             =      0.1160 VOL/VOL
           INITIAL SOIL WATER CONTENT  =    0.3129 VOL/VOL
           EFFECTIVE SAT. HYD. COND.   =  0.369999994000E-03 CM/SEC
    NOTE:  SATURATED HYDRAULIC CONDUCTIVITY IS MULTIPLIED BY  3.00
           FOR ROOT CHANNELS IN TOP HALF OF EVAPORATIVE ZONE.
```

```
                       LAYER  2
                       --------

             TYPE 1 - VERTICAL PERCOLATION LAYER
                MATERIAL TEXTURE NUMBER  12
THICKNESS                     =     30.00   INCHES
POROSITY                      =      0.4710 VOL/VOL
FIELD CAPACITY                =      0.3420 VOL/VOL
WILTING POINT                 =      0.2100 VOL/VOL
INITIAL SOIL WATER CONTENT    =      0.3479 VOL/VOL
EFFECTIVE SAT. HYD. COND.     =  0.419999997000E-04 CM/SEC



                       LAYER  3
                       --------

              TYPE 2 - LATERAL DRAINAGE LAYER
                MATERIAL TEXTURE NUMBER  20
THICKNESS                     =      0.20   INCHES
POROSITY                      =      0.8500 VOL/VOL
FIELD CAPACITY                =      0.0100 VOL/VOL
WILTING POINT                 =      0.0050 VOL/VOL
INITIAL SOIL WATER CONTENT    =      0.0133 VOL/VOL
EFFECTIVE SAT. HYD. COND.     =   10.0000000000     CM/SEC
SLOPE                         =     10.00   PERCENT
DRAINAGE LENGTH               =    240.0    FEET



                       LAYER  4
                       --------

              TYPE 4 - FLEXIBLE MEMBRANE LINER
                MATERIAL TEXTURE NUMBER  36
THICKNESS                     =      0.04   INCHES
POROSITY                      =      0.0000 VOL/VOL
FIELD CAPACITY                =      0.0000 VOL/VOL
WILTING POINT                 =      0.0000 VOL/VOL
INITIAL SOIL WATER CONTENT    =      0.0000 VOL/VOL
EFFECTIVE SAT. HYD. COND.     =  0.399999993000E-12 CM/SEC
FML PINHOLE DENSITY           =      1.00   HOLES/ACRE
FML INSTALLATION DEFECTS      =     10.00   HOLES/ACRE
FML PLACEMENT QUALITY         =  4 - POOR
```

```
                            LAYER  5
                            --------

                  TYPE 3 - BARRIER SOIL LINER
                  MATERIAL TEXTURE NUMBER   0
THICKNESS                  =     24.00   INCHES
POROSITY                   =      0.4270 VOL/VOL
FIELD CAPACITY             =      0.4180 VOL/VOL
WILTING POINT              =      0.3670 VOL/VOL
INITIAL SOIL WATER CONTENT =      0.4270 VOL/VOL
EFFECTIVE SAT. HYD. COND.  =  0.999999975000E-04 CM/SEC


                            LAYER  6
                            --------

              TYPE 1 - VERTICAL PERCOLATION LAYER
                  MATERIAL TEXTURE NUMBER  18
THICKNESS                  =   2484.00   INCHES
POROSITY                   =      0.6710 VOL/VOL
FIELD CAPACITY             =      0.2920 VOL/VOL
WILTING POINT              =      0.0770 VOL/VOL
INITIAL SOIL WATER CONTENT =      0.2920 VOL/VOL
EFFECTIVE SAT. HYD. COND.  =  0.100000005000E-02 CM/SEC


                            LAYER  7
                            --------

                TYPE 2 - LATERAL DRAINAGE LAYER
                  MATERIAL TEXTURE NUMBER   0
THICKNESS                  =     12.00   INCHES
POROSITY                   =      0.4570 VOL/VOL
FIELD CAPACITY             =      0.1310 VOL/VOL
WILTING POINT              =      0.0580 VOL/VOL
INITIAL SOIL WATER CONTENT =      0.1310 VOL/VOL
EFFECTIVE SAT. HYD. COND.  =  0.100000001000     CM/SEC
SLOPE                      =      2.00   PERCENT
DRAINAGE LENGTH            =    155.0    FEET
```

```
                           LAYER  8
                           --------

               TYPE 4 - FLEXIBLE MEMBRANE LINER
                 MATERIAL TEXTURE NUMBER  35
   THICKNESS                   =      0.06   INCHES
   POROSITY                    =      0.0000 VOL/VOL
   FIELD CAPACITY              =      0.0000 VOL/VOL
   WILTING POINT               =      0.0000 VOL/VOL
   INITIAL SOIL WATER CONTENT  =      0.0000 VOL/VOL
   EFFECTIVE SAT. HYD. COND.   =  0.199999996000E-12 CM/SEC
   FML PINHOLE DENSITY         =      1.00   HOLES/ACRE
   FML INSTALLATION DEFECTS    =     10.00   HOLES/ACRE
   FML PLACEMENT QUALITY       =  4 - POOR


                           LAYER  9
                           --------

                 TYPE 3 - BARRIER SOIL LINER
                 MATERIAL TEXTURE NUMBER  16
   THICKNESS                   =     60.00   INCHES
   POROSITY                    =      0.4270 VOL/VOL
   FIELD CAPACITY              =      0.4180 VOL/VOL
   WILTING POINT               =      0.3670 VOL/VOL
   INITIAL SOIL WATER CONTENT  =      0.4270 VOL/VOL
   EFFECTIVE SAT. HYD. COND.   =  0.100000001000E-06 CM/SEC
   SUBSURFACE INFLOW           =      0.03   INCHES/YR


           GENERAL DESIGN AND EVAPORATIVE ZONE DATA
           ----------------------------------------

 NOTE:  SCS RUNOFF CURVE NUMBER WAS COMPUTED FROM DEFAULT
          SOIL DATA BASE USING SOIL TEXTURE # 8 WITH A
          FAIR STAND OF GRASS, A SURFACE SLOPE OF 10.%
          AND A SLOPE LENGTH OF  240. FEET.

SCS RUNOFF CURVE NUMBER             =     80.40
FRACTION OF AREA ALLOWING RUNOFF    =    100.0    PERCENT
AREA PROJECTED ON HORIZONTAL PLANE  =      1.000  ACRES
EVAPORATIVE ZONE DEPTH              =     20.0    INCHES
INITIAL WATER IN EVAPORATIVE ZONE   =      6.667  INCHES
UPPER LIMIT OF EVAPORATIVE STORAGE  =      9.372  INCHES
LOWER LIMIT OF EVAPORATIVE STORAGE  =      3.636  INCHES
```

```
          INITIAL SNOW WATER                     =      0.000  INCHES
          INITIAL WATER IN LAYER MATERIALS       =    775.087  INCHES
          TOTAL INITIAL WATER                    =    775.087  INCHES
          TOTAL SUBSURFACE INFLOW                =      0.03   INCHES/YEAR




                      EVAPOTRANSPIRATION AND WEATHER DATA
                      -----------------------------------

           NOTE:  EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
                    MILWAUKEE             WISCONSIN

               STATION LATITUDE                         =  42.49 DEGREES
               MAXIMUM LEAF AREA INDEX                  =   2.00
               START OF GROWING SEASON (JULIAN DATE)    =    120
               END OF GROWING SEASON (JULIAN DATE)      =    289
               EVAPORATIVE ZONE DEPTH                   =  20.0  INCHES
               AVERAGE ANNUAL WIND SPEED                =   9.00 MPH
               AVERAGE 1ST QUARTER RELATIVE HUMIDITY    =  72.00 %
               AVERAGE 2ND QUARTER RELATIVE HUMIDITY    =  70.00 %
               AVERAGE 3RD QUARTER RELATIVE HUMIDITY    =  74.00 %
               AVERAGE 4TH QUARTER RELATIVE HUMIDITY    =  75.00 %



           NOTE:  PRECIPITATION DATA WAS SYNTHETICALLY GENERATED USING
                    COEFFICIENTS FOR    MILWAUKEE          WISCONSIN

                    NORMAL MEAN MONTHLY PRECIPITATION (INCHES)

      JAN/JUL     FEB/AUG     MAR/SEP     APR/OCT     MAY/NOV     JUN/DEC
      -------     -------     -------     -------     -------     -------
       1.60        1.40        2.15        3.73        3.44        3.62
       3.49        4.22        3.40        2.42        2.57        2.05



           NOTE:  TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING
                    COEFFICIENTS FOR    MILWAUKEE          WISCONSIN

               NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

      JAN/JUL     FEB/AUG     MAR/SEP     APR/OCT     MAY/NOV     JUN/DEC
      -------     -------     -------     -------     -------     -------
      20.30       24.80       34.50       45.10       56.30       66.20
          71.50       70.30       62.80       51.30       38.60
    26.10
```

```
         NOTE:  SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING
                       COEFFICIENTS FOR    MILWAUKEE          WISCONSIN
                         AND STATION LATITUDE  =  42.49 DEGREES




**********************************************************************
      AVERAGE MONTHLY VALUES IN INCHES FOR YEARS     1 THROUGH   30
----------------------------------------------------------------------

                       JAN/JUL  FEB/AUG  MAR/SEP  APR/OCT  MAY/NOV  JUN/DEC
                       -------  -------  -------  -------  -------  -------
  PRECIPITATION
  -------------
  TOTALS                 1.50     1.28     2.10     3.62     3.29     3.72
                         2.94     4.05     3.51     2.43     2.47     2.39

  STD. DEVIATIONS        0.70     0.63     0.89     1.68     1.41     1.76
                         1.63     1.90     1.31     0.95     1.22     1.04

  RUNOFF
  ------
  TOTALS                0.359    0.923    1.920    0.734    0.048    0.053
                        0.009    0.110    0.068    0.012    0.062    0.178

  STD. DEVIATIONS       0.430    0.851    1.264    0.971    0.138    0.158
                        0.032    0.203    0.157    0.032    0.156    0.339

  EVAPOTRANSPIRATION
  ------------------
  TOTALS                0.474    0.391    0.557    2.605    3.442    4.309
                        3.392    3.423    2.349    1.342    0.827    0.458

  STD. DEVIATIONS       0.093    0.123    0.330    0.948    0.986    1.059
                        1.371    1.445    0.786    0.288    0.175    0.101

  LATERAL DRAINAGE COLLECTED FROM LAYER  3
  ----------------------------------------
  TOTALS                0.1913   0.0027   0.1996   1.3366   1.0177   0.2058
                        0.0444   0.0706   0.2239   0.2896   0.7873   0.8687

  STD. DEVIATIONS       0.3148   0.0110   0.4176   0.9390   0.9066   0.3516
                        0.1325   0.3417   0.4372   0.4551   0.8051   0.6952
```

```
PERCOLATION/LEAKAGE THROUGH LAYER  5
   ------------------------------------
   TOTALS           0.0001   0.0000   0.0001   0.0005   0.0004   0.0001
                    0.0000   0.0000   0.0001   0.0001   0.0003   0.0004

   STD. DEVIATIONS  0.0001   0.0000   0.0002   0.0004   0.0004   0.0001
                    0.0001   0.0001   0.0002   0.0002   0.0003   0.0003

   SUBSURFACE INFLOW INTO LAYER  9
   -------------------------------
   TOTALS           0.0000   0.0000   0.0000   0.0000   0.0000   0.0000
                    0.0000   0.0000   0.0000   0.0000   0.0000   0.0000

   LATERAL DRAINAGE COLLECTED FROM LAYER  7
   ----------------------------------------
   TOTALS           0.0030   0.0026   0.0029   0.0033   0.0034   0.0029
                    0.0029   0.0029   0.0029   0.0030   0.0031   0.0033

   STD. DEVIATIONS  0.0002   0.0000   0.0001   0.0003   0.0004   0.0002
                    0.0001   0.0001   0.0002   0.0002   0.0003   0.0003

   PERCOLATION/LEAKAGE THROUGH LAYER  9
   ------------------------------------
   TOTALS           0.0000   0.0000   0.0000   0.0000   0.0000   0.0000
                    0.0000   0.0000   0.0000   0.0000   0.0000   0.0000

   STD. DEVIATIONS  0.0000   0.0000   0.0000   0.0000   0.0000   0.0000
                    0.0000   0.0000   0.0000   0.0000   0.0000   0.0000


 ----------------------------------------------------------------------
          AVERAGES OF MONTHLY AVERAGED DAILY HEADS (INCHES)
 ----------------------------------------------------------------------


   DAILY AVERAGE HEAD ON TOP OF LAYER  4
   -------------------------------------
   AVERAGES         0.0003   0.0000   0.0003   0.0019   0.0014   0.0003
                    0.0001   0.0001   0.0003   0.0004   0.0011   0.0012

   STD. DEVIATIONS  0.0004   0.0000   0.0006   0.0013   0.0013   0.0005
                    0.0002   0.0005   0.0006   0.0006   0.0011   0.0010

   DAILY AVERAGE HEAD ON TOP OF LAYER  8
   -------------------------------------
   AVERAGES         0.0013   0.0013   0.0013   0.0015   0.0015   0.0013
                    0.0013   0.0013   0.0013   0.0013   0.0014   0.0014

   STD. DEVIATIONS  0.0001   0.0000   0.0001   0.0001   0.0002   0.0001
                    0.0000   0.0000   0.0001   0.0001   0.0001   0.0001
```

```
******************************************************************************


******************************************************************************
AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS    1 THROUGH   30
------------------------------------------------------------------------------
                                  INCHES           CU. FEET       PERCENT
                           -------------------   -------------   ---------
 PRECIPITATION               33.32    (   4.736)     120966.1     100.00

 RUNOFF                       4.476   (  2.0827)      16248.26     13.432

 EVAPOTRANSPIRATION          23.569   (  2.9703)      85556.14     70.727

 LATERAL DRAINAGE            5.23801 (  1.99898)     19013.992   15.71844
 COLLECTED FROM LAYER  3

 PERCOLATION/LEAKAGE       0.00223 (  0.00082)          8.111     0.00671
 THROUGH LAYER  5

 AVERAGE HEAD ON TOP               0.001 (    0.000)
   OF LAYER  4

 SUBSURFACE INFLOW INTO  0.00000                          0.000     0.00000
   LAYER  9

 LATERAL DRAINAGE            0.03626 (  0.00084)        131.612    0.10880
 COLLECTED FROM LAYER  7

 PERCOLATION/LEAKAGE       0.00000 (  0.00000)          0.000     0.00000
 THROUGH LAYER  9

 AVERAGE HEAD ON TOP               0.001 (    0.000)
   OF LAYER  8

 CHANGE IN WATER STORAGE  0.038    (  1.4502)        139.61       0.115

******************************************************************************
```

```
**********************************************************************
            PEAK DAILY VALUES FOR YEARS    1 THROUGH   30
----------------------------------------------------------------------
                                           (INCHES)      (CU. FT.)
                                          ----------   -------------
      PRECIPITATION                           4.11         14919.301

      RUNOFF                                  3.046        11057.7012

      DRAINAGE COLLECTED FROM LAYER  3       0.54123       1964.68140

      PERCOLATION/LEAKAGE THROUGH LAYER  5   0.000186         0.67495

      AVERAGE HEAD ON TOP OF LAYER  4            0.023

      MAXIMUM HEAD ON TOP OF LAYER  4            0.038

      LOCATION OF MAXIMUM HEAD IN LAYER  3
            (DISTANCE FROM DRAIN)               42.0 FEET

      DRAINAGE COLLECTED FROM LAYER  7       0.00018          0.64874

      PERCOLATION/LEAKAGE THROUGH LAYER  9   0.000000         0.00000

      AVERAGE HEAD ON TOP OF LAYER  8            0.002

      MAXIMUM HEAD ON TOP OF LAYER  8            0.006

      LOCATION OF MAXIMUM HEAD IN LAYER  7
            (DISTANCE FROM DRAIN)                0.0 FEET

      SNOW WATER                              6.20         22496.8086


      MAXIMUM VEG. SOIL WATER (VOL/VOL)                  0.4360

      MINIMUM VEG. SOIL WATER (VOL/VOL)                  0.1818


   ***  Maximum heads are computed using McEnroe's equations.  ***

            Reference:  Maximum Saturated Depth over Landfill Liner
                        by Bruce M. McEnroe, University of Kansas
                        ASCE Journal of Environmental Engineering
                        Vol. 119, No. 2, March 1993, pp. 262-270.
**********************************************************************
```

```
*********************************************************************
               FINAL WATER STORAGE AT END OF YEAR   30
---------------------------------------------------------------------
                    LAYER        (INCHES)        (VOL/VOL)
                    -----        --------        ---------
                      1           2.0112          0.3352

                      2          11.0167          0.3672

                      3           0.0025          0.0125

                      4           0.0000          0.0000

                      5          10.2480          0.4270

                      6         725.3281          0.2920

                      7           1.5725          0.1310

                      8           0.0000          0.0000

                      9          25.6200          0.4270

                  SNOW WATER      0.442

*********************************************************************
*********************************************************************
```

```
**********************************************************************
**********************************************************************
**           HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE         **
**             HELP MODEL VERSION 3.07  (1 NOVEMBER 1997)          **
**               DEVELOPED BY ENVIRONMENTAL LABORATORY             **
**                 USAE WATERWAYS EXPERIMENT STATION               **
**          FOR USEPA RISK REDUCTION ENGINEERING LABORATORY        **
**********************************************************************
**********************************************************************


PRECIPITATION DATA FILE:    C:\SOURCE\zion\precip7b.D4
TEMPERATURE DATA FILE:      C:\SOURCE\zion\temp7b.D7
SOLAR RADIATION DATA FILE:  C:\SOURCE\zion\solar7b.D13
EVAPOTRANSPIRATION DATA:    C:\source\zion\evap7b.D11
SOIL AND DESIGN DATA FILE:  C:\source\zion\soilm3.D10
OUTPUT DATA FILE:           C:\source\zion\soilm3.OUT



TIME:  16:47     DATE:   2/28/2020



**********************************************************************
    TITLE:  ZION LANDFILL - SITE 2 NORTH EXPANSION PC YEARS 31-100
**********************************************************************



  NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER WERE
        COMPUTED AS NEARLY STEADY-STATE VALUES BY THE PROGRAM.



                                   LAYER  1
                                   --------

                     TYPE 1 - VERTICAL PERCOLATION LAYER
                         MATERIAL TEXTURE NUMBER   8
           THICKNESS                   =      6.00   INCHES
           POROSITY                    =      0.4630 VOL/VOL
           FIELD CAPACITY              =      0.2320 VOL/VOL
           WILTING POINT               =      0.1160 VOL/VOL
           INITIAL SOIL WATER CONTENT  =      0.3128 VOL/VOL
           EFFECTIVE SAT. HYD. COND.   =  0.369999994000E-03 CM/SEC
    NOTE:  SATURATED HYDRAULIC CONDUCTIVITY IS MULTIPLIED BY  3.00
          FOR ROOT CHANNELS IN TOP HALF OF EVAPORATIVE ZONE.
```

```
                        LAYER  2
                        --------

          TYPE 1 - VERTICAL PERCOLATION LAYER
              MATERIAL TEXTURE NUMBER  12
THICKNESS                   =     30.00    INCHES
POROSITY                    =      0.4710 VOL/VOL
FIELD CAPACITY              =      0.3420 VOL/VOL
WILTING POINT               =      0.2100 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.3480 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.419999997000E-04 CM/SEC


                        LAYER  3
                        --------

            TYPE 2 - LATERAL DRAINAGE LAYER
              MATERIAL TEXTURE NUMBER  20
THICKNESS                   =      0.20    INCHES
POROSITY                    =      0.8500 VOL/VOL
FIELD CAPACITY              =      0.0100 VOL/VOL
WILTING POINT               =      0.0050 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.0133 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =   10.0000000000     CM/SEC
SLOPE                       =     10.00    PERCENT
DRAINAGE LENGTH             =    240.0     FEET


                        LAYER  4
                        --------

            TYPE 4 - FLEXIBLE MEMBRANE LINER
              MATERIAL TEXTURE NUMBER  36
THICKNESS                   =      0.04    INCHES
POROSITY                    =      0.0000 VOL/VOL
FIELD CAPACITY              =      0.0000 VOL/VOL
WILTING POINT               =      0.0000 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.0000 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.399999993000E-12 CM/SEC
FML PINHOLE DENSITY         =      1.00    HOLES/ACRE
FML INSTALLATION DEFECTS    =     10.00    HOLES/ACRE
FML PLACEMENT QUALITY       =  4 - POOR
```

```
                         LAYER  5
                         --------

               TYPE 3 - BARRIER SOIL LINER
               MATERIAL TEXTURE NUMBER   0
THICKNESS                   =     24.00   INCHES
POROSITY                    =      0.4270 VOL/VOL
FIELD CAPACITY              =      0.4180 VOL/VOL
WILTING POINT               =      0.3670 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.4270 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.999999975000E-04 CM/SEC


                         LAYER  6
                         --------

             TYPE 1 - VERTICAL PERCOLATION LAYER
               MATERIAL TEXTURE NUMBER  18
THICKNESS                   =   2484.00   INCHES
POROSITY                    =      0.6710 VOL/VOL
FIELD CAPACITY              =      0.2920 VOL/VOL
WILTING POINT               =      0.0770 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.2920 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.100000005000E-02 CM/SEC


                         LAYER  7
                         --------

             TYPE 1 - VERTICAL PERCOLATION LAYER
               MATERIAL TEXTURE NUMBER   0
THICKNESS                   =     12.00   INCHES
POROSITY                    =      0.4570 VOL/VOL
FIELD CAPACITY              =      0.1310 VOL/VOL
WILTING POINT               =      0.0580 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.1341 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.100000001000     CM/SEC
```

```
                         LAYER  8
                         --------

                 TYPE 4 - FLEXIBLE MEMBRANE LINER
                  MATERIAL TEXTURE NUMBER  35
   THICKNESS                   =      0.06   INCHES
   POROSITY                    =      0.0000 VOL/VOL
   FIELD CAPACITY              =      0.0000 VOL/VOL
   WILTING POINT               =      0.0000 VOL/VOL
   INITIAL SOIL WATER CONTENT  =      0.0000 VOL/VOL
   EFFECTIVE SAT. HYD. COND.   =  0.199999996000E-12 CM/SEC
   FML PINHOLE DENSITY         =      1.00   HOLES/ACRE
   FML INSTALLATION DEFECTS    =     10.00   HOLES/ACRE
   FML PLACEMENT QUALITY       =  4 - POOR


                         LAYER  9
                         --------

                  TYPE 3 - BARRIER SOIL LINER
                  MATERIAL TEXTURE NUMBER  16
   THICKNESS                   =     60.00   INCHES
   POROSITY                    =      0.4270 VOL/VOL
   FIELD CAPACITY              =      0.4180 VOL/VOL
   WILTING POINT               =      0.3670 VOL/VOL
   INITIAL SOIL WATER CONTENT  =      0.4270 VOL/VOL
   EFFECTIVE SAT. HYD. COND.   =  0.100000001000E-06 CM/SEC
   SUBSURFACE INFLOW           =      0.03   INCHES/YR


               GENERAL DESIGN AND EVAPORATIVE ZONE DATA
               ----------------------------------------

  NOTE:  SCS RUNOFF CURVE NUMBER WAS COMPUTED FROM DEFAULT
          SOIL DATA BASE USING SOIL TEXTURE # 8 WITH A
          FAIR STAND OF GRASS, A SURFACE SLOPE OF 10.%
          AND A SLOPE LENGTH OF  240. FEET.

 SCS RUNOFF CURVE NUMBER             =    80.40
 FRACTION OF AREA ALLOWING RUNOFF    =   100.0    PERCENT
 AREA PROJECTED ON HORIZONTAL PLANE  =     1.000  ACRES
 EVAPORATIVE ZONE DEPTH              =    20.0    INCHES
 INITIAL WATER IN EVAPORATIVE ZONE   =     6.666  INCHES
 UPPER LIMIT OF EVAPORATIVE STORAGE  =     9.372  INCHES
 LOWER LIMIT OF EVAPORATIVE STORAGE  =     3.636  INCHES
```

```
       INITIAL SNOW WATER                  =      0.000  INCHES
       INITIAL WATER IN LAYER MATERIALS    =    775.123  INCHES
       TOTAL INITIAL WATER                 =    775.123  INCHES
       TOTAL SUBSURFACE INFLOW             =      0.03   INCHES/YEAR


                   EVAPOTRANSPIRATION AND WEATHER DATA
                   -----------------------------------

        NOTE:  EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
                 MILWAUKEE             WISCONSIN

            STATION LATITUDE                       =  42.49 DEGREES
            MAXIMUM LEAF AREA INDEX                =   2.00
            START OF GROWING SEASON (JULIAN DATE)  =    120
            END OF GROWING SEASON (JULIAN DATE)    =    289
            EVAPORATIVE ZONE DEPTH                 =  20.0  INCHES
            AVERAGE ANNUAL WIND SPEED              =   9.00 MPH
            AVERAGE 1ST QUARTER RELATIVE HUMIDITY  =  72.00 %
            AVERAGE 2ND QUARTER RELATIVE HUMIDITY  =  70.00 %
            AVERAGE 3RD QUARTER RELATIVE HUMIDITY  =  74.00 %
            AVERAGE 4TH QUARTER RELATIVE HUMIDITY  =  75.00 %


        NOTE:  PRECIPITATION DATA WAS SYNTHETICALLY GENERATED USING
                 COEFFICIENTS FOR    MILWAUKEE           WISCONSIN

                 NORMAL MEAN MONTHLY PRECIPITATION (INCHES)

JAN/JUL     FEB/AUG     MAR/SEP     APR/OCT     MAY/NOV     JUN/DEC
-------     -------     -------     -------     -------     -------
  1.60        1.40        2.15        3.73        3.44        3.62
  3.49        4.22        3.40        2.42        2.57        2.05


        NOTE:  TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING
                 COEFFICIENTS FOR    MILWAUKEE           WISCONSIN

            NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

JAN/JUL     FEB/AUG     MAR/SEP     APR/OCT     MAY/NOV     JUN/DEC
-------     -------     -------     -------     -------     -------
 20.30       24.80       34.50       45.10       56.30       66.20
 71.50       70.30       62.80       51.30       38.60       26.10
```

```
          NOTE:  SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING
                 COEFFICIENTS FOR    MILWAUKEE           WISCONSIN
                      AND STATION LATITUDE   =  42.49 DEGREES




*******************************************************************************
     AVERAGE MONTHLY VALUES IN INCHES FOR YEARS     1 THROUGH   70
-------------------------------------------------------------------------------

                  JAN/JUL  FEB/AUG  MAR/SEP  APR/OCT  MAY/NOV  JUN/DEC
                  -------  -------  -------  -------  -------  -------
  PRECIPITATION
  -------------
  TOTALS            1.60     1.33     2.18     3.76     3.38     3.54
                    3.20     4.17     3.36     2.72     2.65     2.20

  STD. DEVIATIONS   0.69     0.60     0.92     1.70     1.43     1.72
                    1.65     1.81     1.70     1.55     1.36     1.01

  RUNOFF
  ------
  TOTALS            0.376    0.950    1.877    0.827    0.042    0.038
                    0.015    0.113    0.077    0.032    0.114    0.284

  STD. DEVIATIONS   0.478    0.885    1.191    1.055    0.144    0.120
                    0.045    0.218    0.154    0.074    0.468    0.501

  EVAPOTRANSPIRATION
  ------------------
  TOTALS            0.463    0.396    0.608    2.436    3.540    4.253
                    3.565    3.509    2.311    1.315    0.786    0.449

  STD. DEVIATIONS   0.094    0.112    0.431    0.958    0.870    1.053
                    1.446    1.328    0.831    0.297    0.191    0.127

  LATERAL DRAINAGE COLLECTED FROM LAYER  3
  ----------------------------------------
  TOTALS           0.1579   0.0010   0.1760   1.4028   1.0544   0.2116
                   0.0714   0.0424   0.2768   0.4867   0.9051   0.9251

  STD. DEVIATIONS 0.2473   0.0058   0.3907   0.9672   0.7953   0.2903
                   0.1894   0.2305   0.5880   0.7507   0.9046   0.7590

  PERCOLATION/LEAKAGE THROUGH LAYER  5
  ------------------------------------
```

```
  TOTALS            0.0001    0.0000    0.0001    0.0006    0.0005    0.0001
                    0.0000    0.0000    0.0001    0.0002    0.0004    0.0004

  STD. DEVIATIONS 0.0001    0.0000    0.0002    0.0004    0.0003    0.0001
                    0.0001    0.0001    0.0002    0.0003    0.0004    0.0003

  SUBSURFACE INFLOW INTO LAYER  9
  -------------------------------
  TOTALS            0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
                    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000

  PERCOLATION/LEAKAGE THROUGH LAYER  9
  ------------------------------------
  TOTALS            0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
                    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000

  STD. DEVIATIONS 0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
                    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000


-----------------------------------------------------------------------
          AVERAGES OF MONTHLY AVERAGED DAILY HEADS (INCHES)
-----------------------------------------------------------------------


  DAILY AVERAGE HEAD ON TOP OF LAYER  4
  -------------------------------------
  AVERAGES         0.0002    0.0000    0.0002    0.0020    0.0015    0.0003
                   0.0001    0.0001    0.0004    0.0007    0.0013    0.0013

 STD. DEVIATIONS 0.0003    0.0000    0.0005    0.0014    0.0011    0.0004
                   0.0003    0.0003    0.0008    0.0010    0.0013    0.0010

  DAILY AVERAGE HEAD ON TOP OF LAYER  8
  -------------------------------------
  AVERAGES         3.9663    3.9749    3.9834    3.9930    4.0036    4.0130
                   4.0219    4.0308    4.0397    4.0489    4.0585    4.0685

  STD. DEVIATIONS 2.2777    2.2777    2.2777    2.2775    2.2776    2.2776
                    2.2776    2.2776    2.2776    2.2777    2.2779    2.2781

***********************************************************************
```

```
**********************************************************************
AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS     1 THROUGH   70
----------------------------------------------------------------------
                            INCHES            CU. FEET       PERCENT
                      -------------------   -------------    ---------

 PRECIPITATION           34.09     (  4.566)     123735.3     100.00

 RUNOFF                   4.745    ( 2.0719)      17225.31     13.921

 EVAPOTRANSPIRATION      23.630    ( 2.8766)      85776.11     69.322

 LATERAL DRAINAGE        5.71124 (  2.36607)     20731.797   16.75496
 COLLECTED FROM LAYER  3

 PERCOLATION/LEAKAGE    0.00242 (  0.00094)         8.777     0.00709
 THROUGH LAYER  5

 AVERAGE HEAD ON TOP             0.001 (    0.000)
   OF LAYER  4

 SUBSURFACE INFLOW INTO  0.00000                     0.000    0.00000
   LAYER  9

 PERCOLATION/LEAKAGE    0.00000 (  0.00000)         0.000     0.00000
 THROUGH LAYER  9

 AVERAGE HEAD ON TOP             4.017 (    2.278)
   OF LAYER  8

 CHANGE IN WATER STORAGE  0.035    ( 1.3331)        125.60      0.102

**********************************************************************
```

```
**********************************************************************
           PEAK DAILY VALUES FOR YEARS    1 THROUGH   70
----------------------------------------------------------------------
                                                (INCHES)      (CU. FT.)
                                               ----------   -------------
      PRECIPITATION                               4.11         14919.301

      RUNOFF                                      3.046        11057.7012

      DRAINAGE COLLECTED FROM LAYER  3            0.88269       3204.17676

      PERCOLATION/LEAKAGE THROUGH LAYER  5        0.000286         1.03950

      AVERAGE HEAD ON TOP OF LAYER  4                 0.038

      MAXIMUM HEAD ON TOP OF LAYER  4                 0.079

      LOCATION OF MAXIMUM HEAD IN LAYER  3
            (DISTANCE FROM DRAIN)                     0.0 FEET

      PERCOLATION/LEAKAGE THROUGH LAYER  9        0.000000         0.00000

      AVERAGE HEAD ON TOP OF LAYER  8                 7.938

      SNOW WATER                                      6.20
22496.8086


      MAXIMUM VEG. SOIL WATER (VOL/VOL)                       0.4384

      MINIMUM VEG. SOIL WATER (VOL/VOL)                       0.1818

   ***  Maximum heads are computed using McEnroe's equations.  ***

           Reference:  Maximum Saturated Depth over Landfill Liner
                       by Bruce M. McEnroe, University of Kansas
                       ASCE Journal of Environmental Engineering
                       Vol. 119, No. 2, March 1993, pp. 262-270.

**********************************************************************
```

```
******************************************************************************
                     FINAL WATER STORAGE AT END OF YEAR   70
------------------------------------------------------------------------------
                          LAYER        (INCHES)        (VOL/VOL)
                          -----        --------        ---------
                            1           1.7824          0.2971

                            2          10.4050          0.3468

                            3           0.0020          0.0100

                            4           0.0000          0.0000

                            5          10.2480          0.4270

                            6         725.3281          0.2920

                            7           4.1597          0.3466

                            8           0.0000          0.0000

                            9          25.6200          0.4270

                        SNOW WATER      0.000

******************************************************************************
******************************************************************************
```

# THE HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE (HELP) MODEL

## *USER'S GUIDE FOR VERSION 3*

by

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RISK REDUCTION ENGINEERING LABORATORY
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CINCINNATI, OHIO 45268

## TABLE 4. DEFAULT SOIL, WASTE, AND GEOSYNTHETIC CHARACTERISTICS

| Classification | | | Total Porosity | Field Capacity | Wilting Point | Saturated Hydraulic Conductivity |
|---|---|---|---|---|---|---|
| HELP | USDA | USCS | vol/vol | vol/vol | vol/vol | cm/sec |
| 1 | CoS | SP | 0.417 | 0.045 | 0.018 | 1.0x10$^{-2}$ |
| 2 | S | SW | 0.437 | 0.062 | 0.024 | 5.8x10$^{-3}$ |
| 3 | FS | SW | 0.457 | 0.083 | 0.033 | 3.1x10$^{-3}$ |
| 4 | LS | SM | 0.437 | 0.105 | 0.047 | 1.7x10$^{-3}$ |
| 5 | LFS | SM | 0.457 | 0.131 | 0.058 | 1.0x10$^{-3}$ |
| 6 | SL | SM | 0.453 | 0.190 | 0.085 | 7.2x10$^{-4}$ |
| 7 | FSL | SM | 0.473 | 0.222 | 0.104 | 5.2x10$^{-4}$ |
| 8 | L | ML | 0.463 | 0.232 | 0.116 | 3.7x10$^{-4}$ |
| 9 | SiL | ML | 0.501 | 0.284 | 0.135 | 1.9x10$^{-4}$ |
| 10 | SCL | SC | 0.398 | 0.244 | 0.136 | 1.2x10$^{-4}$ |
| 11 | CL | CL | 0.464 | 0.310 | 0.187 | 6.4x10$^{-5}$ |
| 12 | SiCL | CL | 0.471 | 0.342 | 0.210 | 4.2x10$^{-5}$ |
| 13 | SC | SC | 0.430 | 0.321 | 0.221 | 3.3x10$^{-5}$ |
| 14 | SiC | CH | 0.479 | 0.371 | 0.251 | 2.5x10$^{-5}$ |
| 15 | C | CH | 0.475 | 0.378 | 0.265 | 1.7x10$^{-5}$ |
| 16 | Barrier Soil | | 0.427 | 0.418 | 0.367 | 1.0x10$^{-7}$ |
| 17 | Bentonite Mat (0.6 cm) | | 0.750 | 0.747 | 0.400 | 3.0x10$^{-9}$ |
| 18 | Municipal Waste (900 lb/yd$^3$ or 312 kg/m$^3$) | | 0.671 | 0.292 | 0.077 | 1.0x10$^{-3}$ |
| 19 | Municipal Waste (channeling and dead zones) | | 0.168 | 0.073 | 0.019 | 1.0x10$^{-3}$ |
| 20 | Drainage Net (0.5 cm) | | 0.850 | 0.010 | 0.005 | 1.0x10$^{+1}$ |
| 21 | Gravel | | 0.397 | 0.032 | 0.013 | 3.0x10$^{-1}$ |
| 22 | L* | ML | 0.419 | 0.307 | 0.180 | 1.9x10$^{-5}$ |
| 23 | SiL* | ML | 0.461 | 0.360 | 0.203 | 9.0x10$^{-6}$ |
| 24 | SCL* | SC | 0.365 | 0.305 | 0.202 | 2.7x10$^{-6}$ |
| 25 | CL* | CL | 0.437 | 0.373 | 0.266 | 3.6x10$^{-6}$ |
| 26 | SiCL* | CL | 0.445 | 0.393 | 0.277 | 1.9x10$^{-6}$ |
| 27 | SC* | SC | 0.400 | 0.366 | 0.288 | 7.8x10$^{-7}$ |
| 28 | SiC* | CH | 0.452 | 0.411 | 0.311 | 1.2x10$^{-6}$ |
| 29 | C* | CH | 0.451 | 0.419 | 0.332 | 6.8x10$^{-7}$ |
| 30 | Coal-Burning Electric Plant Fly Ash* | | 0.541 | 0.187 | 0.047 | 5.0x10$^{-5}$ |
| 31 | Coal-Burning Electric Plant Bottom Ash* | | 0.578 | 0.076 | 0.025 | 4.1x10$^{-3}$ |
| 32 | Municipal Incinerator Fly Ash* | | 0.450 | 0.116 | 0.049 | 1.0x10$^{-2}$ |
| 33 | Fine Copper Slag* | | 0.375 | 0.055 | 0.020 | 4.1x10$^{-2}$ |
| 34 | Drainage Net (0.6 cm) | | 0.850 | 0.010 | 0.005 | 3.3x10$^{+1}$ |

* Moderately Compacted (Continued)

## TABLE 4 (continued). DEFAULT SOIL, WASTE, AND GEOSYNTHETIC CHARACTERISTICS

| Classification | | Total Porosity | Field Capacity | Wilting Point | Saturated Hydraulic Conductivity |
|---|---|---|---|---|---|
| HELP | Geomembrane Material | vol/vol | vol/vol | vol/vol | cm/sec |
| 35 | High Density Polyethylene (HDPE) | | | | $2.0\text{x}10^{-13}$ |
| 36 | Low Density Polyethylene (LDPE) | | | | $4.0\text{x}10^{-13}$ |
| 37 | Polyvinyl Chloride (PVC) | | | | $2.0\text{x}10^{-11}$ |
| 38 | Butyl Rubber | | | | $1.0\text{x}10^{-12}$ |
| 39 | Chlorinated Polyethylene (CPE) | | | | $4.0\text{x}10^{-12}$ |
| 40 | Hypalon or Chlorosulfonated Polyethylene (CSPE) | | | | $3.0\text{x}10^{-12}$ |
| 41 | Ethylene-Propylene Diene Monomer (EPDM) | | | | $2.0\text{x}10^{-12}$ |
| 42 | Neoprene | | | | $3.0\text{x}10^{-12}$ |

(concluded)

user-defined soil option accepts non-default soil characteristics for layers assigned soil type numbers greater than 42. This is especially convenient for specifying characteristics of waste layers. User-specified soil characteristics can be assigned any soil type number greater than 42.

When a default soil type is used to describe the top soil layer, the program adjusts the saturated hydraulic conductivities of the soils in the top half of the evaporative zone for the effects of root channels. The saturated hydraulic conductivity value is multiplied by an empirical factor that is computed as a function of the user-specified maximum leaf area index. Example values of this factor are 1.0 for a maximum LAI of 0 (bare ground), 1.8 for a maximum LAI of 1 (poor stand of grass), 3.0 for a maximum LAI of 2 (fair stand of grass), 4.2 for a maximum LAI of 3.3 (good stand of grass) and 5.0 for a maximum LAI of 5 (excellent stand of grass).

The manual option requires values for porosity, field capacity, wilting point, and saturated hydraulic conductivity. These and related soil properties are defined below.

*Soil Water Storage (Volumetric Content)*: the ratio of the volume of water in a soil to the total volume occupied by the soil, water and voids.

*Total Porosity*: the soil water storage/volumetric content at saturation (fraction of total volume).

The initial moisture content of municipal solid waste is a function of the composition of the waste; reported values for fresh wastes range from about 0.08 to 0.20 vol/vol. The average value is about 0.12 vol/vol for compacted municipal solid waste. If using default waste texture 19, where 75% of the volume is inactive, the initial moisture content should be that of only the active portion, 25% of the values reported above.

The soil water storage or content used in the HELP model is on a per volume basis ($\theta$), volume of water ($V_w$) per total (bulk--soil, water and air) soil volume ($V_t = V_s + V_w + V_a$), which is characteristic of practice in agronomy and soil physics. Engineers more commonly express moisture content on a per mass basis ($w$), mass of water ($M_w$) per mass of soil ($M_s$). The two can be related to each other by knowing the dry bulk density ($\rho_{db}$), dry bulk specific gravity ($\Gamma_{db}$) of the soil (ratio of dry bulk density to water density ($\rho_w$)), wet bulk density ($\rho_{wb}$), wet bulk specific gravity ($\Gamma_{wb}$) of the soil (ratio of wet bulk density to water density.

$$\theta = w \frac{\rho_{db}}{\rho_w} = w \, \Gamma_{db} \tag{2}$$

$$\theta = \frac{w}{1 + w} \frac{\rho_{wb}}{\rho_w} = \frac{w}{1 + w} \Gamma_{wb} \tag{3}$$

## 3.6 GEOMEMBRANE CHARACTERISTICS

The user can assign geomembrane liner characteristics (vapor diffusivity/saturated hydraulic conductivity) to a layer using the default option, the user-defined soil option, or the manual option. Saturated hydraulic conductivity for geomembranes is defined in terms of its equivalence to the vapor diffusivity. The porosity, field capacity, wilting point and intial moisture content are not needed for geomembranes. Table 4 shows the default characteristics for 12 geomembrane liners. The user assigns default soil characteristics to a layer simply by specifying the appropriate geomembrane liner texture number. The user-defined option accepts user specified geomembrane liner characteristics for layers assigned textures greater than 42. Manual geomembrane liner characteristics can be assigned any texture greater than 42.

Regardless of the method of specifying the geomembrane "soil" characteristics, the program also requires values for geomembrane liner thickness, pinhole density, installation defect density, geomembrane placement quality, and the transmissivity of geotextiles separating geomembranes and drainage limiting soils. These parameters are defined below.

*Pinhole Density*: the number of defects (diameter of hole equal to or smaller than the geomembrane thickness; hole estimated as 1 mm in diameter) in a given area generally resulting from manufacturing flaws such as polymerization deficiencies.

*Installation Defect Density*: the number of defects (diameter of hole larger than the geomembrane thickness; hole estimated as 1 $cm^2$ in area) per acre resulting primarily from seaming faults and punctures during installation.

*Geotextile Transmissivity*: the product of the in-plane saturated hydraulic conductivity and thickness of the geotextile.

The density of pinholes and installation defects is a subject of speculation. Ideally, geomembranes would not have any defects. If any were known to exist during construction, the defects would be repaired. However, geomembranes are known to leak and therefore reasonably conservative estimates of the defect densities should be specified to determine the maximum probable leakage quantities.

The density of defects has been measured at a number of landfills and other facilities and reported in the literature. These findings provide guidance for estimating the defect densities. Typical geomembranes may have about 0.5 to 1 pinholes per acre (1 to 2 pinholes per hectare) from manufacturing defects. The density of installation defects is a function of the quality of installation, testing, materials, surface preparation, equipment, and QA/QC program. Representative installation defect densities as a function of the quality of installation are given below for landfills being built today with the state-of-the-art in materials, equipment and QA/QC. In the last column the frequency of achieving a particular installation quality is given. The estimates are based on limited data but are characteristic of the recommendations provided in the literature.

| Installation Quality | Defect Density (number per acre) | Frequency (percent) |
|---|---|---|
| Excellent | Up to 1 | 10 |
| Good | 1 to 4 | 40 |
| Fair | 4 to 10 | 40 |
| Poor | 10 to 20* | 10 |

* Higher defect densities have been reported for older landfills with poor installation operations and materials; however, these high densities are not characteristic of modern practice.

The user must also enter the placement quality of the geomembrane liner if pinholes or installation defects are reported. There are six different possible entries for the geomembrane liner placement quality. The program selects which equation will be used to compute the geomembrane based on the placement quality specified and the saturated hydraulic conductivity of the lower permeability soil (drainage limiting soil) adjacent to

# K.7 – Laminar Flow in the Leachate Collection System

APTIM

**Client:** **Zion Landfill, Inc.**
**Project:** **Zion Landfill – Site 2 North Expansion**
**Project #:** **631020105**
**Calculated By:** **SJW** **Date:** **05/2022**
**Checked By:** **DAM** **Date:** **05/2022**

**TITLE:** **LAMINAR FLOW IN THE LEACHATE COLLECTION SYSTEM**

---

## Problem Statement

Determine if the leachate drainage layer will maintain laminar flow in accordance with 35 Ill. Admin. Code Section 811.307 (d), by calculating the Reynold's number, $R_e$.

## Given

- ☐ Freeze and Cherry, *Groundwater*, pages 73, 96-97. (Refer to attached pages).
- ☐ Streeter and Wylie, *Fluid Mechanics Eight Edition*, page 111. (Refer to attached pages).
- ☐ Landfill design specifications contained in this application.

## Assumptions

- ☐ Formula used to calculate the Reynold's number, $R_e$.

$$R_e = \frac{\rho\, v\, D}{\mu}$$

$$v = ki = k\frac{dh}{dl}$$

Where:
$\rho =$ fluid density (grams/cm$^3$)
$\mu =$ absolute viscosity (grams/cm-sec)
$D =$ mean diameter of leachate collection layer granular media (cm)
$v =$ specific discharge (cm/sec)
$k =$ hydraulic conductivity (cm/sec)
$i = (dh/dl) =$ hydraulic gradient

- ☐ Flow through granular media is laminar if Reynold's number does not exceed, "some value between 1 and 10." Therefore, a conservative value of Re = 1.0 is assumed as a division between laminar and turbulent flow (Freeze and Cherry, *Groundwater*, page 73).
- ☐ Temperature range = 40°F to 140°F (4.4°C to 60°C)
- ☐ Fluid Density = $\rho = \rho_w$ at a specific temperature

  = 1.0000 grams/cm$^3$ (40°F)
  = 0.98320 grams/cm$^3$ (140°F)

- ☐ Absolute Viscosity = $\mu = \mu_w$ at a specific temperature

  = 0.015190 grams/cm-sec (40°F)
  = 0.004690 grams/cm-sec (140°F)

- ☐ Diameter = D = 20 mm. = 2 cm
  "D" ranges from 0.075 to 20 mm for sand/gravel. Assume D = 20 mm to be conservative.

☐ Hydraulic Conductivity = k = 1.0 x $10^{-1}$ cm/sec

☐ Hydraulic Gradient = (dh/dl) = 2.0% (0.020 cm/cm), based on the maximum slope across the bottom of the landfill expansion.

## Calculations

Calculate the Reynold's number at: T = 40°F and T = 140°F

At T = 40°F

$$R_e = \frac{\rho\left(k\left(\frac{dh}{dl}\right)\right)D}{\mu} = \frac{(1.0000\ \text{grams/cm}^3)(0.1\ \text{cm/sec})(0.020\ \text{cm/cm})(2\ \text{cm})}{0.015190\ \text{grams/cm-sec}} = 0.263$$

Since 0.263 < 1, flow through the granular media at 40°F is laminar.

At T = 140°F

$$R_e = \frac{\rho\left(k\left(\frac{dh}{dl}\right)\right)D}{\mu} = \frac{(0.98320\ \text{grams/cm}^3)(0.1\ \text{cm/sec})(0.020\ \text{cm/cm})(2\ \text{cm})}{0.004690\ \text{grams/cm-sec}} = 0.839$$

Since 0.839 < 1, flow through the granular media at 140°F is laminar.

## Results

Based on the calculated Reynolds numbers, the leachate drainage layer will maintain laminar flow in accordance with 35 Ill. Admin. Code Section 811.307 (d).

LAMINAR FLOW

Freeze & Cherry

permeability *k*. Bear (1972) summarizes the experimental evidence with the statement that "Darcy's law is valid as long as the Reynolds number based on average grain diameter does not exceed some value between 1 and 10" (p. 126). For this range of Reynolds numbers, all flow through granular media is laminar.

Flow rates that exceed the upper limit of Darcy's law are common in such important rock formations as karstic limestones and dolomites, and cavernous volcanics. Darcian flow rates are almost never exceeded in nonindurated rocks and granular materials. Fractured rocks (and we will use this term to refer to rocks rendered more permeable by joints, fissures, cracks, or partings of any genetic origin) constitute a special case that deserves separate attention.

### *Flow in Fractured Rocks*

The analysis of flow in fractured rocks can be carried out either with the *continuum* approach that has been emphasized thus far in this text or with a *noncontinuum* approach based on the hydraulics of flow in individual fractures. As with granular porous media, the continuum approach involves the replacement of the fractured media by a representative continuum in which spatially defined values of hydraulic conductivity, porosity, and compressibility can be assigned. This approach is valid as long as the fracture spacing is sufficiently dense that the fractured media acts in a hydraulically similar fashion to granular porous media. The conceptualization is the same, although the representative elementary volume is considerably larger for fractured media than for granular media. If the fracture spacings are irregular in a given direction, the media will exhibit trending heterogeneity. If the fracture spacings are different in one direction than they are in another, the media will exhibit anisotropy. Snow (1968, 1969) has shown that many fracture-flow problems can be solved using standard porous-media techniques utilizing Darcy's law and an anisotropic conductivity tensor.

If the fracture density is extremely low, it may be necessary to analyze flow in individual fissures. This approach has been used in geotechnical applications where rock-mechanics analyses indicate that slopes or openings in rock may fail on the basis of fluid pressures that build up on individual critical fractures. The methods of analysis are based on the usual fluid mechanics principles embodied in the Navier-Stokes equations. These methods will not be discussed here. Wittke (1973) provides an introductory review.

Even if we limit ourselves to the continuum approach there are two further problems that must be addressed in the analysis of flow through fractured rock. The first is the question of non-Darcy flow in rock fractures of wide aperture. Sharp and Maini (1972) present laboratory data that support a nonlinear flow law for fractured rock. Wittke (1973) suggests that separate flow laws be specified for the linear-laminar range (Darcy range), a nonlinear laminar range, and a turbulent range. Figure 2.28 puts these concepts into the context of a schematic curve of specific discharge vs. hydraulic gradient. In wide rock fractures, the specific discharges and Reynolds numbers are high, the hydraulic gradients are usually less

Fundamental considerations of the nature of flow in porous media have led investigators to conclude that Darcy's law of proportionality of *macroscopic* velocity and hydraulic gradient is an accurate representation of the "law of flow" as long as velocities are low. Although it is generally concluded that the range of validity cannot be definitely established, Darcy's law is considered widely to be infinitely superior to methods which, though adhering strictly to basic laws, become so complex as to be beyond practical application.

Muskat (1937a), Taylor (1948), Leonards (1962), and others have presented excellent discussions of permeability and Darcy's law. Taylor (1948a) points out that in soils there is a slow transition from purely laminar flow to a slightly turbulent state and concludes that under a hydraulic gradient of 100%, uniform soils with a grain size of 0.5 mm or less always have laminar flow. For a gradient of 800% the diameter is 0.25 mm. This admittedly is a conservative approximation, based on a Reynold's number of 1.0.

Jacob (1950) concludes from experiments with natural and artificial sands of nearly uniform spherical grains that the transition from laminar to turbulent flow in sands requires at least a thousandfold increase in velocity to reach the limit of fully established turbulence. He states that, ". . . a tenfold increase above the approximate critical velocity results in about 50 percent error in the hydraulic gradient as predicted by Darcy's law."

Fishel (1935) reports experiments with very low heads indicate that, ". . . for the material tested (Fort Caswell sand) the rate of flow varies directly as the hydraulic gradient, down to a gradient of 2 or 3 inches to the mile and there are indications that Darcy's law holds for indefinitely low gradients."

In the analysis of seepage in coarse sands and gravels Darcy's law is not strictly applicable. Forchheimer (1902) found the frictional resistance of pervious gravel to be

$$\frac{\Delta h}{\Delta l} = \frac{1.77}{10^3} V + \frac{3.18}{10^6} V^2 \tag{3.4}$$

In Eq. 3.4, $V$ is the velocity in meters per day.

The general form of Eq. 3.4 is

$$\frac{\Delta h}{\Delta l} = aV + bV^2 \tag{3.5}$$

According to Eqs. 3.4 and 3.5, head losses in gravels are greater than indicated by Darcy's law. If permeability tests can be made under conditions similar to those that will exist in a prototype, the errors will tend to be neutralized; however, this is not always possible. It is, therefore, desirable to allow liberal factors of safety in the design of drainage systems containing coarse, clean aggregates where semiturbulent or turbulent flow may develop.

### Applications of Darcy's Law

Applications of Darcy's law to permeability determinations are described in Chapter 2.

The validity of Darcy's law is an essential assumption in the following soil mechanics theories and methods.

1. The theory of consolidation of clays.
2. Quantitative theory of laminar flow of homogeneous fluids through porous media.
3. Practical solutions to Laplace equations by flow nets.

The validity of Darcy's law is an essential assumption for all seepage solutions presented in this text, including:

1. Flow nets for steady seepage through earth cross sections of one or more different permeabilities, for both isotropic and anisotropic conditions (Darcy's law enters into the derivation of the basic differential equation).
2. Calculations involving the *velocities* of masses of water in porous media under steady seepage conditions. (These computations involve the *seepage velocity* $v_s = ki/n_e$.) The *seepage velocity* of moving groundwater can be used as an index of permeability (Sec. 2.7); its magnitude in any water-bearing material or drainage layer is a useful criterion of the rate of movement of water.
3. Approximate nonsteady seepage applications of the flow net to moving saturation lines. (These computations involve the additional use of the *seepage velocity* $v_s = ki/n_e$, which depends on Darcy's law.)
4. Calculations for seepage quantities through saturated soil and rock formations and other porous media. (These determinations involve the *discharge velocity* $v_d = ki$, determined from Darcy's law.)
5. Determination of the discharge capacities of porous aggregate drains, chimneys, sand-filled wells, etc. (These determinations also make use of the *discharge velocity*, defined in 4.)

The relationships represented by Darcy's law, though very simple, represent some of the most powerful tools available to the soils engineer and the drainage engineer. Unfortunately their great benefits

# FLUID MECHANICS

## Eighth Edition

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APPENDIX

# C

# Physical Properties of Fluids

**Table C.1 Physical properties of water in SI units**

| Temp, °C | Specific weight $\gamma$, N/m$^3$ | Density $\rho$, kg/m$^3$ | Viscosity $\mu \times 10^3$, N · s/m$^2$ | Kinematic viscosity $\nu \times 10^6$, m$^2$/s | Surface tension $\sigma \times 10^2$, N/m | Vapor-pressure head $p_v/\gamma$,† m | Bulk modulus of elasticity $K \times 10^{-7}$, N/m$^2$ |
|---|---|---|---|---|---|---|---|
| 0 | 9806 | 999.9 | 1.792 | 1.792 | 7.62 | 0.06 | 204 |
| 5 | 9807 | 1000.0 | 1.519 | 1.519 | 7.54 | 0.09 | 206 |
| 10 | 9804 | 999.7 | 1.308 | 1.308 | 7.48 | 0.12 | 211 |
| 15 | 9798 | 999.1 | 1.140 | 1.141 | 7.41 | 0.17 | 214 |
| 20 | 9789 | 998.2 | 1.005 | 1.007 | 7.36 | 0.25 | 220 |
| 25 | 9778 | 997.1 | 0.894 | 0.897 | 7.26 | 0.33 | 222 |
| 30 | 9764 | 995.7 | 0.801 | 0.804 | 7.18 | 0.44 | 223 |
| 35 | 9749 | 994.1 | 0.723 | 0.727 | 7.10 | 0.58 | 224 |
| 40 | 9730 | 992.2 | 0.656 | 0.661 | 7.01 | 0.76 | 227 |
| 45 | 9711 | 990.2 | 0.599 | 0.605 | 6.92 | 0.98 | 229 |
| 50 | 9690 | 988.1 | 0.549 | 0.556 | 6.82 | 1.26 | 230 |
| 55 | 9666 | 985.7 | 0.506 | 0.513 | 6.74 | 1.61 | 231 |
| 60 | 9642 | 983.2 | 0.469 | 0.477 | 6.68 | 2.03 | 228 |
| 65 | 9616 | 980.6 | 0.436 | 0.444 | 6.58 | 2.56 | 226 |
| 70 | 9589 | 977.8 | 0.406 | 0.415 | 6.50 | 3.20 | 225 |
| 75 | 9560 | 974.9 | 0.380 | 0.390 | 6.40 | 3.96 | 223 |
| 80 | 9530 | 971.8 | 0.357 | 0.367 | 6.30 | 4.86 | 221 |
| 85 | 9499 | 968.6 | 0.336 | 0.347 | 6.20 | 5.93 | 217 |
| 90 | 9466 | 965.3 | 0.317 | 0.328 | 6.12 | 7.18 | 216 |
| 95 | 9433 | 961.9 | 0.299 | 0.311 | 6.02 | 8.62 | 211 |
| 100 | 9399 | 958.4 | 0.284 | 0.296 | 5.94 | 10.33 | 207 |

† $\gamma = 9806$ N/m$^3$.

Note : 1N sec/m$^2$ = 1kg/m.sec

# K.8 – Capacity of Leachate Collection System Piping

APTIM

**Client:** Zion Landfill, Inc.
**Project:** Zion Landfill – Site 2 North Expansion
**Project #:** 631020105
**Calculated By:** SJW **Date:** 05/2022
**Checked By:** DAM **Date:** 05/2022

**TITLE:** **CAPACITY OF LEACHATE COLLECTION SYSTEM PIPING**

## Problem Statement

Determine the following to verify that the leachate collection system piping has sufficient capacity to accommodate the anticipated leachate flow volumes, in accordance with the requirements of 35 Ill. Admin. Code Section 811.308(b).

1. Maximum allowable flow through a 6-in diameter leachate collection pipe.
2. Anticipated leachate flow volume through the leachate collection piping system based on the estimated maximum leachate generation rate due to percolation of moisture through waste.

## Given

- ☐ Calculation in Appendix K.5 Groundwater Seepage Quantities
- ☐ Calculation in Appendix K.6 Hydrologic Evaluation of Landfill Performance (HELP) Model Analysis
- ☐ Uponor Infra Ltd. (2015). *Sclairpipe®: Versatile High Density Polyethylene Pipe.*
- ☐ Landfill cell design, contained in the Design Drawings.

## Assumptions

- ☐ Formula used to calculate the maximum allowable flow for the design pipe:

$$Q_{max} = \frac{1.486}{n} A R_h^{(2/3)} S^{(1/2)}$$

$$A = \frac{\pi D^2}{4}$$

$$R_h = \frac{D}{4}$$

Where,

$Q_{max}$ = Maximum allowable flow (ft$^3$/sec)
$n$ = Manning's roughness coefficient
$A$ = Pipe flow area (ft$^2$)
$D$ = Inside pipe diameter (ft)
$R_h$ = Hydraulic radius, for pipes flowing full
$S$ = Channel slope (ft/ft)

**TITLE:** **CAPACITY OF LEACHATE COLLECTION SYSTEM PIPING**

---

☐ Formula used to calculate anticipated leachate flow volumes:

$$Q = q * A$$

Where,
$Q$ = Leachate flow volume (gal/min)
$q$ = Leachate generation rate (ft/min)
$A$ = Surface area drained by pipe trench (ft$^2$)

☐ The HELP Model has indicated that the maximum leachate generation rate results from the initial lift of waste (Appendix K.6) of the horizontal expansion cells.

☐ Manning's roughness coefficient (n) = 0.010 for HDPE pipe.

☐ The leachate collection pipe underlying the horizontal expansion area is a 6-in SDR-17 pipe. Inner diameter = 5.80 in = 0.483 ft (see Sclairpipe® reference).

☐ Channel slope (horizontal expansion) = $S_1$ = 0.005 ft./ft. (actual slope of leachate collection pipe is 1% in the horizontal expansion; however, to conservatively account for settlement, slope is assumed to be 0.5%)

☐ Peak daily leachate generation rate during operational conditions = $q_{total}$ = 0.11756 in./day = 3.576 ft./year (Appendix K.6).

☐ The area contributing flow to the leachate collection pipe is assumed to be the plan view area of a landfill phase or cell. Cells in the horizontal expansion are generally uniform in size and have been designed to be approximately 1,300 ft length x 310 ft width. The largest cell, Phase 12, is 9.3 acres and has been chosen for this evaluation.

## Calculations

*Maximum allowable flow for a 6-in SDR-17 pipe (Horizontal Expansion), Qmax*

$$Q_{max} = \frac{1.486}{n} AR^{(2/3)} S_1^{(1/2)} = \frac{1.486}{n}\left(\frac{\pi D^2}{4}\right)\left(\frac{D}{4}\right)^{(2/3)} S_1^{(1/2)}$$

$$= \frac{1.486}{0.010}\left(\frac{\pi(0.483\text{ ft})^2}{4}\right)\left(\frac{0.483\text{ ft}}{4}\right)^{(2/3)} (0.005\text{ ft/ft})^{(1/2)} = 0.470\,\frac{\text{ft}^3}{\text{sec}}$$

$$= 0.470\,\frac{\text{ft}^3}{\text{sec}}\left(\frac{7.48\text{ gal}}{\text{ft}^3}\right)\left(\frac{60\text{ sec}}{\text{min}}\right) = \mathbf{211\ gpm}$$

*Leachate Flow Volume*

Convert q to feet per minute:

$$q = 3.576\,\frac{\text{ft.}}{\text{year}}\left(\frac{1\text{ year}}{365\text{ days}}\right)\left(\frac{1\text{ day}}{1{,}440\text{ min.}}\right) = 6.80 \times 10^{-6}\,\frac{\text{ft.}}{\text{min.}}$$

**Client:** Zion Landfill, Inc.
**Project:** Zion Landfill – Site 2 North Expansion
**Project #:** 631020105
**Calculated By:** SJW **Date:** 05/2022
**Checked By:** DAM **Date:** 05/2022

**TITLE: CAPACITY OF LEACHATE COLLECTION SYSTEM PIPING**

---

Calculate the area of a cell contributing leachate from the Horizontal Expansion:

$$A = 9.3 \text{ acres} = 405{,}108 \text{ ft}^2$$

Calculate the actual leachate flow volume for the 6-in SDR-17 pipe based on leachate generation and cell area:

$$Q = q * A$$

$$= \left(6.80 \times 10^{-6} \frac{\text{ft}}{\text{min}}\right)\left(405{,}108 \text{ ft}^2\right)\left(\frac{7.48 \text{ gal}}{\text{ft}^3}\right)$$

$$Q = \mathbf{20.62 \text{ gpm} < 211 \text{ gpm } (Qmax)}$$

**Results**

Based on the results summarized below, all leachate collection system pipes in the horizontal expansion area have sufficient capacity to accommodate the maximum anticipated leachate flow volumes, in accordance with 35 Ill. Admin. Code Section 811.308.

uponor

# Sclairpipe®

## VERSATILE HIGH DENSITY POLYETHYLENE PIPE

## Choose the size that's right for you

Sclairpipe is available in standard Dimensional Ratio's (DR's), in sizes ranging from 4″ to 48″ in diameter. Sclairpipe is available in PE 3608 and PE 4710. With the higher allowable stress rating of PE 4710, the pipe wall can be thinner for the same pressure rating (higher DR).

The Dimensional Ratio relates the minimum wall thickness of the pipe to its outside diameter, and is important to define the pressure rating of a particular pipe. The maximum continuous operating pressure stated is based on the allowable hydrostatic design stress of each specific material (per ASTM D3350 and PPI's TR-3), and the pipe wall thickness (DR), at a service temperature of 73.4°F.

**Uponor, Sclairpipe Product Range, IPS Size, PE3608**

| | PE3608 | | | DR32.5 (50 psi) | | | DR26 (64 psi) | | | DR21 (80 psi) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nominal Pipe Size | Minimum Outside Diameter *(inches)* | Maximum Outside Diameter *(inches)* | Average Outside Diameter *(inches)* | Average Inside Diameter *(inches)* | Minimum Wall Thickness *(inches)* | Average Weight *(lbs/ft)* | Average Inside Diameter *(inches)* | Minimum Wall Thickness *(inches)* | Average Weight *(lbs/ft)* | Average Inside Diameter *(inches)* | Minimum Wall Thickness *(inches)* | Average Weight *(lbs/ft)* |
| 4 | 4.48 | 4.52 | 4.50 | 4.21 | 0.138 | 0.83 | 4.13 | 0.173 | 1.03 | 4.05 | 0.214 | 1.26 |
| 5 | 5.54 | 5.59 | 5.56 | 5.20 | 0.171 | 1.27 | 5.11 | 0.214 | 1.57 | 5.00 | 0.265 | 1.93 |
| 6 | 6.60 | 6.65 | 6.63 | 6.19 | 0.204 | 1.80 | 6.08 | 0.255 | 2.23 | 5.96 | 0.315 | 2.73 |
| 7 | 7.09 | 7.16 | 7.13 | 6.66 | 0.219 | 2.08 | 6.54 | 0.274 | 2.58 | 6.41 | 0.339 | 3.16 |
| 8 | 8.59 | 8.66 | 8.63 | 8.06 | 0.265 | 3.05 | 7.92 | 0.332 | 3.78 | 7.75 | 0.411 | 4.63 |
| 10 | 10.70 | 10.80 | 10.75 | 10.05 | 0.331 | 4.74 | 9.87 | 0.413 | 5.87 | 9.66 | 0.512 | 7.19 |
| 12 | 12.69 | 12.81 | 12.75 | 11.92 | 0.392 | 6.66 | 11.71 | 0.490 | 8.26 | 11.46 | 0.607 | 10.12 |
| 13 | 13.31 | 13.44 | 13.38 | 12.50 | 0.412 | 7.33 | 12.28 | 0.514 | 9.09 | 12.02 | 0.637 | 11.14 |
| 14 | 13.94 | 14.06 | 14.00 | 13.09 | 0.431 | 8.03 | 12.86 | 0.538 | 9.95 | 12.59 | 0.667 | 12.20 |
| 16 | 15.93 | 16.07 | 16.00 | 14.96 | 0.492 | 10.49 | 14.70 | 0.615 | 13.00 | 14.38 | 0.762 | 15.94 |
| 18 | 17.92 | 18.08 | 18.00 | 16.83 | 0.554 | 13.28 | 16.53 | 0.692 | 16.46 | 16.18 | 0.857 | 20.17 |
| 20 | 19.91 | 20.09 | 20.00 | 18.70 | 0.615 | 16.39 | 18.37 | 0.769 | 20.32 | 17.98 | 0.952 | 24.90 |
| 22 | 21.90 | 22.10 | 22.00 | 20.56 | 0.677 | 19.83 | 20.21 | 0.846 | 24.58 | 19.78 | 1.048 | 30.13 |
| 24 | 23.89 | 24.11 | 24.00 | 22.43 | 0.738 | 23.60 | 22.04 | 0.923 | 29.25 | 21.58 | 1.143 | 35.85 |
| 26 | 25.88 | 26.12 | 26.00 | 24.30 | 0.800 | 27.70 | 23.88 | 1.000 | 34.33 | 23.38 | 1.238 | 42.08 |
| 28 | 27.87 | 28.13 | 28.00 | 26.17 | 0.862 | 32.13 | 25.72 | 1.077 | 39.82 | 25.17 | 1.333 | 48.80 |
| 30 | 29.87 | 30.14 | 30.00 | 28.04 | 0.923 | 36.88 | 27.55 | 1.154 | 45.71 | 26.97 | 1.429 | 56.02 |
| 32 | 31.86 | 32.14 | 32.00 | 29.91 | 0.985 | 41.96 | 29.39 | 1.231 | 52.01 | 28.77 | 1.524 | 63.74 |
| 36 | 35.84 | 36.16 | 36.00 | 33.65 | 1.108 | 53.11 | 33.06 | 1.385 | 65.82 | 32.37 | 1.714 | 80.67 |
| 40 | 39.82 | 40.18 | 40.00 | 37.39 | 1.231 | 65.56 | 36.74 | 1.538 | 81.26 | 35.96 | 1.905 | 99.59 |
| 42 | 41.81 | 42.19 | 42.00 | 39.26 | 1.292 | 72.28 | 38.58 | 1.615 | 89.59 | 37.76 | 2.000 | 109.80 |
| 48 | 47.78 | 48.22 | 48.00 | 44.87 | 1.477 | 94.41 | 44.09 | 1.846 | 117.02 | 43.15 | 2.286 | 143.42 |

Pipe dimensions are in accordance with ASTM F714 and AWWA C906
Pressure Ratings are for water at 73.4 deg F.
Some of the pipe sizes and DR's above are available only on request. Check with your representative for availability.
Other dimensions and DR's not listed may be available upon special request.
All dimensions are in inches unless otherwise noted.
Weights are calculated by the methodology established in PPI's TR-7 and are applicable to PE 3608.

The standard stocked length of Sclairpipe pipe is 50 feet, in sizes above 4″ in diameter with longer lengths available on request.

**Please visit our web site (www.uponor.ca) and use our online design tools to determine the pipe size best suited to your specific application.**

| DR17 (100 psi) | | | DR13.5 (128 psi) | | | DR11 (160 psi) | | | DR9 (200 psi) | | | DR7.3 (254 psi) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average Inside Diameter *(inches)* | Minimum Wall Thickness *(inches)* | Average Weight *(lbs/ft)* | Average Inside Diameter *(inches)* | Minimum Wall Thickness *(inches)* | Average Weight *(lbs/ft)* | Average Inside Diameter *(inches)* | Minimum Wall Thickness *(inches)* | Average Weight *(lbs/ft)* | Average Inside Diameter *(inches)* | Minimum Wall Thickness *(inches)* | Average Weight *(lbs/ft)* | Average Inside Diameter *(inches)* | Minimum Wall Thickness *(inches)* | Average Weight *(lbs/ft)* |
| 3.94 | 0.265 | 1.54 | 3.79 | 0.333 | 1.90 | 3.63 | 0.409 | 2.29 | 3.44 | 0.500 | 2.73 | 3.19 | 0.616 | 3.26 |
| 4.87 | 0.327 | 2.35 | 4.69 | 0.412 | 2.91 | 4.49 | 0.506 | 3.50 | 4.25 | 0.618 | 4.18 | 3.95 | 0.762 | 4.99 |
| 5.80 | 0.390 | 3.33 | 5.58 | 0.491 | 4.12 | 5.35 | 0.602 | 4.96 | 5.06 | 0.736 | 5.92 | 4.70 | 0.908 | 7.08 |
| 6.24 | 0.419 | 3.85 | 6.01 | 0.528 | 4.77 | 5.75 | 0.648 | 5.74 | 5.45 | 0.792 | 6.85 | 5.06 | 0.976 | 8.18 |
| 7.55 | 0.507 | 5.65 | 7.27 | 0.639 | 6.99 | 6.96 | 0.784 | 8.41 | 6.59 | 0.958 | 10.04 | 6.12 | 1.182 | 11.99 |
| 9.41 | 0.632 | 8.77 | 9.06 | 0.796 | 10.86 | 8.68 | 0.977 | 13.07 | 8.22 | 1.194 | 15.59 | 7.63 | 1.473 | 18.63 |
| 11.16 | 0.750 | 12.34 | 10.75 | 0.944 | 15.28 | 10.29 | 1.159 | 18.38 | 9.75 | 1.417 | 21.94 | 9.05 | 1.747 | 26.21 |
| 11.71 | 0.787 | 13.58 | 11.27 | 0.991 | 16.81 | 10.80 | 1.216 | 20.23 | 10.22 | 1.486 | 24.14 | 9.49 | 1.832 | 28.84 |
| 12.25 | 0.824 | 14.88 | 11.80 | 1.037 | 18.42 | 11.30 | 1.273 | 22.17 | 10.70 | 1.556 | 26.45 | 9.93 | 1.918 | 31.60 |
| 14.00 | 0.941 | 19.44 | 13.49 | 1.185 | 24.06 | 12.92 | 1.455 | 28.95 | 12.23 | 1.778 | 34.55 | 11.35 | 2.192 | 41.27 |
| 15.76 | 1.059 | 24.60 | 15.17 | 1.333 | 30.45 | 14.53 | 1.636 | 36.64 | 13.76 | 2.000 | 43.72 | 12.77 | 2.466 | 52.23 |
| 17.51 | 1.176 | 30.37 | 16.86 | 1.481 | 37.59 | 16.15 | 1.818 | 45.24 | 15.29 | 2.222 | 53.98 | 14.19 | 2.740 | 64.48 |
| 19.26 | 1.294 | 36.75 | 18.55 | 1.630 | 45.48 | 17.76 | 2.000 | 54.74 | 16.82 | 2.444 | 65.31 | 15.61 | 3.014 | 78.02 |
| 21.01 | 1.412 | 43.74 | 20.23 | 1.778 | 54.13 | 19.37 | 2.182 | 65.14 | 18.35 | 2.667 | 77.73 | 17.03 | 3.288 | 92.85 |
| 22.76 | 1.529 | 51.33 | 21.92 | 1.926 | 63.52 | 20.99 | 2.364 | 76.45 | 19.88 | 2.889 | 91.22 | 18.45 | 3.562 | 108.97 |
| 24.51 | 1.647 | 59.53 | 23.60 | 2.074 | 73.67 | 22.60 | 2.545 | 88.66 | 21.40 | 3.111 | 105.80 | 19.87 | 3.836 | 126.38 |
| 26.26 | 1.765 | 68.34 | 25.29 | 2.222 | 84.57 | 24.22 | 2.727 | 101.78 | 22.93 | 3.333 | 121.45 | | | |
| 28.01 | 1.882 | 77.75 | 26.97 | 2.370 | 96.22 | 25.83 | 2.909 | 115.80 | 24.46 | 3.556 | 138.19 | | | |
| 31.51 | 2.118 | 98.41 | 30.35 | 2.667 | 121.78 | 29.06 | 3.273 | 146.57 | | | | | | |
| 35.01 | 2.353 | 121.49 | 33.72 | 2.963 | 150.35 | 32.29 | 3.636 | 180.95 | | | | | | |
| 36.76 | 2.471 | 133.94 | 35.40 | 3.111 | 165.76 | 33.91 | 3.818 | 199.49 | | | | | | |
| 42.01 | 2.824 | 174.94 | 40.46 | 3.556 | 216.50 | | | | | | | | | |

Sclair IPS Cut Sheet_PE3608_r201407

- All dimensions are in inches unless otherwise specified.
- Pressure ratings are based on load durations of 50 years at a service temperature of 73.4F. The HDS (pipe wall allowable stress) for PE 3608 and PE 4710 are 800 psi and 1,000 psi respectively.
- Dimensions and tolerances per ASTM F714. Pipe weights calculated using PPI TR-7 using PE3608 density of 0.953 gm/cc and 0.958 gm/cc for PE4710 materials.
- The ASTM D3350 cell classifications conform to the requirements of the applicable pipe specification (ASTM F714, AWWA C906, etc.).
- Contact Uponor Infra for sizes, DR's and DIPS offering not shown.

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# K.9 – Leachate Storage Volume Requirements

**Client:** Zion Landfill, Inc.
**Project:** Zion Landfill – Site 2 North Expansion
**Project #:** 631020105
**Calculated By:** SJW **Date:** 05/2022
**Checked By:** DAM **Date:** 05/2022

**TITLE:** **LEACHATE STORAGE VOLUME REQUIREMENTS**

---

## Problem Statement

Determine the 1-day and 5-day leachate generation rate to evaluate the size of existing on-site leachate storage tanks (refer to Appendix K.6), in accordance with the requirements of 35 Ill. Admin. Code Section 811.309 (d)(1) & (6).

## Given

- ☐ Landfill cell design, contained in the Design Drawings.
- ☐ The proposed waste unit, including the expansion area, is approximately 258.7 acres.
- ☐ Zion Landfill houses two 32,000 gallon leachate storage tanks on the south side of the facility and one 165,000 gallon leachate storage tank on the north side of the facility, which provide excess storage capacity for the currently permitted landfill. The 165,000 gallon tank on the north side of the existing waste footprint will be removed prior to constructing the expansion, and a new 160,000 gallon leachate storage tank will be constructed north of the proposed expansion area.

## Assumptions

- ☐ $q_{OP}$ = 1,742 gallons/acre-day. Maximum monthly leachate generation rate due to percolation of moisture through the waste during operating periods (Appendix K.6).
- ☐ $q_{CL}$ = 3.0 gallons/acre-day. Maximum monthly leachate generation rate due to percolation of moisture through the waste during the post-closure period (Appendix K.6).

## Calculations

Calculate storage volume necessary for 1 day's storage and 5 day's storage.

35 Ill. Admin. Code Section 811.309(d)(1) requires that the leachate storage facility must be able to store a minimum of at least five days' worth of accumulated leachate at the maximum generation rate used in designing the leachate drainage system in accordance with 811.307. Since 811.307(b)(2)(B) states that the leachate drainage system shall be designed with the assumption that the final cover is in place, the leachate storage volume calculation assumes that all phases of Site 2 are closed. The footprint of Site 2 is assumed to generate 3.0 gal/acre-day during post-closure.

Closed phases of Site 2 = 258.7 acres (@ 3.0 gal/acre-day)

Determine required leachate storage volume using the modeled leachate generation rate under closed conditions:

$$V_{1\text{-day}}=(258.7\text{ acres})\left(\frac{3.0\text{ gal}}{\text{acre-day}}\right)=\left(\frac{\mathbf{776.1\ gal}}{\mathbf{day}}\right)$$

$$V_{5\text{-day}} = \left(\frac{776.1\text{ gal}}{\text{day}}\right)(5\text{ days}) = \mathbf{3{,}880.5\ gal}$$

## Results

| Storage Time | Minimum Storage Volume Required (gallons) |
|---|---|
| 1-Day | 776.1 |
| 5-Day | 3,880.5 |

As previously stated, Zion Landfill houses two 32,000-gallon leachate storage tanks on the south side of the facility, which will remain in place after the expansion. A new 160,000-gallon leachate storage tank will be constructed north of the expanded waste footprint. The total combined capacity of the existing and proposed storage tanks provides more than the minimum required storage volume of 3,880.5 gallons.

# K.10 – Bottom Liner System Design Equivalency

**Client:** Zion Landfill, Inc.
**Project:** Zion Landfill – Site 2 North Expansion
**Project #:** 631020105
**Calculated By:** SJW **Date:** 05/2022
**Checked By:** DAM **Date:** 05/2022

# TITLE: BOTTOM LINER SYSTEM DESIGN EQUIVALENCY

## Problem Statement

Demonstrate that the proposed bottom liner system design (60-mil HDPE geomembrane plus 5-ft of compacted soil) will perform as well as or better than a 5-ft compacted soil liner meeting the requirements of 35 Ill. Admin. Code Section 811.306 (d)(1-4). The equivalent performance shall be evaluated at maximum annual leachate flow conditions pursuant to 35 Ill. Admin. Code Section 811.306 (d)(5)(B).

## Given

- ☐ Calculation in Appendix K.6 Hydrologic Evaluation of Landfill Performance (HELP) Model Analysis
- ☐ Specific HELP model design parameters in Appendix K.6 Hydrologic Evaluation of Landfill Performance (HELP) Model Analysis
- ☐ Design specifications for the proposed liner system.

## Assumptions

The Zion Landfill is subject to steady-state conditions which does not account for absorption of moisture into the waste on a magnitude that is anticipated at the landfill. It is anticipated that the waste will absorb a large percentage of moisture, and only a small amount will percolate into the leachate drainage layer.

Since groundwater seepage into the bottom liner removes all outward gradient from the bottom liner in the HELP model by default, groundwater seepage has been removed from this equivalency demonstration to allow comparison of the percolation/leakage through the bottom liner.

Model 1: Proposed equivalent 5-ft composite liner system

1. Minimum liner thickness = 5-ft of compacted low permeable cohesive soil plus 60-mil HDPE geomembrane.
2. Maximum hydraulic conductivity of liner = 1 x $10^{-7}$ cm/sec = 3.3 x $10^{-9}$ ft/sec
3. HDPE geomembrane liner thickness = 60 mil = 0.06-in = 0.005-ft
4. Saturated HDPE geomembrane hydraulic conductivity = 2.0 x $10^{-13}$ cm/sec = 6.56 x $10^{-15}$ ft/sec (HELP Model User's Guide, Table 4)

Model 2: 5-ft compacted soil liner

1. Minimum liner thickness = 5-ft of compacted low permeability cohesive soil.
2. Maximum hydraulic conductivity of liner = 1 x $10^{-7}$ cm/sec = 3.3 x $10^{-9}$ ft/sec

**Client:** **Zion Landfill, Inc.**
**Project:** **Zion Landfill – Site 2 North Expansion**
**Project #:** **631020105**
**Calculated By:** **SJW** **Date:** **05/2022**
**Checked By:** **DAM** **Date:** **05/2022**

**TITLE:** **BOTTOM LINER SYSTEM DESIGN EQUIVALENCY**

## HELP Model Scenarios

Each of the two models below are identical with the exception of the bottom liner system component. Model 2 within this appendix represents the 5-ft compacted soil liner as defined by 35 Ill. Admin. Code 811.306 (d)(1-4). Both models include the proposed final cover. Model 1 within this appendix represents the proposed equivalent composite liner design which utilizes a 5-ft low permeability cohesive soil layer followed by a 60-mil HDPE geomembrane liner.

*Appendix K.10 – Model 1: Proposed equivalent composite liner design*

The peak daily leachate percolation/leakage through the proposed equivalent composite liner design is **0.00030 ft$^3$/day** during the post-closure period assuming steady-state conditions**.**

*Appendix K.10 – Model 2: 5-ft compacted soil liner design defined by 35 Ill. Admin. Code 811.306 (d)(1-4).*

The peak daily leachate percolation/leakage through the 5-ft. compacted soil liner design is **0.67289 ft$^3$/day** during the post-closure period assuming steady-state conditions**.**

## Results

According to the HELP Model results, the proposed equivalent composite liner design performs better than the design defined by 35 Ill. Admin. Code 811.306 (d)(1-4) based on the leachate head seepage through the bottom liner system.

```
**********************************************************************
**********************************************************************
**           HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE          **
**             HELP MODEL VERSION 3.07  (1 NOVEMBER 1997)           **
**               DEVELOPED BY ENVIRONMENTAL LABORATORY              **
**                 USAE WATERWAYS EXPERIMENT STATION                **
**          FOR USEPA RISK REDUCTION ENGINEERING LABORATORY         **
**********************************************************************
**********************************************************************


PRECIPITATION DATA FILE:    C:\SOURCE\zion\precip3b.D4
TEMPERATURE DATA FILE:      C:\SOURCE\zion\temp3b.D7
SOLAR RADIATION DATA FILE:  C:\SOURCE\zion\solar3b.D13
EVAPOTRANSPIRATION DATA:    C:\source\zion\evap3b.D11
SOIL AND DESIGN DATA FILE:  C:\source\zion\PCWOGS.D10
OUTPUT DATA FILE:           C:\source\zion\PCWOGS.OUT


TIME:  15:38     DATE:   3/ 2/2020


**********************************************************************
     TITLE:  POST CLOSURE YEARS 1-30 WITHOUT GROUNDWATER SEEPAGE
**********************************************************************


  NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER WERE
              COMPUTED AS NEARLY STEADY-STATE VALUES BY THE PROGRAM.


                                   LAYER  1
                                   --------

                     TYPE 1 - VERTICAL PERCOLATION LAYER
                         MATERIAL TEXTURE NUMBER   8
           THICKNESS                   =      6.00   INCHES
           POROSITY                    =      0.4630 VOL/VOL
           FIELD CAPACITY              =      0.2320 VOL/VOL
           WILTING POINT               =      0.1160 VOL/VOL
           INITIAL SOIL WATER CONTENT  =      0.3129 VOL/VOL
           EFFECTIVE SAT. HYD. COND.   =  0.369999994000E-03 CM/SEC
         NOTE:  SATURATED HYDRAULIC CONDUCTIVITY IS MULTIPLIED BY
3.00
                  FOR ROOT CHANNELS IN TOP HALF OF EVAPORATIVE ZONE.
```

```
                            LAYER  2
                            --------

                  TYPE 1 - VERTICAL PERCOLATION LAYER
                      MATERIAL TEXTURE NUMBER  12
     THICKNESS                   =     30.00    INCHES
     POROSITY                    =      0.4710 VOL/VOL
     FIELD CAPACITY              =      0.3420 VOL/VOL
     WILTING POINT               =      0.2100 VOL/VOL
     INITIAL SOIL WATER CONTENT  =      0.3479 VOL/VOL
     EFFECTIVE SAT. HYD. COND.   =  0.419999997000E-04 CM/SEC



                            LAYER  3
                            --------

                    TYPE 2 - LATERAL DRAINAGE LAYER
                      MATERIAL TEXTURE NUMBER  20
     THICKNESS                   =      0.20    INCHES
     POROSITY                    =      0.8500 VOL/VOL
     FIELD CAPACITY              =      0.0100 VOL/VOL
     WILTING POINT               =      0.0050 VOL/VOL
     INITIAL SOIL WATER CONTENT  =      0.0133 VOL/VOL
     EFFECTIVE SAT. HYD. COND.   =   10.0000000000     CM/SEC
     SLOPE                       =     10.00    PERCENT
     DRAINAGE LENGTH             =    240.0     FEET



                            LAYER  4
                            --------

                    TYPE 4 - FLEXIBLE MEMBRANE LINER
                      MATERIAL TEXTURE NUMBER  36
     THICKNESS                   =      0.04    INCHES
     POROSITY                    =      0.0000 VOL/VOL
     FIELD CAPACITY              =      0.0000 VOL/VOL
     WILTING POINT               =      0.0000 VOL/VOL
     INITIAL SOIL WATER CONTENT  =      0.0000 VOL/VOL
     EFFECTIVE SAT. HYD. COND.   =  0.399999993000E-12 CM/SEC
     FML PINHOLE DENSITY         =      1.00    HOLES/ACRE
     FML INSTALLATION DEFECTS    =     10.00    HOLES/ACRE
     FML PLACEMENT QUALITY       =  4 - POOR
```

```
                        LAYER  5
                        --------

              TYPE 3 - BARRIER SOIL LINER
              MATERIAL TEXTURE NUMBER   0
THICKNESS                   =     24.00   INCHES
POROSITY                    =      0.4270 VOL/VOL
FIELD CAPACITY              =      0.4180 VOL/VOL
WILTING POINT               =      0.3670 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.4270 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.999999975000E-04 CM/SEC


                        LAYER  6
                        --------

          TYPE 1 - VERTICAL PERCOLATION LAYER
              MATERIAL TEXTURE NUMBER  18
THICKNESS                   =   2484.00   INCHES
POROSITY                    =      0.6710 VOL/VOL
FIELD CAPACITY              =      0.2920 VOL/VOL
WILTING POINT               =      0.0770 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.2920 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.100000005000E-02 CM/SEC


                        LAYER  7
                        --------

            TYPE 2 - LATERAL DRAINAGE LAYER
              MATERIAL TEXTURE NUMBER   0
THICKNESS                   =     12.00   INCHES
POROSITY                    =      0.4570 VOL/VOL
FIELD CAPACITY              =      0.1310 VOL/VOL
WILTING POINT               =      0.0580 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.1310 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.100000001000     CM/SEC
SLOPE                       =      2.00   PERCENT
DRAINAGE LENGTH             =    155.0    FEET
```

```
                              LAYER  8
                              --------

                   TYPE 4 - FLEXIBLE MEMBRANE LINER
                     MATERIAL TEXTURE NUMBER  35
   THICKNESS                    =       0.06   INCHES
   POROSITY                     =       0.0000 VOL/VOL
   FIELD CAPACITY               =       0.0000 VOL/VOL
   WILTING POINT                =       0.0000 VOL/VOL
   INITIAL SOIL WATER CONTENT   =       0.0000 VOL/VOL
   EFFECTIVE SAT. HYD. COND.    =   0.199999996000E-12 CM/SEC
   FML PINHOLE DENSITY          =       1.00   HOLES/ACRE
   FML INSTALLATION DEFECTS     =      10.00   HOLES/ACRE
   FML PLACEMENT QUALITY        =   4 - POOR


                              LAYER  9
                              --------

                     TYPE 3 - BARRIER SOIL LINER
                     MATERIAL TEXTURE NUMBER  16
   THICKNESS                    =      60.00   INCHES
   POROSITY                     =       0.4270 VOL/VOL
   FIELD CAPACITY               =       0.4180 VOL/VOL
   WILTING POINT                =       0.3670 VOL/VOL
   INITIAL SOIL WATER CONTENT   =       0.4270 VOL/VOL
   EFFECTIVE SAT. HYD. COND.    =   0.100000001000E-06 CM/SEC


               GENERAL DESIGN AND EVAPORATIVE ZONE DATA
               ----------------------------------------

  NOTE:  SCS RUNOFF CURVE NUMBER WAS COMPUTED FROM DEFAULT
          SOIL DATA BASE USING SOIL TEXTURE # 8 WITH A
          FAIR STAND OF GRASS, A SURFACE SLOPE OF 10.%
          AND A SLOPE LENGTH OF  240. FEET.

SCS RUNOFF CURVE NUMBER             =     80.40
FRACTION OF AREA ALLOWING RUNOFF    =    100.0    PERCENT
AREA PROJECTED ON HORIZONTAL PLANE  =      1.000  ACRES
EVAPORATIVE ZONE DEPTH              =     20.0    INCHES
INITIAL WATER IN EVAPORATIVE ZONE   =      6.667  INCHES
UPPER LIMIT OF EVAPORATIVE STORAGE  =      9.372  INCHES
LOWER LIMIT OF EVAPORATIVE STORAGE  =      3.636  INCHES
```

```
     INITIAL SNOW WATER                     =      0.000  INCHES
     INITIAL WATER IN LAYER MATERIALS       =    775.086  INCHES
     TOTAL INITIAL WATER                    =    775.086  INCHES
     TOTAL SUBSURFACE INFLOW                =      0.00   INCHES/YEAR


                 EVAPOTRANSPIRATION AND WEATHER DATA
                 -----------------------------------

      NOTE:  EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
               MILWAUKEE             WISCONSIN

          STATION LATITUDE                          =  42.49 DEGREES
          MAXIMUM LEAF AREA INDEX                   =   2.00
          START OF GROWING SEASON (JULIAN DATE)     =    120
          END OF GROWING SEASON (JULIAN DATE)       =    289
          EVAPORATIVE ZONE DEPTH                    =  20.0  INCHES
          AVERAGE ANNUAL WIND SPEED                 =   9.00 MPH
          AVERAGE 1ST QUARTER RELATIVE HUMIDITY     =  72.00 %
          AVERAGE 2ND QUARTER RELATIVE HUMIDITY     =  70.00 %
          AVERAGE 3RD QUARTER RELATIVE HUMIDITY     =  74.00 %
          AVERAGE 4TH QUARTER RELATIVE HUMIDITY     =  75.00 %


      NOTE:  PRECIPITATION DATA WAS SYNTHETICALLY GENERATED USING
               COEFFICIENTS FOR    MILWAUKEE           WISCONSIN

               NORMAL MEAN MONTHLY PRECIPITATION (INCHES)

JAN/JUL     FEB/AUG     MAR/SEP     APR/OCT     MAY/NOV     JUN/DEC
-------     -------     -------     -------     -------     -------
  1.60        1.40        2.15        3.73        3.44        3.62
  3.49        4.22        3.40        2.42        2.57        2.05


      NOTE:  TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING
               COEFFICIENTS FOR    MILWAUKEE           WISCONSIN

          NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

JAN/JUL     FEB/AUG     MAR/SEP     APR/OCT     MAY/NOV     JUN/DEC
-------     -------     -------     -------     -------     -------
 20.30       24.80       34.50       45.10       56.30       66.20
 71.50       70.30       62.80       51.30       38.60       26.10
```

```
        NOTE:  SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING
                    COEFFICIENTS FOR    MILWAUKEE          WISCONSIN
                      AND STATION LATITUDE  =  42.49 DEGREES




******************************************************************************
     AVERAGE MONTHLY VALUES IN INCHES FOR YEARS    1 THROUGH   30
------------------------------------------------------------------------------

                     JAN/JUL  FEB/AUG  MAR/SEP  APR/OCT  MAY/NOV  JUN/DEC
                     -------  -------  -------  -------  -------  -------
  PRECIPITATION
  -------------
  TOTALS               1.50     1.28     2.10     3.62     3.29     3.72
                       2.94     4.05     3.51     2.43     2.47     2.39

  STD. DEVIATIONS      0.70     0.63     0.89     1.68     1.41     1.76
                       1.63     1.90     1.31     0.95     1.22     1.04

  RUNOFF
  ------
  TOTALS               0.359    0.923    1.920    0.734    0.048    0.053
                       0.009    0.110    0.068    0.012    0.062    0.178

  STD. DEVIATIONS      0.430    0.851    1.264    0.971    0.138    0.158
                       0.032    0.203    0.157    0.032    0.156    0.339

  EVAPOTRANSPIRATION
  ------------------
  TOTALS               0.474    0.391    0.557    2.605    3.442    4.309
                       3.392    3.423    2.349    1.342    0.827    0.458

  STD. DEVIATIONS      0.093    0.123    0.330    0.948    0.986    1.059
                       1.371    1.445    0.786    0.288    0.175    0.101

  LATERAL DRAINAGE COLLECTED FROM LAYER  3
  ----------------------------------------
  TOTALS              0.1913   0.0027   0.1996   1.3366   1.0177   0.2058
                      0.0444   0.0706   0.2239   0.2896   0.7873   0.8687

  STD. DEVIATIONS     0.3148   0.0110   0.4176   0.9390   0.9066   0.3516
                      0.1325   0.3417   0.4372   0.4551   0.8051   0.6952

  PERCOLATION/LEAKAGE THROUGH LAYER  5
  ------------------------------------
```

```
  TOTALS           0.0001   0.0000   0.0001   0.0005   0.0004   0.0001
                   0.0000   0.0000   0.0001   0.0001   0.0003   0.0004

  STD. DEVIATIONS  0.0001   0.0000   0.0002   0.0004   0.0004   0.0001
                   0.0001   0.0001   0.0002   0.0002   0.0003   0.0003

  LATERAL DRAINAGE COLLECTED FROM LAYER  7
  ----------------------------------------
  TOTALS           0.0001   0.0000   0.0001   0.0005   0.0005   0.0001
                   0.0000   0.0000   0.0001   0.0001   0.0003   0.0004

  STD. DEVIATIONS  0.0002   0.0000   0.0001   0.0003   0.0004   0.0002
                   0.0001   0.0001   0.0002   0.0002   0.0003   0.0003

  PERCOLATION/LEAKAGE THROUGH LAYER  9
  ------------------------------------
  TOTALS           0.0000   0.0000   0.0000   0.0000   0.0000   0.0000
                   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000

  STD. DEVIATIONS  0.0000   0.0000   0.0000   0.0000   0.0000   0.0000
                   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000


----------------------------------------------------------------------
        AVERAGES OF MONTHLY AVERAGED DAILY HEADS (INCHES)
----------------------------------------------------------------------


  DAILY AVERAGE HEAD ON TOP OF LAYER  4
  -------------------------------------
  AVERAGES         0.0003   0.0000   0.0003   0.0019   0.0014   0.0003
                   0.0001   0.0001   0.0003   0.0004   0.0011   0.0012

  STD. DEVIATIONS  0.0004   0.0000   0.0006   0.0013   0.0013   0.0005
                   0.0002   0.0005   0.0006   0.0006   0.0011   0.0010

  DAILY AVERAGE HEAD ON TOP OF LAYER  8
  -------------------------------------
  AVERAGES         0.0001   0.0000   0.0000   0.0002   0.0002   0.0001
                   0.0000   0.0000   0.0000   0.0001   0.0001   0.0002

  STD. DEVIATIONS  0.0001   0.0000   0.0001   0.0001   0.0002   0.0001
                   0.0000   0.0000   0.0001   0.0001   0.0001   0.0001

**********************************************************************
```

```
**********************************************************************
AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS    1 THROUGH   30
----------------------------------------------------------------------
                            INCHES            CU. FEET       PERCENT
                      -------------------   -------------   ---------
 PRECIPITATION           33.32    (   4.736)    120966.1     100.00

 RUNOFF                   4.476    (  2.0827)     16248.26     13.432

 EVAPOTRANSPIRATION      23.569    (  2.9703)     85556.14     70.727

 LATERAL DRAINAGE        5.23801 (  1.99898)     19013.992   15.71844
 COLLECTED FROM LAYER  3

 PERCOLATION/LEAKAGE    0.00223 (  0.00082)         8.111     0.00671
 THROUGH LAYER  5

 AVERAGE HEAD ON TOP             0.001 (    0.000)
   OF LAYER  4

 LATERAL DRAINAGE       0.00223 (  0.00084)         8.099    0.00669
 COLLECTED FROM LAYER  7

 PERCOLATION/LEAKAGE    0.00000 (  0.00000)         0.014     0.00001
 THROUGH LAYER  9

 AVERAGE HEAD ON TOP             0.000 (    0.000)
   OF LAYER  8

 CHANGE IN WATER STORAGE  0.038    (  1.4502)       139.61      0.115

**********************************************************************
```

```
******************************************************************************
            PEAK DAILY VALUES FOR YEARS     1 THROUGH   30
------------------------------------------------------------------------------
                                                (INCHES)      (CU. FT.)
                                               ----------    -------------
      PRECIPITATION                               4.11         14919.301

      RUNOFF                                      3.046        11057.7012

      DRAINAGE COLLECTED FROM LAYER  3           0.54123       1964.68140

      PERCOLATION/LEAKAGE THROUGH LAYER  5       0.000186         0.67495

      AVERAGE HEAD ON TOP OF LAYER  4                0.023

      MAXIMUM HEAD ON TOP OF LAYER  4                0.038

      LOCATION OF MAXIMUM HEAD IN LAYER  3
            (DISTANCE FROM DRAIN)                   42.0 FEET

      DRAINAGE COLLECTED FROM LAYER  7           0.00009          0.31043

      PERCOLATION/LEAKAGE THROUGH LAYER  9       0.000000         0.00030

      AVERAGE HEAD ON TOP OF LAYER  8                0.001

      MAXIMUM HEAD ON TOP OF LAYER  8                0.003

      LOCATION OF MAXIMUM HEAD IN LAYER  7
            (DISTANCE FROM DRAIN)                    0.0 FEET

      SNOW WATER                                  6.20         22496.8086


      MAXIMUM VEG. SOIL WATER (VOL/VOL)                    0.4360

      MINIMUM VEG. SOIL WATER (VOL/VOL)                    0.1818


   ***  Maximum heads are computed using McEnroe's equations.  ***

            Reference:  Maximum Saturated Depth over Landfill Liner
                        by Bruce M. McEnroe, University of Kansas
                        ASCE Journal of Environmental Engineering
                        Vol. 119, No. 2, March 1993, pp. 262-270.


******************************************************************************
```

```
**********************************************************************
               FINAL WATER STORAGE AT END OF YEAR   30
----------------------------------------------------------------------
                    LAYER        (INCHES)       (VOL/VOL)
                    -----        --------       ---------
                      1            2.0112         0.3352

                      2           11.0167         0.3672

                      3            0.0025         0.0125

                      4            0.0000         0.0000

                      5           10.2480         0.4270

                      6          725.3281         0.2920

                      7            1.5720         0.1310

                      8            0.0000         0.0000

                      9           25.6200         0.4270

                  SNOW WATER       0.442

**********************************************************************
**********************************************************************
```

```
**********************************************************************
**********************************************************************
**                                                                  **
**           HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE          **
**             HELP MODEL VERSION 3.07  (1 NOVEMBER 1997)           **
**              DEVELOPED BY ENVIRONMENTAL LABORATORY               **
**                USAE WATERWAYS EXPERIMENT STATION                 **
**          FOR USEPA RISK REDUCTION ENGINEERING LABORATORY         **
**                                                                  **
**********************************************************************
**********************************************************************


 PRECIPITATION DATA FILE:    C:\SOURCE\zion\precip3b.D4
 TEMPERATURE DATA FILE:      C:\SOURCE\zion\temp3b.D7
 SOLAR RADIATION DATA FILE:  C:\SOURCE\zion\solar3b.D13
 EVAPOTRANSPIRATION DATA:    C:\source\zion\evap3b.D11
 SOIL AND DESIGN DATA FILE:  C:\source\zion\BLEQVR.D10
 OUTPUT DATA FILE:           C:\source\zion\BLEQVR.OUT



 TIME:  15:43     DATE:   3/ 2/2020



**********************************************************************
   TITLE:  ZION LANDFILL - SITE 2 NORTH EXPANSION BOTTOM LINER EQV.
**********************************************************************



   NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER WERE
             COMPUTED AS NEARLY STEADY-STATE VALUES BY THE PROGRAM.


                                LAYER  1
                                --------

                      TYPE 1 - VERTICAL PERCOLATION LAYER
                          MATERIAL TEXTURE NUMBER   8
           THICKNESS                  =     6.00   INCHES
           POROSITY                   =     0.4630 VOL/VOL
           FIELD CAPACITY             =     0.2320 VOL/VOL
           WILTING POINT              =     0.1160 VOL/VOL
           INITIAL SOIL WATER CONTENT =     0.3129 VOL/VOL
           EFFECTIVE SAT. HYD. COND.  =  0.369999994000E-03 CM/SEC
         NOTE:  SATURATED HYDRAULIC CONDUCTIVITY IS MULTIPLIED BY
3.00
                FOR ROOT CHANNELS IN TOP HALF OF EVAPORATIVE ZONE.
```

```
                        LAYER  2
                        --------

              TYPE 1 - VERTICAL PERCOLATION LAYER
                MATERIAL TEXTURE NUMBER  12
THICKNESS                   =     30.00   INCHES
POROSITY                    =      0.4710 VOL/VOL
FIELD CAPACITY              =      0.3420 VOL/VOL
WILTING POINT               =      0.2100 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.3479 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.419999997000E-04 CM/SEC



                        LAYER  3
                        --------

                TYPE 2 - LATERAL DRAINAGE LAYER
                MATERIAL TEXTURE NUMBER  20
THICKNESS                   =      0.20   INCHES
POROSITY                    =      0.8500 VOL/VOL
FIELD CAPACITY              =      0.0100 VOL/VOL
WILTING POINT               =      0.0050 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.0133 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =   10.0000000000     CM/SEC
SLOPE                       =     10.00   PERCENT
DRAINAGE LENGTH             =    240.0    FEET



                        LAYER  4
                        --------

                TYPE 4 - FLEXIBLE MEMBRANE LINER
                MATERIAL TEXTURE NUMBER  36
THICKNESS                   =      0.04   INCHES
POROSITY                    =      0.0000 VOL/VOL
FIELD CAPACITY              =      0.0000 VOL/VOL
WILTING POINT               =      0.0000 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.0000 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.399999993000E-12 CM/SEC
FML PINHOLE DENSITY         =      1.00   HOLES/ACRE
FML INSTALLATION DEFECTS    =     10.00   HOLES/ACRE
FML PLACEMENT QUALITY       =  4 - POOR
```

```
                        LAYER  5
                        --------

              TYPE 3 - BARRIER SOIL LINER
              MATERIAL TEXTURE NUMBER   0
THICKNESS                   =     24.00    INCHES
POROSITY                    =      0.4270 VOL/VOL
FIELD CAPACITY              =      0.4180 VOL/VOL
WILTING POINT               =      0.3670 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.4270 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.999999975000E-04 CM/SEC



                        LAYER  6
                        --------

          TYPE 1 - VERTICAL PERCOLATION LAYER
              MATERIAL TEXTURE NUMBER  18
THICKNESS                   =   2484.00    INCHES
POROSITY                    =      0.6710 VOL/VOL
FIELD CAPACITY              =      0.2920 VOL/VOL
WILTING POINT               =      0.0770 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.2920 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.100000005000E-02 CM/SEC



                        LAYER  7
                        --------

            TYPE 2 - LATERAL DRAINAGE LAYER
              MATERIAL TEXTURE NUMBER   0
THICKNESS                   =     12.00    INCHES
POROSITY                    =      0.4570 VOL/VOL
FIELD CAPACITY              =      0.1310 VOL/VOL
WILTING POINT               =      0.0580 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.1310 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.100000001000     CM/SEC
SLOPE                       =      2.00    PERCENT
DRAINAGE LENGTH             =    155.0     FEET
```

```
                         LAYER  8
                         --------

               TYPE 3 - BARRIER SOIL LINER
               MATERIAL TEXTURE NUMBER  16
        THICKNESS                  =     60.00   INCHES
        POROSITY                   =      0.4270 VOL/VOL
        FIELD CAPACITY             =      0.4180 VOL/VOL
        WILTING POINT              =      0.3670 VOL/VOL
        INITIAL SOIL WATER CONTENT =      0.4270 VOL/VOL
        EFFECTIVE SAT. HYD. COND.  =  0.100000001000E-06 CM/SEC




            GENERAL DESIGN AND EVAPORATIVE ZONE DATA
            ----------------------------------------

       NOTE:  SCS RUNOFF CURVE NUMBER WAS COMPUTED FROM DEFAULT
               SOIL DATA BASE USING SOIL TEXTURE # 8 WITH A
               FAIR STAND OF GRASS, A SURFACE SLOPE OF 10.%
               AND A SLOPE LENGTH OF  240. FEET.

      SCS RUNOFF CURVE NUMBER               =     80.40
      FRACTION OF AREA ALLOWING RUNOFF      =    100.0    PERCENT
      AREA PROJECTED ON HORIZONTAL PLANE    =      1.000  ACRES
      EVAPORATIVE ZONE DEPTH                =     20.0    INCHES
      INITIAL WATER IN EVAPORATIVE ZONE     =      6.667  INCHES
      UPPER LIMIT OF EVAPORATIVE STORAGE    =      9.372  INCHES
      LOWER LIMIT OF EVAPORATIVE STORAGE    =      3.636  INCHES
      INITIAL SNOW WATER                    =      0.000  INCHES
      INITIAL WATER IN LAYER MATERIALS      =    775.086  INCHES
      TOTAL INITIAL WATER                   =    775.086  INCHES
      TOTAL SUBSURFACE INFLOW               =      0.00   INCHES/YEAR




             EVAPOTRANSPIRATION AND WEATHER DATA
             -----------------------------------

       NOTE:  EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
               MILWAUKEE            WISCONSIN

           STATION LATITUDE                        =  42.49 DEGREES
           MAXIMUM LEAF AREA INDEX                 =   2.00
           START OF GROWING SEASON (JULIAN DATE)   =    120
           END OF GROWING SEASON (JULIAN DATE)     =    289
```

```
          EVAPORATIVE ZONE DEPTH                     =  20.0  INCHES
          AVERAGE ANNUAL WIND SPEED                  =   9.00 MPH
          AVERAGE 1ST QUARTER RELATIVE HUMIDITY      =  72.00 %
          AVERAGE 2ND QUARTER RELATIVE HUMIDITY      =  70.00 %
          AVERAGE 3RD QUARTER RELATIVE HUMIDITY      =  74.00 %
          AVERAGE 4TH QUARTER RELATIVE HUMIDITY      =  75.00 %


      NOTE:  PRECIPITATION DATA WAS SYNTHETICALLY GENERATED USING
               COEFFICIENTS FOR    MILWAUKEE           WISCONSIN

               NORMAL MEAN MONTHLY PRECIPITATION (INCHES)

  JAN/JUL     FEB/AUG     MAR/SEP     APR/OCT     MAY/NOV     JUN/DEC
  -------     -------     -------     -------     -------     -------
    1.60        1.40        2.15        3.73        3.44        3.62
    3.49        4.22        3.40        2.42        2.57        2.05


      NOTE:  TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING
               COEFFICIENTS FOR    MILWAUKEE           WISCONSIN

          NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

  JAN/JUL     FEB/AUG     MAR/SEP     APR/OCT     MAY/NOV     JUN/DEC
  -------     -------     -------     -------     -------     -------
   20.30       24.80       34.50       45.10       56.30       66.20
   71.50       70.30       62.80       51.30       38.60       26.10


   NOTE:  SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING
               COEFFICIENTS FOR    MILWAUKEE           WISCONSIN
                AND STATION LATITUDE  =  42.49 DEGREES




*******************************************************************************
     AVERAGE MONTHLY VALUES IN INCHES FOR YEARS    1 THROUGH   30
-------------------------------------------------------------------------------

                  JAN/JUL  FEB/AUG  MAR/SEP  APR/OCT  MAY/NOV  JUN/DEC
                  -------  -------  -------  -------  -------  -------
  PRECIPITATION
  -------------
```

```
TOTALS            1.50     1.28     2.10     3.62     3.29     3.72
                  2.94     4.05     3.51     2.43     2.47     2.39

STD. DEVIATIONS   0.70     0.63     0.89     1.68     1.41     1.76
                  1.63     1.90     1.31     0.95     1.22     1.04

RUNOFF
------
TOTALS           0.359    0.923    1.920    0.734    0.048    0.053
                 0.009    0.110    0.068    0.012    0.062    0.178

STD. DEVIATIONS  0.430    0.851    1.264    0.971    0.138    0.158
                 0.032    0.203    0.157    0.032    0.156    0.339

EVAPOTRANSPIRATION
------------------
TOTALS           0.474    0.391    0.557    2.605    3.442    4.309
                 3.392    3.423    2.349    1.342    0.827    0.458

STD. DEVIATIONS  0.093    0.123    0.330    0.948    0.986    1.059
                 1.371    1.445    0.786    0.288    0.175    0.101

LATERAL DRAINAGE COLLECTED FROM LAYER  3
----------------------------------------
TOTALS          0.1913   0.0027   0.1996   1.3366   1.0177   0.2058
                0.0444   0.0706   0.2239   0.2896   0.7873   0.8687

STD. DEVIATIONS 0.3148   0.0110   0.4176   0.9390   0.9066   0.3516
                0.1325   0.3417   0.4372   0.4551   0.8051   0.6952

PERCOLATION/LEAKAGE THROUGH LAYER  5
------------------------------------
TOTALS          0.0001   0.0000   0.0001   0.0005   0.0004   0.0001
                0.0000   0.0000   0.0001   0.0001   0.0003   0.0004

STD. DEVIATIONS 0.0001   0.0000   0.0002   0.0004   0.0004   0.0001
                0.0001   0.0001   0.0002   0.0002   0.0003   0.0003

LATERAL DRAINAGE COLLECTED FROM LAYER  7
----------------------------------------
TOTALS          0.0000   0.0000   0.0000   0.0000   0.0000   0.0000
                0.0000   0.0000   0.0000   0.0000   0.0000   0.0000

STD. DEVIATIONS 0.0000   0.0000   0.0000   0.0000   0.0000   0.0000
                0.0000   0.0000   0.0000   0.0000   0.0000   0.0000

PERCOLATION/LEAKAGE THROUGH LAYER  8
------------------------------------
TOTALS          0.0001   0.0000   0.0001   0.0005   0.0004   0.0001
                0.0000   0.0000   0.0001   0.0001   0.0003   0.0004
```

```
   STD. DEVIATIONS 0.0001    0.0000    0.0002    0.0004    0.0004    0.0001
                   0.0001    0.0001    0.0002    0.0002    0.0003    0.0003


----------------------------------------------------------------------
          AVERAGES OF MONTHLY AVERAGED DAILY HEADS (INCHES)
----------------------------------------------------------------------


   DAILY AVERAGE HEAD ON TOP OF LAYER  4
   -------------------------------------
   AVERAGES        0.0003    0.0000    0.0003    0.0019    0.0014    0.0003
                   0.0001    0.0001    0.0003    0.0004    0.0011    0.0012

   STD. DEVIATIONS 0.0004    0.0000    0.0006    0.0013    0.0013    0.0005
                   0.0002    0.0005    0.0006    0.0006    0.0011    0.0010

   DAILY AVERAGE HEAD ON TOP OF LAYER  8
   -------------------------------------
   AVERAGES        0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
                   0.0000    0.0000    0.0000    0.0000    0.0000    0.0000

   STD. DEVIATIONS 0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
                   0.0000    0.0000    0.0000    0.0000    0.0000    0.0000

**********************************************************************


**********************************************************************
 AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS    1 THROUGH   30
----------------------------------------------------------------------
                                INCHES            CU. FEET      PERCENT
                        -------------------    -------------   ---------
  PRECIPITATION           33.32    (   4.736)     120966.1     100.00

  RUNOFF                   4.476   (  2.0827)      16248.26     13.432

  EVAPOTRANSPIRATION      23.569   (  2.9703)      85556.14     70.727

  LATERAL DRAINAGE         5.23801 (  1.99898)     19013.992   15.71844
  COLLECTED FROM LAYER  3

  PERCOLATION/LEAKAGE     0.00223 (  0.00082)         8.111     0.00671
  THROUGH LAYER  5

  AVERAGE HEAD ON TOP              0.001 (    0.000)
    OF LAYER  4
```

```
 LATERAL DRAINAGE      0.00000 (  0.00000)         0.005    0.00000
 COLLECTED FROM LAYER  7

 PERCOLATION/LEAKAGE   0.00223 (  0.00081)         8.106     0.00670
 THROUGH LAYER  8

 AVERAGE HEAD ON TOP             0.000 (    0.000)
   OF LAYER  8

 CHANGE IN WATER STORAGE  0.038   (  1.4502)        139.61      0.115


***********************************************************************
```

```
**********************************************************************
             PEAK DAILY VALUES FOR YEARS    1 THROUGH   30
----------------------------------------------------------------------
                                             (INCHES)      (CU. FT.)
                                            ----------   -------------
       PRECIPITATION                           4.11         14919.301

       RUNOFF                                  3.046        11057.7012

       DRAINAGE COLLECTED FROM LAYER  3       0.54123       1964.68140

       PERCOLATION/LEAKAGE THROUGH LAYER  5   0.000186         0.67495

       AVERAGE HEAD ON TOP OF LAYER  4            0.023

       MAXIMUM HEAD ON TOP OF LAYER  4            0.038

       LOCATION OF MAXIMUM HEAD IN LAYER  3
             (DISTANCE FROM DRAIN)               42.0 FEET

       DRAINAGE COLLECTED FROM LAYER  7       0.00000          0.00206

       PERCOLATION/LEAKAGE THROUGH LAYER  8       0.000185
0.67289

       AVERAGE HEAD ON TOP OF LAYER  8            0.000

       MAXIMUM HEAD ON TOP OF LAYER  8            0.000

       LOCATION OF MAXIMUM HEAD IN LAYER  7
             (DISTANCE FROM DRAIN)                0.0 FEET

       SNOW WATER                             6.20         22496.8086


       MAXIMUM VEG. SOIL WATER (VOL/VOL)                  0.4360

       MINIMUM VEG. SOIL WATER (VOL/VOL)                  0.1818

    ***  Maximum heads are computed using McEnroe's equations.  ***

             Reference:  Maximum Saturated Depth over Landfill Liner
                         by Bruce M. McEnroe, University of Kansas
                         ASCE Journal of Environmental Engineering
                         Vol. 119, No. 2, March 1993, pp. 262-270.

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             FINAL WATER STORAGE AT END OF YEAR   30
----------------------------------------------------------------------
                    LAYER        (INCHES)       (VOL/VOL)
                    -----        --------       ---------
                      1           2.0112          0.3352

                      2          11.0167          0.3672

                      3           0.0025          0.0125

                      4           0.0000          0.0000

                      5          10.2480          0.4270

                      6         725.3281          0.2920

                      7           1.5720          0.1310

                      8          25.6200          0.4270

                  SNOW WATER      0.442

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```

# K.11 – Final Cover System Design Equivalency

**Client:** **Zion Landfill, Inc.**
**Project:** **Zion Landfill – Site 2 North Expansion**
**Project #:** **631020105**
**Calculated By:** **SJW** **Date:** **05/2022**
**Checked By:** **DAM** **Date:** **05/2022**

**TITLE:** **FINAL COVER SYSTEM DESIGN EQUIVALENCY**

### Problem Statement

Demonstrate that the proposed low permeability layer of the proposed final cover design (40-mil LLDPE geomembrane plus 2 ft of compacted soil) will perform as well as or better as a 3-ft low permeability compacted soil layer with a permeability of 1 x $10^{-7}$ cm/sec, meeting the requirements of 35 Ill. Admin. Code Section 811.314 (b)(3)(A)(iii). The equivalent performance shall be evaluated at maximum annual leachate flow conditions pursuant to 35 Ill. Admin. Code Section 811.314.

### Given

- ☐ Calculation in Appendix K.6 Hydrologic Evaluation of Landfill Performance (HELP) Model Analysis
- ☐ Specific HELP model design parameters in Appendix K.6 Hydrologic Evaluation of Landfill Performance (HELP) Model Analysis
- ☐ Design specifications for the proposed final cover system.
- ☐ The HELP Model User's Guide for Version 3 (1994), Table 4 – *Default Soil, Waste, Geosynthetic Characteristics,* and Section 4.6.3 – *Layer Types*

### Assumptions

Since groundwater seepage into the bottom liner removes all outward gradient from the bottom liner in the HELP model by default, groundwater seepage has been removed from this equivalency demonstration to allow comparison of the percolation/leakage through the bottom liner.

Model 1: Proposed equivalent composite low-permeability layer of the final cover system

1. Minimum protective cover thickness = 2 ft plus 40-mil LLDPE geomembrane.
2. Maximum hydraulic conductivity of low permeability layer = 1 x $10^{-4}$ cm/sec.
3. LLDPE geomembrane liner thickness = 40 mil = 0.04 in = 0.003 ft
4. The 40 mil LLDPE geomembrane liner is overlain by a geocomposite drainage layer and three feet of protective/vegetative soils
5. Saturated LLDPE hydraulic conductivity = 4.0 x $10^{-13}$ cm/sec = 1.31 x $10^{-14}$ ft/sec

Model 2: 3 ft. low permeability layer

1. Minimum layer thickness = 3-ft of compacted low permeability cohesive soil.
2. Maximum hydraulic conductivity of layer = 1 x $10^{-7}$ cm/sec = 3.3 x $10^{-9}$ ft/sec
3. The 3-foot low permeability layer will be overlain by a geocomposite drainage layer and three feet of protective/vegetative soils.

**Client:** **Zion Landfill, Inc.**
**Project:** **Zion Landfill – Site 2 North Expansion**
**Project #:** **631020105**
**Calculated By:** **SJW** **Date:** **05/2022**
**Checked By:** **DAM** **Date:** **05/2022**

**TITLE:** **FINAL COVER SYSTEM DESIGN EQUIVALENCY**

---

## HELP Model Scenario Results

Each of the two models below are identical with the exception of the final cover system component. Model 2 within this appendix represents the 3-ft compacted soil low-permeability layer as defined by 35 Ill. Admin. Code 811.314 (b)(3)(A). Model 1 represents the proposed equivalent composite liner design which utilizes a 2-ft low permeability cohesive soil layer followed by a 40-mil LLDPE geomembrane liner and a geocomposite drainage layer.

*Appendix K.11 – Model 1: Proposed equivalent final cover design*

The peak daily leachate percolation/leakage through the bottom of the landfill using the proposed equivalent final cover design is **0.00030 ft$^3$/day** during the post-closure period assuming steady-state conditions**.**

*Appendix K.11: Model 2: 3-ft compacted soil low-permeability layer as defined by 35 Ill. Admin. Code 811.314 (b)(3)(A)*

The peak daily leachate percolation/leakage through the bottom of the landfill using the 3-ft. compacted soil low-permeability layer design is **0.00765 ft$^3$/day** during the post-closure period assuming steady-state conditions**.**

## Conclusion

According to the HELP Model results, the proposed equivalent composite liner design performance is superior to the design defined by 35 Ill. Admin. Code 811.314(b)(3)(A), based on the precipitation allowed to pass through the final cover.

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**********************************************************************
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**                                                                  **
**             HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE        **
**               HELP MODEL VERSION 3.07  (1 NOVEMBER 1997)         **
**                 DEVELOPED BY ENVIRONMENTAL LABORATORY            **
**                   USAE WATERWAYS EXPERIMENT STATION              **
**            FOR USEPA RISK REDUCTION ENGINEERING LABORATORY       **
**                                                                  **
**********************************************************************
**********************************************************************


 PRECIPITATION DATA FILE:     C:\SOURCE\zion\precip3b.D4
 TEMPERATURE DATA FILE:       C:\SOURCE\zion\temp3b.D7
 SOLAR RADIATION DATA FILE:   C:\SOURCE\zion\solar3b.D13
 EVAPOTRANSPIRATION DATA:     C:\source\zion\evap3b.D11
 SOIL AND DESIGN DATA FILE:   C:\source\zion\PCWOGS.D10
 OUTPUT DATA FILE:            C:\source\zion\PCWOGS.OUT



 TIME:  15:38     DATE:   3/ 2/2020



**********************************************************************
     TITLE:  POST CLOSURE YEARS 1-30 WITHOUT GROUNDWATER SEEPAGE
**********************************************************************


   NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER WERE
               COMPUTED AS NEARLY STEADY-STATE VALUES BY THE PROGRAM.


                                   LAYER  1
                                   --------

                      TYPE 1 - VERTICAL PERCOLATION LAYER
                          MATERIAL TEXTURE NUMBER   8
           THICKNESS                    =      6.00   INCHES
           POROSITY                     =      0.4630 VOL/VOL
           FIELD CAPACITY               =      0.2320 VOL/VOL
           WILTING POINT                =      0.1160 VOL/VOL
           INITIAL SOIL WATER CONTENT   =      0.3129 VOL/VOL
           EFFECTIVE SAT. HYD. COND.    =  0.369999994000E-03 CM/SEC
      NOTE:  SATURATED HYDRAULIC CONDUCTIVITY IS MULTIPLIED BY
3.00
                  FOR ROOT CHANNELS IN TOP HALF OF EVAPORATIVE ZONE.
```

```
                        LAYER  2
                        --------

          TYPE 1 - VERTICAL PERCOLATION LAYER
              MATERIAL TEXTURE NUMBER  12
THICKNESS                   =     30.00   INCHES
POROSITY                    =      0.4710 VOL/VOL
FIELD CAPACITY              =      0.3420 VOL/VOL
WILTING POINT               =      0.2100 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.3479 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.419999997000E-04 CM/SEC



                        LAYER  3
                        --------

            TYPE 2 - LATERAL DRAINAGE LAYER
              MATERIAL TEXTURE NUMBER  20
THICKNESS                   =      0.20   INCHES
POROSITY                    =      0.8500 VOL/VOL
FIELD CAPACITY              =      0.0100 VOL/VOL
WILTING POINT               =      0.0050 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.0133 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =   10.0000000000     CM/SEC
SLOPE                       =     10.00   PERCENT
DRAINAGE LENGTH             =    240.0    FEET



                        LAYER  4
                        --------

            TYPE 4 - FLEXIBLE MEMBRANE LINER
              MATERIAL TEXTURE NUMBER  36
THICKNESS                   =      0.04   INCHES
POROSITY                    =      0.0000 VOL/VOL
FIELD CAPACITY              =      0.0000 VOL/VOL
WILTING POINT               =      0.0000 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.0000 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.399999993000E-12 CM/SEC
FML PINHOLE DENSITY         =      1.00   HOLES/ACRE
FML INSTALLATION DEFECTS    =     10.00   HOLES/ACRE
FML PLACEMENT QUALITY       =  4 - POOR
```

```
                        LAYER  5
                        --------

              TYPE 3 - BARRIER SOIL LINER
              MATERIAL TEXTURE NUMBER   0
THICKNESS                  =     24.00   INCHES
POROSITY                   =      0.4270 VOL/VOL
FIELD CAPACITY             =      0.4180 VOL/VOL
WILTING POINT              =      0.3670 VOL/VOL
INITIAL SOIL WATER CONTENT =      0.4270 VOL/VOL
EFFECTIVE SAT. HYD. COND.  =  0.999999975000E-04 CM/SEC



                        LAYER  6
                        --------

          TYPE 1 - VERTICAL PERCOLATION LAYER
              MATERIAL TEXTURE NUMBER  18
THICKNESS                  =   2484.00   INCHES
POROSITY                   =      0.6710 VOL/VOL
FIELD CAPACITY             =      0.2920 VOL/VOL
WILTING POINT              =      0.0770 VOL/VOL
INITIAL SOIL WATER CONTENT =      0.2920 VOL/VOL
EFFECTIVE SAT. HYD. COND.  =  0.100000005000E-02 CM/SEC



                        LAYER  7
                        --------

            TYPE 2 - LATERAL DRAINAGE LAYER
              MATERIAL TEXTURE NUMBER   0
THICKNESS                  =     12.00   INCHES
POROSITY                   =      0.4570 VOL/VOL
FIELD CAPACITY             =      0.1310 VOL/VOL
WILTING POINT              =      0.0580 VOL/VOL
INITIAL SOIL WATER CONTENT =      0.1310 VOL/VOL
EFFECTIVE SAT. HYD. COND.  =  0.100000001000     CM/SEC
SLOPE                      =      2.00   PERCENT
DRAINAGE LENGTH            =    155.0    FEET
```

```
                              LAYER  8
                              --------

                   TYPE 4 - FLEXIBLE MEMBRANE LINER
                     MATERIAL TEXTURE NUMBER  35
    THICKNESS                     =      0.06   INCHES
    POROSITY                      =      0.0000 VOL/VOL
    FIELD CAPACITY                =      0.0000 VOL/VOL
    WILTING POINT                 =      0.0000 VOL/VOL
    INITIAL SOIL WATER CONTENT    =      0.0000 VOL/VOL
    EFFECTIVE SAT. HYD. COND.     =  0.199999996000E-12 CM/SEC
    FML PINHOLE DENSITY           =      1.00   HOLES/ACRE
    FML INSTALLATION DEFECTS      =     10.00   HOLES/ACRE
    FML PLACEMENT QUALITY         =  4 - POOR


                              LAYER  9
                              --------

                     TYPE 3 - BARRIER SOIL LINER
                     MATERIAL TEXTURE NUMBER  16
    THICKNESS                     =     60.00   INCHES
    POROSITY                      =      0.4270 VOL/VOL
    FIELD CAPACITY                =      0.4180 VOL/VOL
    WILTING POINT                 =      0.3670 VOL/VOL
    INITIAL SOIL WATER CONTENT    =      0.4270 VOL/VOL
    EFFECTIVE SAT. HYD. COND.     =  0.100000001000E-06 CM/SEC


               GENERAL DESIGN AND EVAPORATIVE ZONE DATA
               ----------------------------------------

  NOTE:  SCS RUNOFF CURVE NUMBER WAS COMPUTED FROM DEFAULT
           SOIL DATA BASE USING SOIL TEXTURE # 8 WITH A
           FAIR STAND OF GRASS, A SURFACE SLOPE OF 10.%
           AND A SLOPE LENGTH OF  240. FEET.

 SCS RUNOFF CURVE NUMBER              =     80.40
 FRACTION OF AREA ALLOWING RUNOFF     =    100.0    PERCENT
 AREA PROJECTED ON HORIZONTAL PLANE   =      1.000  ACRES
 EVAPORATIVE ZONE DEPTH               =     20.0    INCHES
 INITIAL WATER IN EVAPORATIVE ZONE    =      6.667  INCHES
 UPPER LIMIT OF EVAPORATIVE STORAGE   =      9.372  INCHES
 LOWER LIMIT OF EVAPORATIVE STORAGE   =      3.636  INCHES
```

```
      INITIAL SNOW WATER                  =      0.000  INCHES
      INITIAL WATER IN LAYER MATERIALS    =    775.086  INCHES
      TOTAL INITIAL WATER                 =    775.086  INCHES
      TOTAL SUBSURFACE INFLOW             =      0.00   INCHES/YEAR


                  EVAPOTRANSPIRATION AND WEATHER DATA
                  -----------------------------------

       NOTE:  EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
                MILWAUKEE             WISCONSIN

           STATION LATITUDE                        =  42.49 DEGREES
           MAXIMUM LEAF AREA INDEX                 =   2.00
           START OF GROWING SEASON (JULIAN DATE)   =    120
           END OF GROWING SEASON (JULIAN DATE)     =    289
           EVAPORATIVE ZONE DEPTH                  =  20.0  INCHES
           AVERAGE ANNUAL WIND SPEED               =   9.00 MPH
           AVERAGE 1ST QUARTER RELATIVE HUMIDITY   =  72.00 %
           AVERAGE 2ND QUARTER RELATIVE HUMIDITY   =  70.00 %
           AVERAGE 3RD QUARTER RELATIVE HUMIDITY   =  74.00 %
           AVERAGE 4TH QUARTER RELATIVE HUMIDITY   =  75.00 %


       NOTE:  PRECIPITATION DATA WAS SYNTHETICALLY GENERATED USING
                COEFFICIENTS FOR    MILWAUKEE          WISCONSIN

                NORMAL MEAN MONTHLY PRECIPITATION (INCHES)

JAN/JUL     FEB/AUG     MAR/SEP     APR/OCT     MAY/NOV     JUN/DEC
-------     -------     -------     -------     -------     -------
  1.60        1.40        2.15        3.73        3.44        3.62
  3.49        4.22        3.40        2.42        2.57        2.05


       NOTE:  TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING
                COEFFICIENTS FOR    MILWAUKEE          WISCONSIN

           NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

JAN/JUL     FEB/AUG     MAR/SEP     APR/OCT     MAY/NOV     JUN/DEC
-------     -------     -------     -------     -------     -------
 20.30       24.80       34.50       45.10       56.30       66.20
 71.50       70.30       62.80       51.30       38.60       26.10
```

```
          NOTE:  SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING
                    COEFFICIENTS FOR    MILWAUKEE          WISCONSIN
                     AND STATION LATITUDE  =  42.49 DEGREES




*******************************************************************************
     AVERAGE MONTHLY VALUES IN INCHES FOR YEARS    1 THROUGH   30
-------------------------------------------------------------------------------

                   JAN/JUL  FEB/AUG  MAR/SEP  APR/OCT  MAY/NOV  JUN/DEC
                   -------  -------  -------  -------  -------  -------
  PRECIPITATION
  -------------
  TOTALS             1.50     1.28     2.10     3.62     3.29     3.72
                     2.94     4.05     3.51     2.43     2.47     2.39

  STD. DEVIATIONS    0.70     0.63     0.89     1.68     1.41     1.76
                     1.63     1.90     1.31     0.95     1.22     1.04

  RUNOFF
  ------
  TOTALS             0.359    0.923    1.920    0.734    0.048    0.053
                     0.009    0.110    0.068    0.012    0.062    0.178

  STD. DEVIATIONS    0.430    0.851    1.264    0.971    0.138    0.158
                     0.032    0.203    0.157    0.032    0.156    0.339

  EVAPOTRANSPIRATION
  ------------------
  TOTALS             0.474    0.391    0.557    2.605    3.442    4.309
                     3.392    3.423    2.349    1.342    0.827    0.458

  STD. DEVIATIONS    0.093    0.123    0.330    0.948    0.986    1.059
                     1.371    1.445    0.786    0.288    0.175    0.101

  LATERAL DRAINAGE COLLECTED FROM LAYER  3
  ----------------------------------------
  TOTALS            0.1913   0.0027   0.1996   1.3366   1.0177   0.2058
                    0.0444   0.0706   0.2239   0.2896   0.7873   0.8687

  STD. DEVIATIONS   0.3148   0.0110   0.4176   0.9390   0.9066   0.3516
                    0.1325   0.3417   0.4372   0.4551   0.8051   0.6952

  PERCOLATION/LEAKAGE THROUGH LAYER  5
  ------------------------------------
```

```
   TOTALS            0.0001   0.0000   0.0001   0.0005   0.0004   0.0001
                     0.0000   0.0000   0.0001   0.0001   0.0003   0.0004

   STD. DEVIATIONS 0.0001   0.0000   0.0002   0.0004   0.0004   0.0001
                     0.0001   0.0001   0.0002   0.0002   0.0003   0.0003

   LATERAL DRAINAGE COLLECTED FROM LAYER  7
   ----------------------------------------
   TOTALS            0.0001   0.0000   0.0001   0.0005   0.0005   0.0001
                     0.0000   0.0000   0.0001   0.0001   0.0003   0.0004

   STD. DEVIATIONS 0.0002   0.0000   0.0001   0.0003   0.0004   0.0002
                     0.0001   0.0001   0.0002   0.0002   0.0003   0.0003

   PERCOLATION/LEAKAGE THROUGH LAYER  9
   ------------------------------------
   TOTALS            0.0000   0.0000   0.0000   0.0000   0.0000   0.0000
                     0.0000   0.0000   0.0000   0.0000   0.0000   0.0000

   STD. DEVIATIONS 0.0000   0.0000   0.0000   0.0000   0.0000   0.0000
                     0.0000   0.0000   0.0000   0.0000   0.0000   0.0000


----------------------------------------------------------------------
        AVERAGES OF MONTHLY AVERAGED DAILY HEADS (INCHES)
----------------------------------------------------------------------


   DAILY AVERAGE HEAD ON TOP OF LAYER  4
   -------------------------------------
   AVERAGES          0.0003   0.0000   0.0003   0.0019   0.0014   0.0003
                     0.0001   0.0001   0.0003   0.0004   0.0011   0.0012

   STD. DEVIATIONS 0.0004   0.0000   0.0006   0.0013   0.0013   0.0005
                     0.0002   0.0005   0.0006   0.0006   0.0011   0.0010

   DAILY AVERAGE HEAD ON TOP OF LAYER  8
   -------------------------------------
   AVERAGES          0.0001   0.0000   0.0000   0.0002   0.0002   0.0001
                     0.0000   0.0000   0.0000   0.0001   0.0001   0.0002

   STD. DEVIATIONS 0.0001   0.0000   0.0001   0.0001   0.0002   0.0001
                     0.0000   0.0000   0.0001   0.0001   0.0001   0.0001

**********************************************************************
```

```
**********************************************************************
AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS    1 THROUGH   30
----------------------------------------------------------------------
                            INCHES            CU. FEET       PERCENT
                      -------------------   -------------   ---------
 PRECIPITATION           33.32    (   4.736)     120966.1     100.00

 RUNOFF                   4.476   (  2.0827)      16248.26     13.432

 EVAPOTRANSPIRATION      23.569   (  2.9703)      85556.14     70.727

 LATERAL DRAINAGE        5.23801 (  1.99898)     19013.992   15.71844
 COLLECTED FROM LAYER  3

 PERCOLATION/LEAKAGE    0.00223 (  0.00082)         8.111     0.00671
 THROUGH LAYER  5

 AVERAGE HEAD ON TOP             0.001 (    0.000)
   OF LAYER  4

 LATERAL DRAINAGE       0.00223 (  0.00084)         8.099    0.00669
 COLLECTED FROM LAYER  7

 PERCOLATION/LEAKAGE    0.00000 (  0.00000)         0.014     0.00001
 THROUGH LAYER  9

 AVERAGE HEAD ON TOP             0.000 (    0.000)
   OF LAYER  8

 CHANGE IN WATER STORAGE  0.038   (  1.4502)        139.61      0.115

**********************************************************************
```

```
**********************************************************************
            PEAK DAILY VALUES FOR YEARS    1 THROUGH   30
----------------------------------------------------------------------
                                            (INCHES)       (CU. FT.)
                                            ----------   -------------

      PRECIPITATION                           4.11         14919.301

      RUNOFF                                  3.046        11057.7012

      DRAINAGE COLLECTED FROM LAYER  3       0.54123       1964.68140

      PERCOLATION/LEAKAGE THROUGH LAYER  5   0.000186         0.67495

      AVERAGE HEAD ON TOP OF LAYER  4            0.023

      MAXIMUM HEAD ON TOP OF LAYER  4            0.038

      LOCATION OF MAXIMUM HEAD IN LAYER  3
            (DISTANCE FROM DRAIN)               42.0 FEET

      DRAINAGE COLLECTED FROM LAYER  7       0.00009          0.31043

      PERCOLATION/LEAKAGE THROUGH LAYER  9   0.000000         0.00030

      AVERAGE HEAD ON TOP OF LAYER  8            0.001

      MAXIMUM HEAD ON TOP OF LAYER  8            0.003

      LOCATION OF MAXIMUM HEAD IN LAYER  7
            (DISTANCE FROM DRAIN)                0.0 FEET

      SNOW WATER                              6.20         22496.8086


      MAXIMUM VEG. SOIL WATER (VOL/VOL)                  0.4360

      MINIMUM VEG. SOIL WATER (VOL/VOL)                  0.1818


   ***  Maximum heads are computed using McEnroe's equations.  ***

            Reference:   Maximum Saturated Depth over Landfill Liner
                         by Bruce M. McEnroe, University of Kansas
                         ASCE Journal of Environmental Engineering
                         Vol. 119, No. 2, March 1993, pp. 262-270.


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**********************************************************************
                FINAL WATER STORAGE AT END OF YEAR   30
----------------------------------------------------------------------
                     LAYER        (INCHES)        (VOL/VOL)
                     -----        --------        ---------
                       1           2.0112           0.3352

                       2          11.0167           0.3672

                       3           0.0025           0.0125

                       4           0.0000           0.0000

                       5          10.2480           0.4270

                       6         725.3281           0.2920

                       7           1.5720           0.1310

                       8           0.0000           0.0000

                       9          25.6200           0.4270

                   SNOW WATER      0.442

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```

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******************************************************************************
******************************************************************************
**                                                                          **
**                                                                          **
**              HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE               **
**             HELP MODEL VERSION 3.07  (1 NOVEMBER 1997)                   **
**              DEVELOPED BY ENVIRONMENTAL LABORATORY                       **
**                USAE WATERWAYS EXPERIMENT STATION                         **
**            FOR USEPA RISK REDUCTION ENGINEERING LABORATORY               **
**                                                                          **
**                                                                          **
******************************************************************************
******************************************************************************


 PRECIPITATION DATA FILE:     C:\SOURCE\zion\precip3b.D4
 TEMPERATURE DATA FILE:       C:\SOURCE\zion\temp3b.D7
 SOLAR RADIATION DATA FILE:   C:\SOURCE\zion\solar3b.D13
 EVAPOTRANSPIRATION DATA:     C:\source\zion\evap3b.D11
 SOIL AND DESIGN DATA FILE:   C:\source\zion\fceqvr.D10
 OUTPUT DATA FILE:            C:\source\zion\fceqvr.OUT



 TIME:  15:30     DATE:   3/ 2/2020



******************************************************************************
     TITLE:  ZION LANDFILL - SITE 2 NORTH EXPANSION PC YEARS 1-30
******************************************************************************


   NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER WERE
               COMPUTED AS NEARLY STEADY-STATE VALUES BY THE PROGRAM.


                                   LAYER  1
                                   --------

                      TYPE 1 - VERTICAL PERCOLATION LAYER
                          MATERIAL TEXTURE NUMBER   8
            THICKNESS                   =      6.00   INCHES
            POROSITY                    =      0.4630 VOL/VOL
            FIELD CAPACITY              =      0.2320 VOL/VOL
            WILTING POINT               =      0.1160 VOL/VOL
            INITIAL SOIL WATER CONTENT  =      0.3129 VOL/VOL
            EFFECTIVE SAT. HYD. COND.   =  0.369999994000E-03 CM/SEC
    NOTE:  SATURATED HYDRAULIC CONDUCTIVITY IS MULTIPLIED BY  3.00
                FOR ROOT CHANNELS IN TOP HALF OF EVAPORATIVE ZONE.
```

```
                        LAYER  2
                        --------

          TYPE 1 - VERTICAL PERCOLATION LAYER
              MATERIAL TEXTURE NUMBER  12
THICKNESS                   =     30.00   INCHES
POROSITY                    =      0.4710 VOL/VOL
FIELD CAPACITY              =      0.3420 VOL/VOL
WILTING POINT               =      0.2100 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.3479 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.419999997000E-04 CM/SEC



                        LAYER  3
                        --------

            TYPE 2 - LATERAL DRAINAGE LAYER
              MATERIAL TEXTURE NUMBER  20
THICKNESS                   =      0.20   INCHES
POROSITY                    =      0.8500 VOL/VOL
FIELD CAPACITY              =      0.0100 VOL/VOL
WILTING POINT               =      0.0050 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.0127 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =   10.0000000000     CM/SEC
SLOPE                       =     10.00   PERCENT
DRAINAGE LENGTH             =    240.0    FEET



                        LAYER  4
                        --------

              TYPE 3 - BARRIER SOIL LINER
              MATERIAL TEXTURE NUMBER  16
THICKNESS                   =     36.00   INCHES
POROSITY                    =      0.4270 VOL/VOL
FIELD CAPACITY              =      0.4180 VOL/VOL
WILTING POINT               =      0.3670 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.4270 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.100000001000E-06 CM/SEC
```

```
                        LAYER  5
                        --------

          TYPE 1 - VERTICAL PERCOLATION LAYER
              MATERIAL TEXTURE NUMBER  18
THICKNESS                   =   2484.00   INCHES
POROSITY                    =      0.6710 VOL/VOL
FIELD CAPACITY              =      0.2920 VOL/VOL
WILTING POINT               =      0.0770 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.2920 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.100000005000E-02 CM/SEC



                        LAYER  6
                        --------

            TYPE 2 - LATERAL DRAINAGE LAYER
              MATERIAL TEXTURE NUMBER   0
THICKNESS                   =     12.00   INCHES
POROSITY                    =      0.4570 VOL/VOL
FIELD CAPACITY              =      0.1310 VOL/VOL
WILTING POINT               =      0.0580 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.1323 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.100000001000     CM/SEC
SLOPE                       =      2.00   PERCENT
DRAINAGE LENGTH             =    155.0    FEET



                        LAYER  7
                        --------

            TYPE 4 - FLEXIBLE MEMBRANE LINER
              MATERIAL TEXTURE NUMBER  35
THICKNESS                   =      0.06   INCHES
POROSITY                    =      0.0000 VOL/VOL
FIELD CAPACITY              =      0.0000 VOL/VOL
WILTING POINT               =      0.0000 VOL/VOL
INITIAL SOIL WATER CONTENT  =      0.0000 VOL/VOL
EFFECTIVE SAT. HYD. COND.   =  0.199999996000E-12 CM/SEC
FML PINHOLE DENSITY         =      1.00   HOLES/ACRE
FML INSTALLATION DEFECTS    =     10.00   HOLES/ACRE
FML PLACEMENT QUALITY       =  4 - POOR
```

```
                            LAYER  8
                            --------

                  TYPE 3 - BARRIER SOIL LINER
                  MATERIAL TEXTURE NUMBER  16
  THICKNESS                      =     60.00   INCHES
  POROSITY                       =      0.4270 VOL/VOL
  FIELD CAPACITY                 =      0.4180 VOL/VOL
  WILTING POINT                  =      0.3670 VOL/VOL
  INITIAL SOIL WATER CONTENT     =      0.4270 VOL/VOL
  EFFECTIVE SAT. HYD. COND.      =  0.100000001000E-06 CM/SEC




               GENERAL DESIGN AND EVAPORATIVE ZONE DATA
               ----------------------------------------

 NOTE:  SCS RUNOFF CURVE NUMBER WAS COMPUTED FROM DEFAULT
          SOIL DATA BASE USING SOIL TEXTURE # 8 WITH A
          FAIR STAND OF GRASS, A SURFACE SLOPE OF 10.%
          AND A SLOPE LENGTH OF  240. FEET.

SCS RUNOFF CURVE NUMBER            =     80.40
FRACTION OF AREA ALLOWING RUNOFF   =    100.0    PERCENT
AREA PROJECTED ON HORIZONTAL PLANE =      1.000  ACRES
EVAPORATIVE ZONE DEPTH             =     20.0    INCHES
INITIAL WATER IN EVAPORATIVE ZONE  =      6.667  INCHES
UPPER LIMIT OF EVAPORATIVE STORAGE =      9.372  INCHES
LOWER LIMIT OF EVAPORATIVE STORAGE =      3.636  INCHES
INITIAL SNOW WATER                 =      0.000  INCHES
INITIAL WATER IN LAYER MATERIALS   =    780.225  INCHES
TOTAL INITIAL WATER                =    780.225  INCHES
TOTAL SUBSURFACE INFLOW            =      0.00   INCHES/YEAR




                EVAPOTRANSPIRATION AND WEATHER DATA
                -----------------------------------

 NOTE:  EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
          MILWAUKEE             WISCONSIN

     STATION LATITUDE                         =  42.49 DEGREES
     MAXIMUM LEAF AREA INDEX                  =   2.00
     START OF GROWING SEASON (JULIAN DATE)    =    120
     END OF GROWING SEASON (JULIAN DATE)      =    289
     EVAPORATIVE ZONE DEPTH                   =  20.0  INCHES
```

```
          AVERAGE ANNUAL WIND SPEED             =   9.00 MPH
          AVERAGE 1ST QUARTER RELATIVE HUMIDITY  =  72.00 %
          AVERAGE 2ND QUARTER RELATIVE HUMIDITY  =  70.00 %
          AVERAGE 3RD QUARTER RELATIVE HUMIDITY  =  74.00 %
          AVERAGE 4TH QUARTER RELATIVE HUMIDITY  =  75.00 %


      NOTE:  PRECIPITATION DATA WAS SYNTHETICALLY GENERATED USING
               COEFFICIENTS FOR    MILWAUKEE          WISCONSIN

               NORMAL MEAN MONTHLY PRECIPITATION (INCHES)

JAN/JUL      FEB/AUG      MAR/SEP      APR/OCT      MAY/NOV      JUN/DEC
-------      -------      -------      -------      -------      -------
 1.60         1.40         2.15         3.73         3.44         3.62
 3.49         4.22         3.40         2.42         2.57         2.05


      NOTE:  TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING
               COEFFICIENTS FOR    MILWAUKEE          WISCONSIN

          NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

JAN/JUL      FEB/AUG      MAR/SEP      APR/OCT      MAY/NOV      JUN/DEC
-------      -------      -------      -------      -------      -------
 20.30        24.80        34.50        45.10        56.30        66.20
 71.50        70.30        62.80        51.30        38.60        26.10


   NOTE:  SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING
               COEFFICIENTS FOR    MILWAUKEE          WISCONSIN
                AND STATION LATITUDE   =  42.49 DEGREES




**********************************************************************
    AVERAGE MONTHLY VALUES IN INCHES FOR YEARS    1 THROUGH   30
----------------------------------------------------------------------

                  JAN/JUL  FEB/AUG  MAR/SEP  APR/OCT  MAY/NOV  JUN/DEC
                  -------  -------  -------  -------  -------  -------
  PRECIPITATION
  -------------
  TOTALS             1.50     1.28     2.10     3.62     3.29     3.72
```

```
                   2.94     4.05     3.51     2.43     2.47     2.39

 STD. DEVIATIONS   0.70     0.63     0.89     1.68     1.41     1.76
                   1.63     1.90     1.31     0.95     1.22     1.04

 RUNOFF
 ------
 TOTALS           0.359    0.923    1.920    0.734    0.048    0.053
                  0.009    0.110    0.068    0.012    0.062    0.178

STD. DEVIATIONS   0.430    0.851    1.264    0.971    0.138    0.158
                  0.032    0.203    0.157    0.032    0.156    0.339

 EVAPOTRANSPIRATION
 ------------------
 TOTALS           0.474    0.391    0.557    2.605    3.442    4.309
                  3.392    3.423    2.349    1.342    0.827    0.458

 STD. DEVIATIONS  0.093    0.123    0.330    0.948    0.986    1.059
                  1.371    1.445    0.786    0.288    0.175    0.101

 LATERAL DRAINAGE COLLECTED FROM LAYER  3
 ----------------------------------------
 TOTALS          0.1609   0.0018   0.1925   1.2710   0.9388   0.1746
                 0.0350   0.0677   0.2029   0.2605   0.7337   0.7954

 STD. DEVIATIONS 0.2839   0.0076   0.4030   0.9270   0.8869   0.3291
                 0.1108   0.3342   0.4075   0.4215   0.7775   0.6724

 PERCOLATION/LEAKAGE THROUGH LAYER  4
 ------------------------------------
 TOTALS          0.0304   0.0008   0.0072   0.0662   0.0793   0.0312
                 0.0094   0.0030   0.0211   0.0292   0.0540   0.0736

 STD. DEVIATIONS 0.0339   0.0033   0.0155   0.0324   0.0316   0.0310
                 0.0225   0.0083   0.0334   0.0379   0.0391   0.0351

 LATERAL DRAINAGE COLLECTED FROM LAYER  6
 ----------------------------------------
 TOTALS          0.0396   0.0024   0.0044   0.0569   0.0821   0.0379
                 0.0111   0.0023   0.0186   0.0285   0.0489   0.0723

 STD. DEVIATIONS 0.0346   0.0071   0.0105   0.0328   0.0258   0.0316
                 0.0232   0.0059   0.0311   0.0378   0.0383   0.0336

 PERCOLATION/LEAKAGE THROUGH LAYER  8
 ------------------------------------
 TOTALS         0.0000   0.0000   0.0000   0.0000   0.0001   0.0000
                0.0000   0.0000   0.0000   0.0000   0.0000   0.0000
```

```
  STD. DEVIATIONS 0.0000   0.0000   0.0000   0.0000   0.0000   0.0000
                  0.0000   0.0000   0.0000   0.0000   0.0000   0.0000


----------------------------------------------------------------------
        AVERAGES OF MONTHLY AVERAGED DAILY HEADS (INCHES)
----------------------------------------------------------------------


  DAILY AVERAGE HEAD ON TOP OF LAYER  4
  ------------------------------------
  AVERAGES        0.0002   0.0000   0.0003   0.0018   0.0013   0.0002
                  0.0000   0.0001   0.0003   0.0004   0.0010   0.0011

  STD. DEVIATIONS 0.0004   0.0000   0.0006   0.0013   0.0012   0.0005
                  0.0002   0.0005   0.0006   0.0006   0.0011   0.0009

  DAILY AVERAGE HEAD ON TOP OF LAYER  7
  ------------------------------------
  AVERAGES        0.0175   0.0011   0.0019   0.0259   0.0362   0.0173
                  0.0049   0.0010   0.0085   0.0126   0.0223   0.0319

  STD. DEVIATIONS 0.0153   0.0034   0.0046   0.0150   0.0114   0.0144
                  0.0102   0.0026   0.0142   0.0167   0.0175   0.0148

**********************************************************************


**********************************************************************
 AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS    1 THROUGH   30
----------------------------------------------------------------------
                              INCHES            CU. FEET       PERCENT
                      -------------------    ------------    ---------
 PRECIPITATION           33.32    (   4.736)     120966.1      100.00

 RUNOFF                   4.476   (  2.0827)      16248.26     13.432

 EVAPOTRANSPIRATION      23.569   (  2.9703)      85556.14     70.727

 LATERAL DRAINAGE        4.83498 (  1.90797)     17550.965   14.50899
 COLLECTED FROM LAYER  3

 PERCOLATION/LEAKAGE    0.40527 (  0.12273)      1471.141     1.21616
 THROUGH LAYER  4

 AVERAGE HEAD ON TOP             0.001 (    0.000)
   OF LAYER  4

 LATERAL DRAINAGE       0.40502 (  0.12498)      1470.223    1.21540
```

```
 COLLECTED FROM LAYER  6

 PERCOLATION/LEAKAGE    0.00026 (  0.00008)         0.937     0.00077
 THROUGH LAYER  8

 AVERAGE HEAD ON TOP             0.015 (    0.005)
   OF LAYER  7

 CHANGE IN WATER STORAGE  0.038   (  1.4499)        139.60      0.115

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            PEAK DAILY VALUES FOR YEARS    1 THROUGH   30
------------------------------------------------------------------------------
                                                    (INCHES)      (CU. FT.)
                                                   ----------    -------------
      PRECIPITATION                                   4.11         14919.301

      RUNOFF                                          3.046        11057.7012

      DRAINAGE COLLECTED FROM LAYER  3               0.53802       1953.01245

      PERCOLATION/LEAKAGE THROUGH LAYER  4           0.003404        12.35541

      AVERAGE HEAD ON TOP OF LAYER  4                    0.023

      MAXIMUM HEAD ON TOP OF LAYER  4                    0.039

      LOCATION OF MAXIMUM HEAD IN LAYER  3
            (DISTANCE FROM DRAIN)                       36.2 FEET

      DRAINAGE COLLECTED FROM LAYER  6               0.00340         12.33990

      PERCOLATION/LEAKAGE THROUGH LAYER  8               0.000002
0.00765

      AVERAGE HEAD ON TOP OF LAYER  7                    0.046

      MAXIMUM HEAD ON TOP OF LAYER  7                    0.092

      LOCATION OF MAXIMUM HEAD IN LAYER  6
            (DISTANCE FROM DRAIN)                        1.7 FEET

      SNOW WATER                                     6.20         22496.8086


      MAXIMUM VEG. SOIL WATER (VOL/VOL)                         0.4360

      MINIMUM VEG. SOIL WATER (VOL/VOL)                         0.1818

    ***  Maximum heads are computed using McEnroe's equations.  ***

            Reference:  Maximum Saturated Depth over Landfill Liner
                        by Bruce M. McEnroe, University of Kansas
                        ASCE Journal of Environmental Engineering
                        Vol. 119, No. 2, March 1993, pp. 262-270.

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*****************************************************************
              FINAL WATER STORAGE AT END OF YEAR   30
-----------------------------------------------------------------
                   LAYER       (INCHES)      (VOL/VOL)
                   -----       --------      ---------
                     1           2.0112        0.3352

                     2          11.0167        0.3672

                     3           0.0024        0.0119

                     4          15.3720        0.4270

                     5         725.3281        0.2920

                     6           1.5870        0.1322

                     7           0.0000        0.0000

                     8          25.6200        0.4270

                 SNOW WATER      0.442

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