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LANDFILL LEACHATE CLOGGING OF GEOTEXTILE (AND SOIL) FILTERS

by

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16. ABSTRACT The primary leachate collection system of most solid waste landfills contains a filter layer which has historically been a granular soil. Recently, however, various types of geotextile filters have been used to replace the natural soil filters. A project using six different landfill leachates and aimed at investigating the functioning of different geotextile filters is the focus of this 36 month long study.

The initial 12 months, referred to as Phase I, investigated flow rates in various filters under aerobic conditions at six different landfill sites using the site-specific leachates. The study inadvertently found that the overlying granular soil clogged as much as the geotextile filter that was located downstream. The effects of different types and styles of geotextiles was generally masked by the upstream soil clogging. An important finding in this task was the biodegradation of the geotextiles was not evidenced and was concluded to be a non-issue.

The subsequent 24 months of study, referred to as Phase II(a), led to the development of a vastly improved flow rate monitoring device.

In a separate task, referred to as Phase II(b) and conducted simultanteously with Phase II(a), biocide treated geosynthetics were utilized at the two sites with the most aggressive leachates. While the biocides may have been effective in killing micro-organisms, the remnants were as troublesome as the viable bacteria in creating subsequent clogging.

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FOREWORD

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

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

This publication is one of the products of that research and provides a vital communication link between the researcher and the user community. This document focuses on the generation of simulated field test data relevant to the design, construction and performance of landfill leachate collection systems. The data provided influences design and performance of all such systems which rely upon leachate collection and removal.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

ABSTRACT

The primary leachate collection system of most solid waste landfills contains a filter layer which has typically been a granular soil. Recently, however, various types of geotextile filters have been used to replace the natural soil filter. Natural soil filters are designed using conventional geotechnical engineering practice and these techniques have been modified and adapted for the design of geotextile filters. A project using six different landfill leachates and aimed at investigating the functioning of these filters is the focus of this 36 month long study.

The initial 12 months, referred to as Phase I, investigated flow rates in geotextile filters under aerobic conditions at six different landfill sites using the site-specific leachates. The study inadvertently found that the overlying granular soil clogged as much as the geotextile filter that was located downstream. The effects of different types and styles of geotextiles was generally masked by the upstream soil clogging. A separate anaerobic incubation task under no-flow conditions showed clogging to be present but to a significantly lesser extent than with the aerobic flow tests. This clogging was felt to be completely biological in nature rather than a combination of sediment and biological processes. An important finding in this task was that biodegradation of the geotextiles was not evidenced and was concluded to be a non-issue.

The subsequent 24 months of study, referred to as Phase II, led to the development of a vastly improved flow rate monitoring device which has recently become an ASTM Standard Test Method, i.e., D1987-91, available May 1, 1991. Using these new flow columns, which are made from PVC fittings locally available at hardware stores and are very inexpensive, a wide range of variables were evaluated:

- four different styles of geotextiles
- geotextile alone versus sand/geotextile filters
- anaerobic versus aerobic conditions
- six (very different) landfill leachates

The above 96 columns ($4 \times 2 \times 2 \times 6$) were evaluated for their flow rate behavior over time and found to essentially replicate the first year's aerobic test results. Varying degrees of clogging by sediment (particulates) and micro-organisms did occur for the various geotextile and natural soil filters which were evaluated.

After establishing this point, a series of remediation attempts were evaluated. The flow rate conditions showed measurable improvement. Water backflushing was the most effective, leachate backflushing and nitrogen gas backflushing were intermediate, and vacuum extraction was least effective. If remediation is attempted, the periodicity of remediation should probably be on a six month cycle.

In a separate third task, biocide treated geosynthetics were utilized at the two sites with the most aggressive leachates. While the biocides may have been effective in killing micro-organisms, the remnants were as troublesome as the viable bacteria in creating subsequent clogging.

As final recommendations regarding geotextile and soil filters placed over different types of leachate drains it is felt that:

(a) Under the continuous flow of landfill leachate a gradually decreasing flow rate will occur for all types of filters (soil or geotextile) eventually reaching a terminal value.

(b) The terminal value of flow rate will vary according to the type of filter, the type of leachate and the hydraulic gradient.

(c) The terminal flow rate for any given filter system must be compared to the design required flow rate to ultimately assess the adequacy of the filter's design.

(d) Design criteria should be developed which considers the amount, size and type of microorganisms and sediment present in the leachate along with conventional issues such as hydraulic gradient and type of filter.

(e) Leachate collection systems at landfills which are decommissioned, or exhumed for other reasons, should be investigated in light of the above recommendations.

(f) This particular project should be followed by another effort aimed at a larger variety of geotextile filters along with design guidance and field performance of existing systems.

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The cooperation of the six landfill owner/operators whose sites were utilized in this study was also invaluable. We offer this acknowledgement anonymously at the respect of their wishes.

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INTRODUCTION AND SCOPE

The management of liquids within a landfill represents a key element in their proper functioning and overall design concept. The liquid itself comes from moisture within the waste as it is received and placed in the facility, plus any precipitation that falls on the site during its working lifetime. This total liquid is referred to as "leachate" since it leaches various constituents from the waste itself. Leachate varies greatly both in quality and in quantity.

Regarding the quality of leachate, it is directly related to the nature of the solid waste placed in the facility. One would naturally expect that hazardous waste leachate would be different from non-hazardous, or domestic, waste leachate; but there is even tremendous difference within each of these categories. Chian and De Walle[1] published data on the nature of domestic landfill leachates illustrating how leachates vary tremendously in their quality, see Table 1. Recently EPA[2] and Haxo[3] have reviewed landfill leachate collected in the 1980's and found numerous changes in the chemical composition. However these studies were directed at the chemical resistance of the liner system. The focus of this study is on filter clogging (rather than liner degradation) in which the precipitates and micro-organisms are of primary interest. Regarding the quantity of leachate, both the waste itself and the geographic location of the facility are important. For example, sewage sludge is often intermingled with municipal solid waste resulting in a much higher liquid content than a landfill accepting construction demolition debris. Perhaps more importantly, as far as leachate quantity is concerned, is the geographic location of the landfill vis-a-vis the local amount of precipitation. Identical landfills sited in the Seattle, Philadelphia and Las Vegas areas will have quantities of leachate directly reflecting their local precipitation, i.e., a greater quantity would be generated in Seattle than in Philadelphia, which in turn will be greater than Las Vegas. The HELP computer model is a valuable tool in estimating leachate quantities, see Schroeder, et al.[4]

Whatever the quality and quantity of leachate, it will move gravitationally downgradient through the waste material to the base of the landfill where it encounters the primary leachate collection and removal system. Here the leachate is accepted into a drainage layer (generally gravel, but also other high permeability material like geonets and geocomposites), where it travels to a perforated pipe system. Within the perforated pipe, its velocity is greatly increased as it travels to a sump area at the low elevation end of the facility. A submersible pump is then used which lifts the collected leachate out of the sump into a manhole or large diameter pipe, where it is transported for proper treatment and subsequent

Table 1 - Characteristics of Leachates Generated in a Landfill by Solid Waste Materials, after Chian and DeWalle[1]

Property Measured	Value (mg/L)*
Chemical oxygen demand (COD)	40 - 89,520
Biological oxygen demand (BOD)	81 - 33,360
Total organic carbon (TOC)	256 - 28,000
pH	3.7 - 8.5
Total solids (TS)	0 - 59,200
Total dissolved solids (TDS)	584 - 44,900
Total suspended solids (TSS)	10 - 700
Specific conductance	2810 - 16,800
Alkalinity ($CaCO_3$)	0 - 20,800
Hardness ($CaCO_3$)	0 - 22,800
Total phosphorus (P)	0 - 130
Ortho-phosphorus (P)	6.5 - 85
$NH_4 - N$	0 - 1106
$NO_3 + NO_2 - N$	0.2 - 10.29
Calcium (Ca^{2+})	60 - 7200
Chlorine (Cl^-)	4.7 - 2467
Sodium (Na^+)	0 - 7700
Sulfate $(-SO_3)^{2+}$	1 - 1558
Manganese (Mn)	0.09 - 125
Magnesium (Mg)	17 - 15,600
Iron (Fe)	0 - 2,820
Zinc (Zn)	0 - 370
Copper (Cu)	0 - 9.9
Cadmium (Ca)	0.03 - 17
Lead (Pb)	≤0.10 - 2.0

*All values in milligrams per liter, except specific conductance, which is in microseismens per centimeter, and pH, which is in pH units.

disposal. Figure 1 shows two different concepts of the general scheme just described. One concept has entirely natural soil materials and the other is a hybrid between natural and geosynthetic materials.

One important item not mentioned previously, but is illustrated in both profiles in Figure 1, is the filter material located between the waste and drainage material. In Figure 1(a) it is depicted as a sand, while in Figure 1(b) it is shown as a geotextile. *This filter layer is the complete focus of this project.*

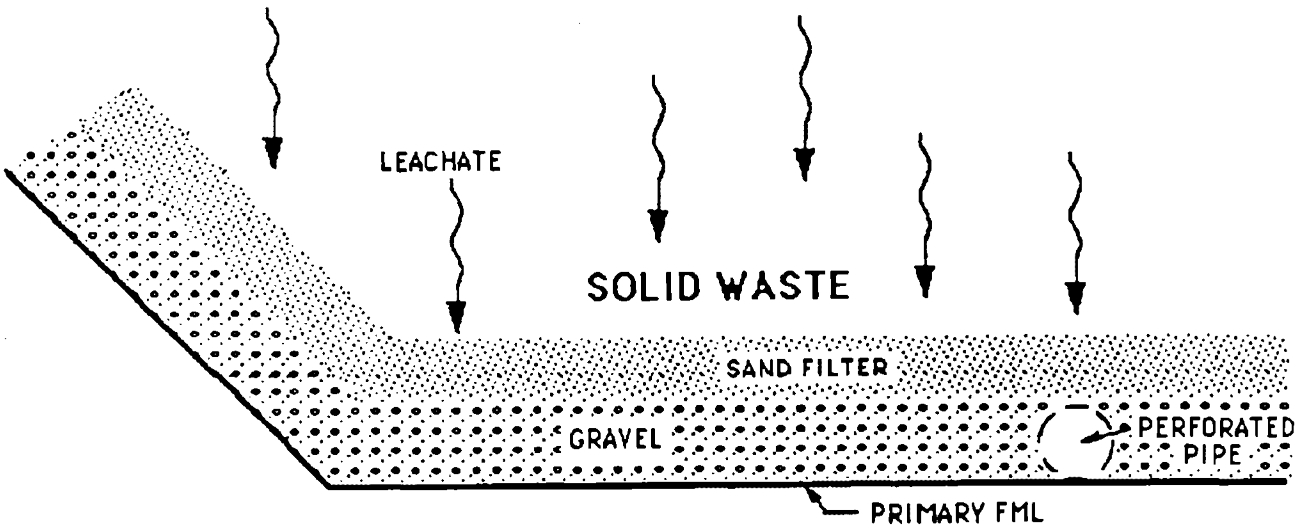
The logic of a filter layer placed upstream of a drainage layer in a landfill is the same as that of a filter placed in an earth dam, behind a retaining wall, adjacent to a highway, etc., i.e., its function is that of filtration. Three mechanisms are required for the success of such filter materials:

- They must be sufficiently permeable to pass liquid while minimizing upstream pore water pressure.
- They must be sufficiently tight to prevent excessive loss of upstream soil.
- They must not completely clog, or shutoff flow, during their service lifetime.

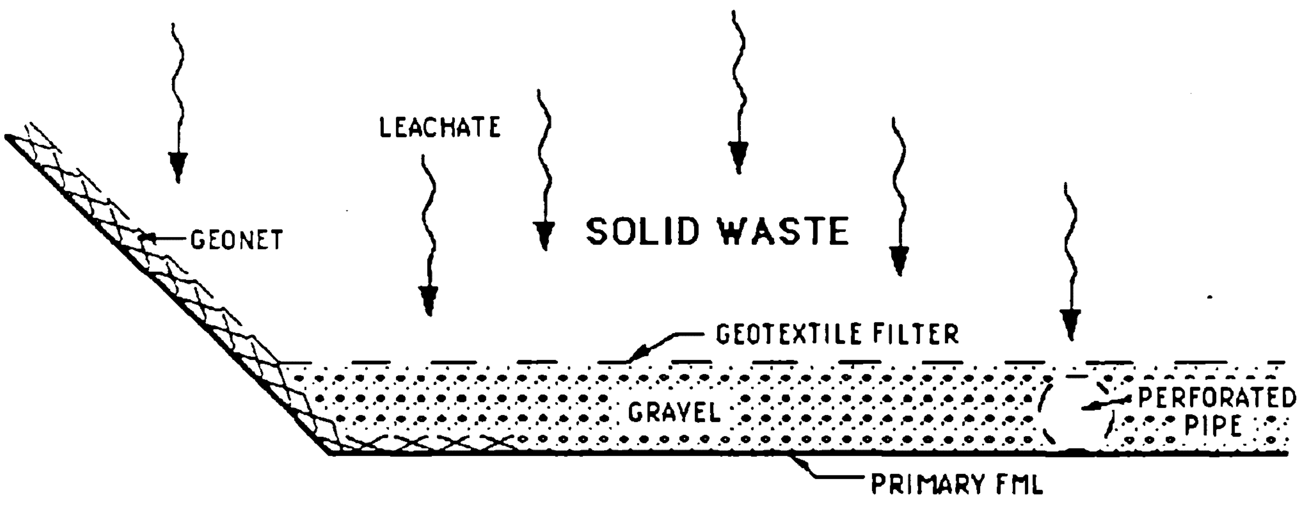
There is a long, and quite successful, history pertaining to the use of natural soil filters in geotechnical engineering and transportation engineering practice. Various theoretical and empirical rules have been established to the point where a relatively high degree of confidence exists. These concepts are taught regularly in colleges and universities in a number of engineering and science courses.

The advent of geotextile filters is a relatively recent event. Their use versus natural soil filters is very provocative. They use less space, are easier to transport, are easier to place and invariably are less expensive. While there is an ever growing list of successful geotextile filters (the earliest dating back to 1968, see Barrett[5]), their use with landfill leachate instead of water is much less established. Thus, the initial focus of this project was toward an investigation of geotextile filters in the landfill environment. However, as the project developed, it was recognized that the soil filters had to be re-examined in light of their leachate filtration. Thus it will become evident that both geotextile filters and natural soil filters have drawn our attention and will be equally examined in this study.

The report covers the entirety of this three-year project which was performed in three separate phases. The first phase (which lasted 12 months) turned out to be somewhat exploratory. It resulted in the development of a testing program which was successful in its general findings but proved to be inadequate in providing specific detail, mainly due to an



(a) Natural Soil Collection System



(b) Geosynthetic Collection System

Figure 1 - Generalized cross sections of primary leachate collection systems for solid waste landfills

inadequate test setup methodology. It, however, will be presented in its entirety since its qualitative findings are relevant. The second phase (lasting 24 months), greatly improved on the measurement methodology. This improvement ultimately led to a test setup and a set of procedures which has recently been adapted by ASTM as a Standard Test Method. It provided quite extensive and detailed quantitative information. Within this second phase a number of biological related clogging remediation techniques were investigated.

A third effort was directed toward the study of biocide treated geonets and geotextiles. It was performed over a 14 month period coincident with the Phase II study. This study is included in this Report as Appendix "A". Collectively, results of these different Phases have supplied the background information leading toward our final conclusions and recommendations.

GEOTEXTILES AND SOILS USED IN THIS STUDY

Various cross sections of different materials, all of which attempt to simulate the profiles shown in Figure 1, were utilized. The first phase of the study used a sand/geotextile/geonet cross section, as was illustrated in Figure 1(b) and is often located on the sidewalls of a landfill. These tests were aerobic* and involved percolating leachate moving vertically through the sand and geotextile, followed by horizontal flow within the geonet. There also were parallel studies conducted on the various geotextiles which were constantly submerged in leachate, thus anaerobic* conditions. The six different geotextiles are listed in Table 2(a), with their relevant physical and mechanical properties given in Table 2(b). The sand used in the aerobic tests was a subrounded uniform size, Ottawa sand with a 0.42 mm (No. 40 sieve) average particle size. Its hydraulic conductivity is approximately 0.02 cm/sec (0.04 ft/min). Since the hydraulic conductivity of the sand is high, it was felt that clogging could develop in either it or in the geotextile. As will be seen later, usually the sand clogged before the geotextile.

The second phase of the study used sand/geotextile/gravel and geotextile/gravel cross sections to simulate the sketches of Figures 1(b) and 1(a), respectively. They were constantly counterpointed against one another to see if either the sand or the geotextiles were more susceptible to clogging. The geotextiles evaluated are given in Table 3(a), along with their physical and mechanical properties which are included in Table 3(b). The sand used above the geotextiles (when it was used) was again a subrounded, uniform size, Ottawa sand with a 0.42 mm (No. 40 sieve) average particle size. Its hydraulic conductivity is approximately 0.02 cm/sec (0.04 ft/min). It was the same type of sand used in the tests of the first phase described earlier. The gravel located beneath the geotextile was 1.0 to 1.5 inch in diameter and was used as a support when placing soil above the geotextile. Its openings are so large that flow was considered to be unimpeded when passing through this layer. Subsequent visual examination after the testing was complete confirmed this assumption. Both aerobic and anaerobic conditions were evaluated. The actual test device was vastly improved in contrast to the setup used in the phase one tests.

*Aerobic, referring to alternately wet and dry conditions, and anaerobic, referring to constantly saturated, will be used throughout this report. While the aerobic description is accurate, it is recognized that keeping a system saturated does not guarantee "complete" anaerobic conditions. It does, however, describe how the samples were maintained and subsequently tested.

Table 2 - Description of Geotextiles Used in Phase One of This Study

(a) Description of Geotextiles

Type of Fabric Construction	Polymer Type	Filament Type	Designation and Polymer Type	Used at Site Number 1	2	3	4	5	6
woven monofilament (calendered)	polypropylene	continuous	W (C)-PP	√	√	√	√		
woven monofilament (non-calendered)	polypropylene	continuous	W (N)-PP	√				√	√
nonwoven needled	polypropylene	continuous	NW (N)-PP1	√	√	√	√	√	√
nonwoven needled	polyester	continuous	NW (N)-PET	√	√	√	√	√	√
nonwoven needled	polypropylene	staple	NW (N)-PP2	√	√				
nonwoven needled	polyethylene	continuous	NW (N)-PE			√	√	√	√
nonwoven heat bonded	polypropylene	continuous	NW (HS)-PP					√	√

(b) Physical and Mechanical Properties of Geotextiles

Designation and Polymer Type	Thickness(1)* (mil)	(mm)	Mass per Unit Area (oz/yd^2)	(g/m^2)	POA(2) (%)	AOS(3) O_{95} (mm)	(Sieve No.)	Permittivity(4) (sec^{-1})	Hydraulic Conductivity (cm/sec)	(ft/min)
W (C)-PP	14	0.36	5.9	200	4	0.21-0.15	70 - 100	0.14	0.005	0.010
W (N)-PP	20	0.51	6.5	220	10	0.42-0.21	40 - 70	2.3	0.12	0.24
NW (N)-PP1	87	2.2	8.3	280	n/a	0.21-0.15	70 - 100	2.1	0.46	0.92
NW (N)-PET	75	1.9	7.1	240	n/a	0.21-0.15	70 - 100	2.0	0.38	0.76
NW (N)-PP2	102	2.6	7.7	260	n/a	0.21-0.15	70 - 100	1.8	0.47	0.94
NW (N)-PE	110	2.8	13.3	450	n/a	0.21-0.15	70 - 100	0.96	0.27	0.54
NW (HB)-PP	17	0.43	4.1	140	n/a	$\simeq$0.15	$\simeq$ 100	0.65	0.028	0.056

* (1) Under 43 lb/ft^2 (2.0 kPa) normal pressure
(2) Percent open area
(3) Apparent opening size
(4) Constant head test at 2.0 in. (50 mm) head

Table 3 - Description of Geotextiles Used in Phase Two of This Study

(a) Physical Description of Geotextiles

Type of Fabric Construction	Polymer Type	Filament Type	Designation	Used at Site Number 1	2	3	4	5	6
woven monofilament (non-calendered)	polypropylene	continuous	WM (NC)	√	√	√	√	√	√
nonwoven heat bonded	polypropylene	continuous	NW (HB)	√	√	√	√	√	√
nonwoven needled	polyester	continuous	NW (N) 16	√	√	√	√	√	√
nonwoven needled	polyester	continuous	NW (N) 8	√	√	√	√	√	√

(b) Physical and Mechanical Properties of Geotextiles

Designation	Thickness[1]* (mil)	(mm)	Mass per Unit Area (oz/yd^2)	(g/m^2)	POA[2] (%)	AOS[3] O_{95} (mm)	(Sieve No.)	Permittivity[4] (sec^{-1})	Hydraulic Conductivity (cm/sec)	(ft/min)
WM (NC)	24	0.61	7.0	240	6.0	0.21	70	1.2	0.073	0.14
NW (HB)	16	0.41	4.0	140	n/a	0.21-0.15	70-100	0.6	0.025	0.049
NW (N) 16	195	4.9	16.0	540	n/a	0.21	70	0.7	0.35	0.69
NW (N) 8	93	2.4	8.0	270	n/a	0.15	100	1.4	0.33	0.65

* (1) Under 43 lb/ft^2 (2.0 kPa) normal pressure
(2) Percent open area
(3) Apparent opening size
(4) Constant head test at 2.0 in. (50 mm) head

The biocide study mimicked the second phase of testing, with the exception that the geotextiles (or geonets) were manufactured with the inclusion of varying amounts of biocide. The geotextiles and sand that were used, along with the results, are included in Appendix "A".

LANDFILL SITE AND LEACHATE CHARACTERISTICS

Upon obtaining proper authorization and permission from the respective facility owners, six landfills located within 200 miles of Philadelphia, Pennsylvania were utilized for this study*. All six sites were used for the entire duration of this three year study. All were municipal (i.e., domestic) landfills, however, some were intermingled with industrial waste of various types and amounts. The amount of waste placed at each site varied tremendously; from 100 to 8,000 tons per day. Perhaps more importantly, the leachate management scheme, along with the age of the facilities varied; thus, the quality of the leachate varied greatly. Table 4 gives what we feel are the most important leachate characteristics for the purpose of filter assessment, i.e., the pH, COD, TS and BOD_5 values. Table 4(a) gives the values at the time of the project's start-up, and Table 4(b) gives the comparable values at the project's completion some three years later.

To be noted from the COD, TS and BOD_5 values listed in Table 4 is that each set of data appears related to a particular landfill's leachate. In essence, when the COD is high, so are the TS and BOD_5 values; similarly when one is low, the others are also low. (There is no clear relationship to the pH values.) An ordering of the leachate strengths at the beginning of the study ranging from "strongest" to "weakest" can be established as follows:

NJ4	strongest leachate
DE3	↑
NY 2	
PA1	to
PA6	↓
MD5	weakest leachate

Furthermore, there are additional clearly distinct differences between the NJ4 and DE3 leachates, both of which are very strong, and the NY2, PA1, PA6 and MD5 leachates, all of which are relatively weak. It was anticipated that this general trend in leachate quality should have some relationship with the long term flow trends to be established in the actual testing. Two values in this table are particularly significant, the total solids (TS) and the biochemical oxygen demand (BOD). It stands to reason that the higher the TS value, the more sediment and particulate material is in the leachate; and the filter (either natural soil or geotextile) must cope with this fine material. It is important to note that filters are designed on the basis of their upstream soil particles and not on the sediment or turbidity of the liquid passing through them. In a similar manner, the higher the BOD values, the more micro-organisms (various

*All sites will remain anonymous in this Report. We sincerely thank the owners of these facilities for giving us access to their sites and extend special appreciation to the field personnel for their excellent cooperation.

Table 4 - Details of Municipal Landfill Leachates Evaluated in this Study and Approximate Leachate Characteristics

(a) Characteristics at the Start-Up Date for Each Site

Site Designation	Start-Up Date	Leachate Management Scheme	Approximate Leachate Characteristics at Start-Up			
			pH	COD (mg/L)*	TS (mg/L)	BOD_5 (mg/L)
PA-1	Nov. 18, 1987	Continuously Removed	8.0	15,000	8,000	2,000
NY-2	Dec. 10, 1987	Recycled through Landfill and Continuously Removed	5.5	20,000	8,000	5,000
DE-3	Jan. 25, 1988	Recycled through Landfill	5.8	40,000	17,000	24,000
NJ-4	April 5, 1988	Continuously Removed	7.4	45,000	16,000	25,000
MD-5	June 6, 1988	Continuously Removed	6.8	1,000	100	150
PA-6	June 28, 1988	Continuously Removed	6.5	10,000	5,000	2,500

(b) Characteristics at the Termination of the Project for Each Site

Site Designation	Date of Final Readings	Leachate Management Scheme	Approximate Leachate Characteristics at Completion			
			pH	COD (mg/L)	TS (mg/L)	BOD_5 (mg/L)
PA-1	Oct. 29, 1990	Continuously Removed	8.0	10,500	5,000	3,000
NY-2	Oct. 30, 1990	Continuously Removed	6.3	13,000	7,000	5,000
DE-3	Oct. 31, 1990	Recycled through Landfill	6.5	25,000	15,000	15,000
NJ-4	Oct. 30, 1990	Continuously Removed	7.0	30,000	17,000	17,000
MD-5	Oct. 31, 1990	Continuously Removed	7.1	17,000	20,000	7,000
PA-6	Oct. 29, 1990	Continuously Removed	6.3	7,000	18,000	2,500

*COD = chemical oxygen demand
TS = total solids content
BOD_5 = biochemical oxygen demand at five days

forms of bacteria) that are present in the leachate. Here again, the filter must cope with these micro-organisms with the hope that they will pass through the filter and be removed with the leachate from within the downgradient sump area. An indication of the size of the sediment <u>and</u> micro-organisms in the six different leachates is given in Figure 2. Both types of particulates fall in a relatively tight size range almost entirely within the silt-size classification. For comparison purposes, the particle size of the Ottawa sand used above the geotextiles is also shown.

In addition to the high BOD_5 values shown in Table 4(a), a further indication of the bacteria present in the leachates at the six selected landfill sites is given in Figure 3. Figure 3(a) presents the number of biological cells per milliliter of leachate established by total direct count. Note that the vertical scale is logarithmic and the values range between 10^8 and 10^9 cells per ml. The values were obtained microscopically in a separate study which is given in detail in Rios and Gealt[6]. Within this total count, the number of living cells, called the "viable titer" is given in Figure 3(b). While considerable scatter exists, the numbers are still huge, i.e., between 10^6 and 10^7 *living* biological cells exist per ml of leachate. This represents 35 to 60% of the total count. Other details as to likely type of bacteria, techniques for counting, etc., are given in the reference cited. *As anticipated, biological activity exists in municipal waste landfill leachates on a massive scale.*

Lastly, the possibility of a clogging synergism between sediment in the leachate coupled with high micro-organism content cannot be discounted. Indeed there are references available suggesting the possibility of landfill drainage system clogging. Bass[7] presented several case histories of sedimentation, biological growth and chemical precipitation clogging of leachate collection systems. He states, "it would be difficult to rule out biological clogging as a failure mechanism based on first principles". Ramke[8] states in his report on German landfill experiences, "the most frequent cause for failure is formation of deposits in the seepage water collectors or in the filter layer".

Thus, the realization that some clogging of collection systems might occur should be acknowledged. What remains at issue is what is the degree of clogging; and, if felt to be excessive, what techniques are available to remediate the situation. This research effort, presented in separate phases, attempts to answer these questions. Phase One is for 12 months duration and Phase Two (with improved monitoring devices and a series of remediation attempts) is for 24 months duration. They will be presented sequentially in the next two Chapters. Phase Three, on biocide treated geotextiles and geonets is included as an Appendix.

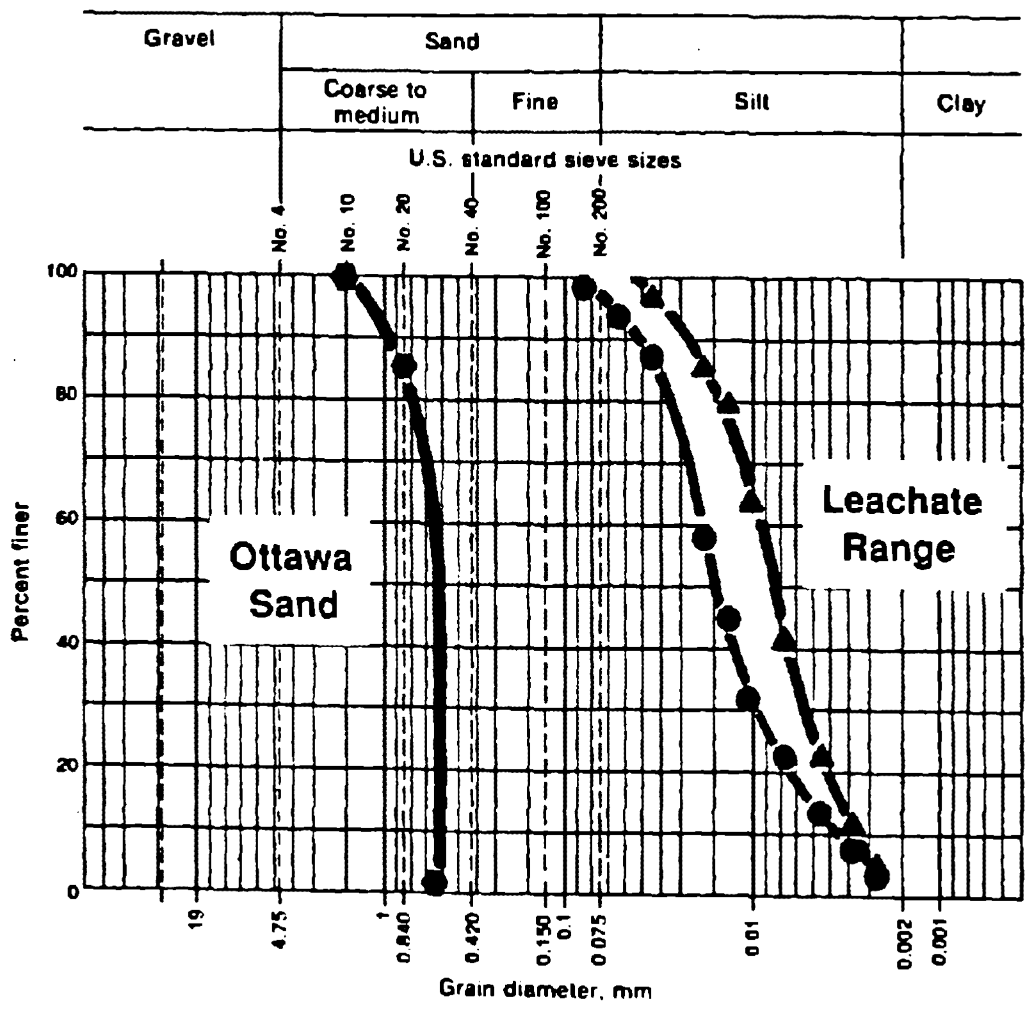
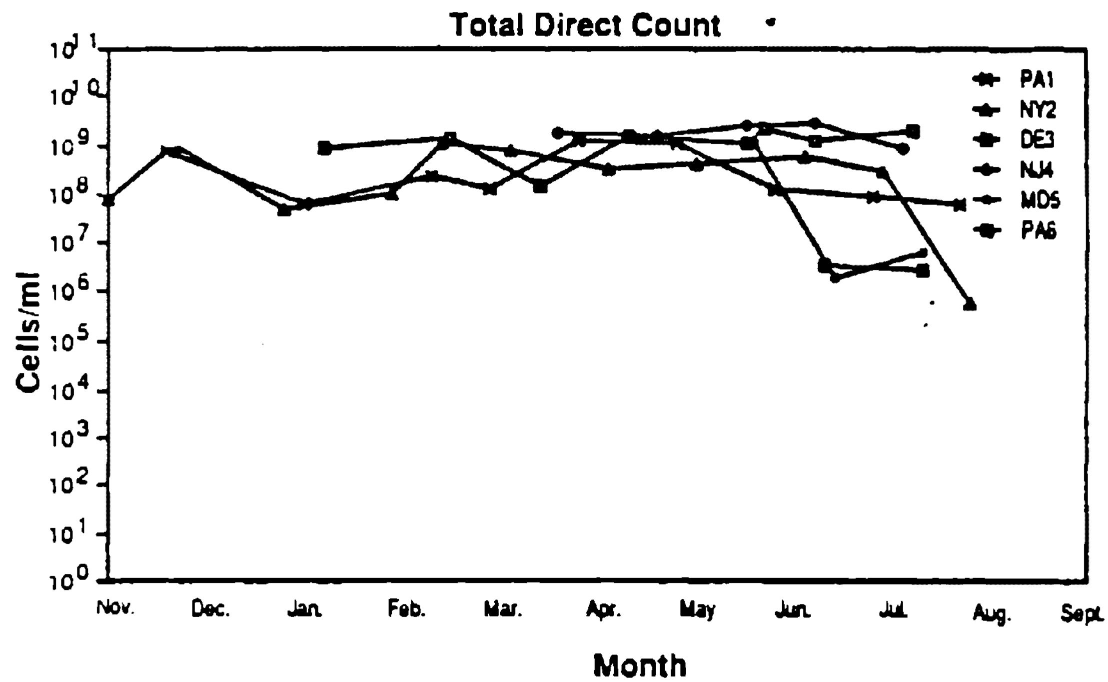


Figure 2 - Particle size range of sediment and micro-organisms in the landfill leachates with Ottawa sand shown for comparison



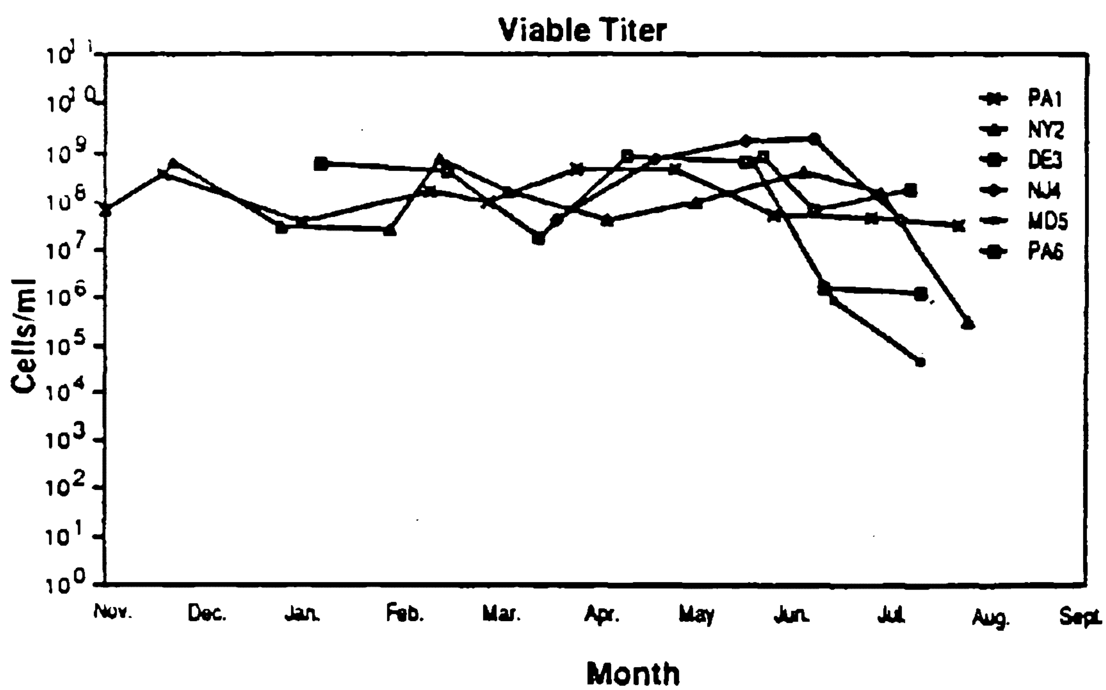


Figure 3 - Total bacteria count and viable (living) count of leachate samples from the six landfill sites evaluated in this study, after Rios and Gealt[6]

PHASE I - FIRST YEAR STUDY

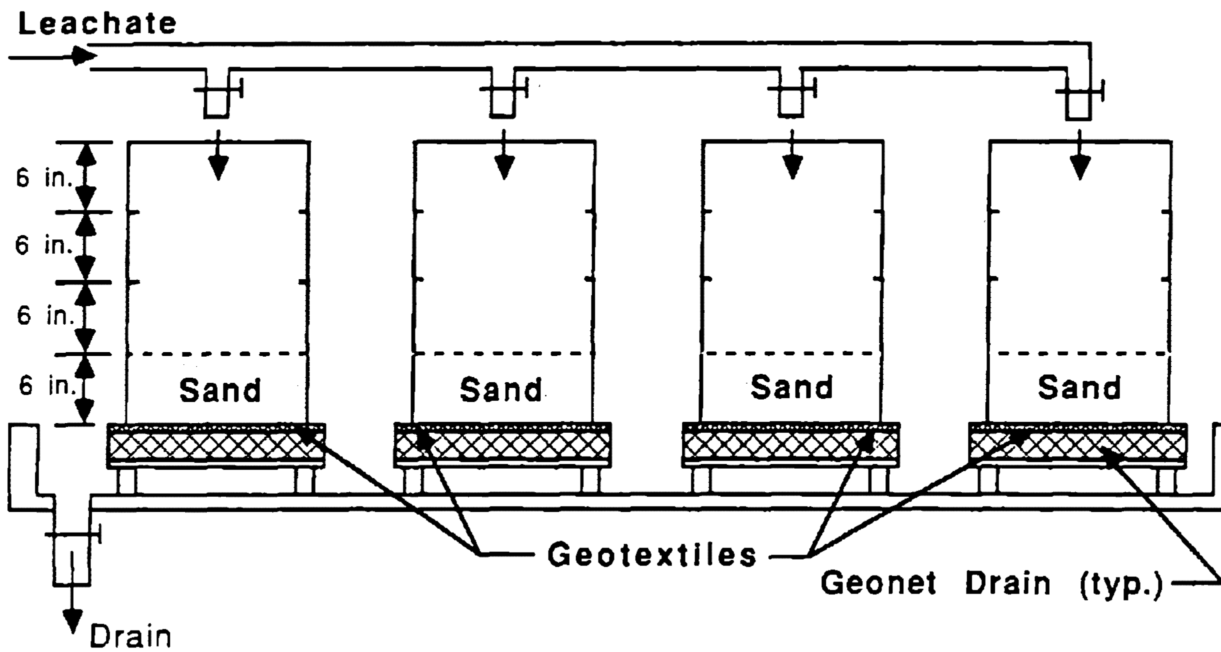
This phase of the project, which lasted for 12 months, was focused toward direct simulation of soil/geotextile/geonet cross sections under aerobic conditions and of immersed geotextiles in isolation under anaercbic conditions.

Aerobic Flow Tests and Results

The initial portion of primary leachate flow in a landfill during its filling operations is clearly aerobic. Furthermore, the collection area around the primary leachate removal sump and manhole may also be functioning under aerobic conditions. In order to model these situations, flow boxes of the type shown in Figure 4 were constructed. They were made to simulate the bottom of a landfill with the geotextile as the filter over a drain; in this case a geonet drain. Whether the drain is a geonet, gravel or perforated pipe, however, is of little direct consequence since biological and precipitate clogging is more apt to occur in the small spaces of the filter rather than the significantly larger voids of the drain, whatever its type. The use of the open graded Ottawa sand above the geotextile filters was done so that better flow control could be maintained during the 12 month long tests. The use of sand over the geotextile was meant to simulate a soil working blanket which is often placed above the primary leachate collection system before solid waste filling begins.

The wooden boxes used for these aerobic flow tests were 24 in. high with a cross section measuring 12 in. by 12 in. They were made leakproof by silicon caulking and were then painted with epoxy paint. The bottom portion of the boxes are flanged such that various geotextiles can be incorporated in them. For all of these tests, a geonet is located beneath the different geotextiles being investigated. A wooden base plate is directly beneath the geonet and it is bolted to the upper box flanges and caulked on three sides. The fourth side (i.e., the front of the box) is open which permits conveyance of the leachate out of the geonet drain after it passes through the soil/geotextile system, see the lower right side photograph of Figure 4. Ottawa sand (poorly graded, rounded particles, retained on a No. 40 size sieve) is placed on the geotextile to a depth of 6 in. leaving the upper 18 in. of the box available for falling head leachate tests.

Sets of at least four boxes (and sometimes as many as six if the landfill owners wished to evaluate their specific materials and cross sections) are setup at the landfill site near the reservoir or underground storage tanks where the leachate is temporarily stored. Usually the boxes are housed in a small shed or maintenance building with no temperature nor humidity control. Thus, ambient conditions prevail, e.g., during the winter months the boxes undoubtedly experienced freezing conditions numerous times.



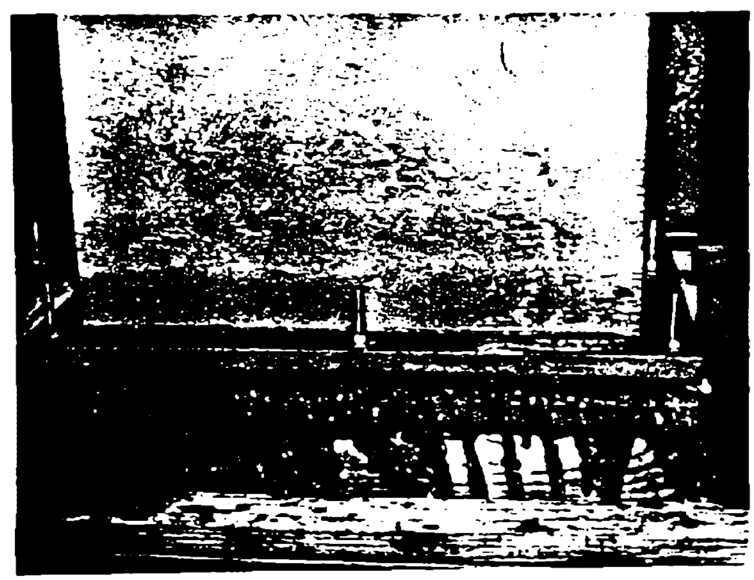


Figure 4 - Aerobic flow rate test setups and photographs of the actual flow tests in operation

The leachate from a particular landfill site is pumped to the experimental flow system either directly from the landfill sump area or from storage tanks located either above or below ground. Leachate dousing is performed on a periodic basis, which is either once or twice a month. Otherwise, the boxes and their contents are either moist or nearly dry. Thus aerobic conditions are assured. On monthly intervals, flow rate tests of a falling head nature are conducted. The time of flight for the head to fall from 24 to 18 in.; from 18 to 12 in. and from 12 to 6 in. (i.e., to the top of the sand) is measured. The resulting value obtained is the flow rate per unit area, or "flux". It is measured in units of gallons per minute per square foot of surface area, i.e. gal/min-ft^2. The results of these tests for the seven geotextiles at the six landfill sites over the 12-month test period are given as Figures 5 through 10. The actual data is given in Reference 9. They are coded according to the geotextile types listed in Table 2 and the landfill designations listed in Table 4. The following observations are made on the basis of the trends that are established in these figures.

(a) Flow rates measured after the initial startup always decreased over time. Usually the initial decrease was quite sharp.

(b) For most cases, the decrease then continued with either a linear, slightly exponential or sharply exponential trend.

(c) In some cases the flow rate decreased to a level that was not measurable, at least within the limits of our experimental system.

(d) There was some undulation of the flow rate trends which might be related to temperature effects, i.e., low viscosity (hence high flow rates) during summer months and/or high viscosity and perhaps frozen zones (hence low flow rates) during winter months.

(e) Regarding landfill site PA-1, the W(C)-PP geotextile clogged below detection limits within 4.5 months. This woven geotextile has a 4% open area and when exhumed was seen to be embedded with particulates to a high degree. Figure 11 shows photographs of this box as it was disassembled and the resulting condition of the geotextile. The lower photograph shows the open geotextile around the edges which was under the flanged portions of the box and not exposed to leachate flow. Also noted was a color difference (it was rust colored) in the sand above the geotextile. This appears to indicate the occurrence of biological clogging via iron and/or manganese precipitation. This particular box was replaced by the W(N)-PP geotextile with a 10% open area and its performance over the subsequent 6.5

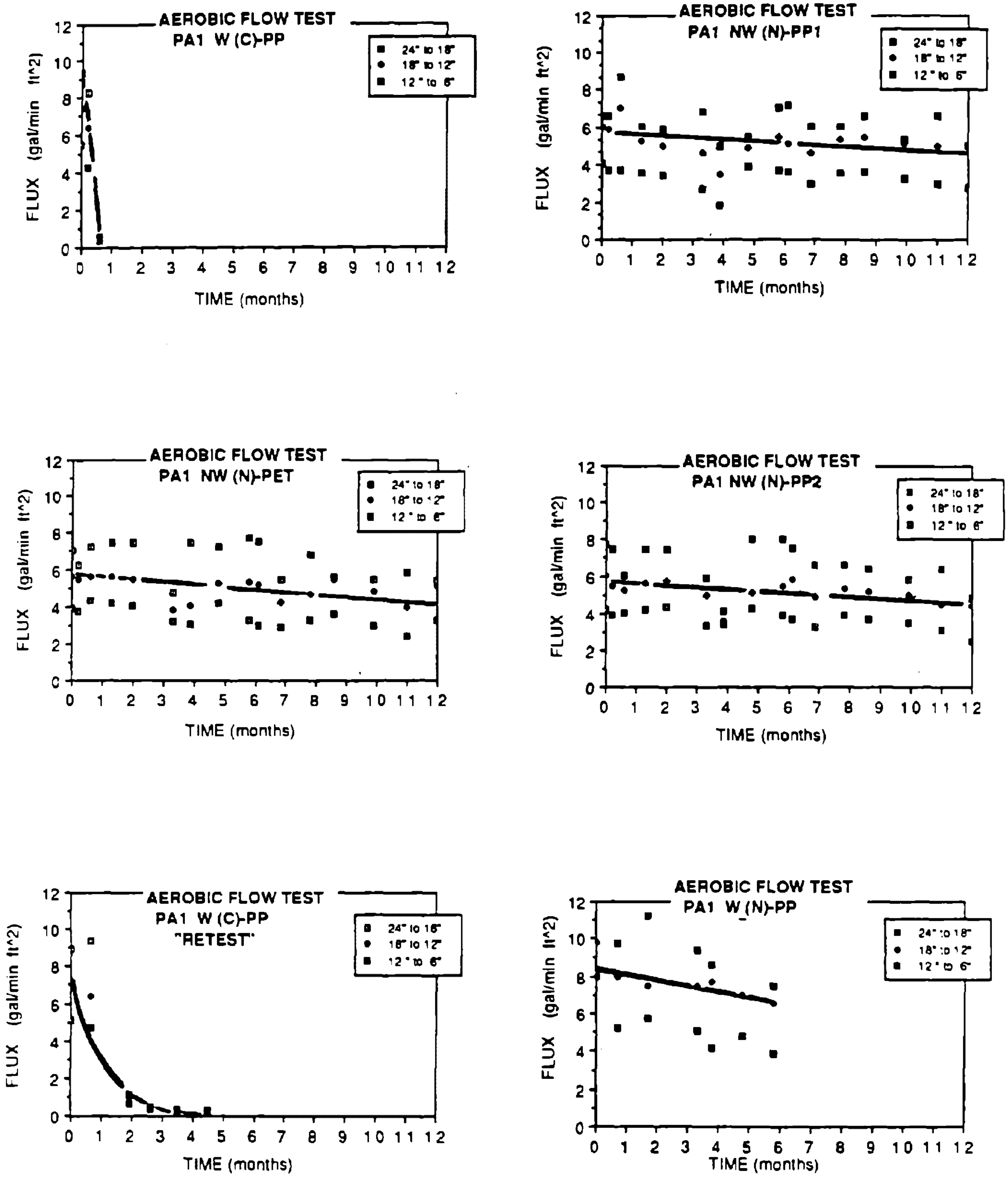


Figure 5 - Aerobic flow rate test results for all geotextiles at Site PA-1

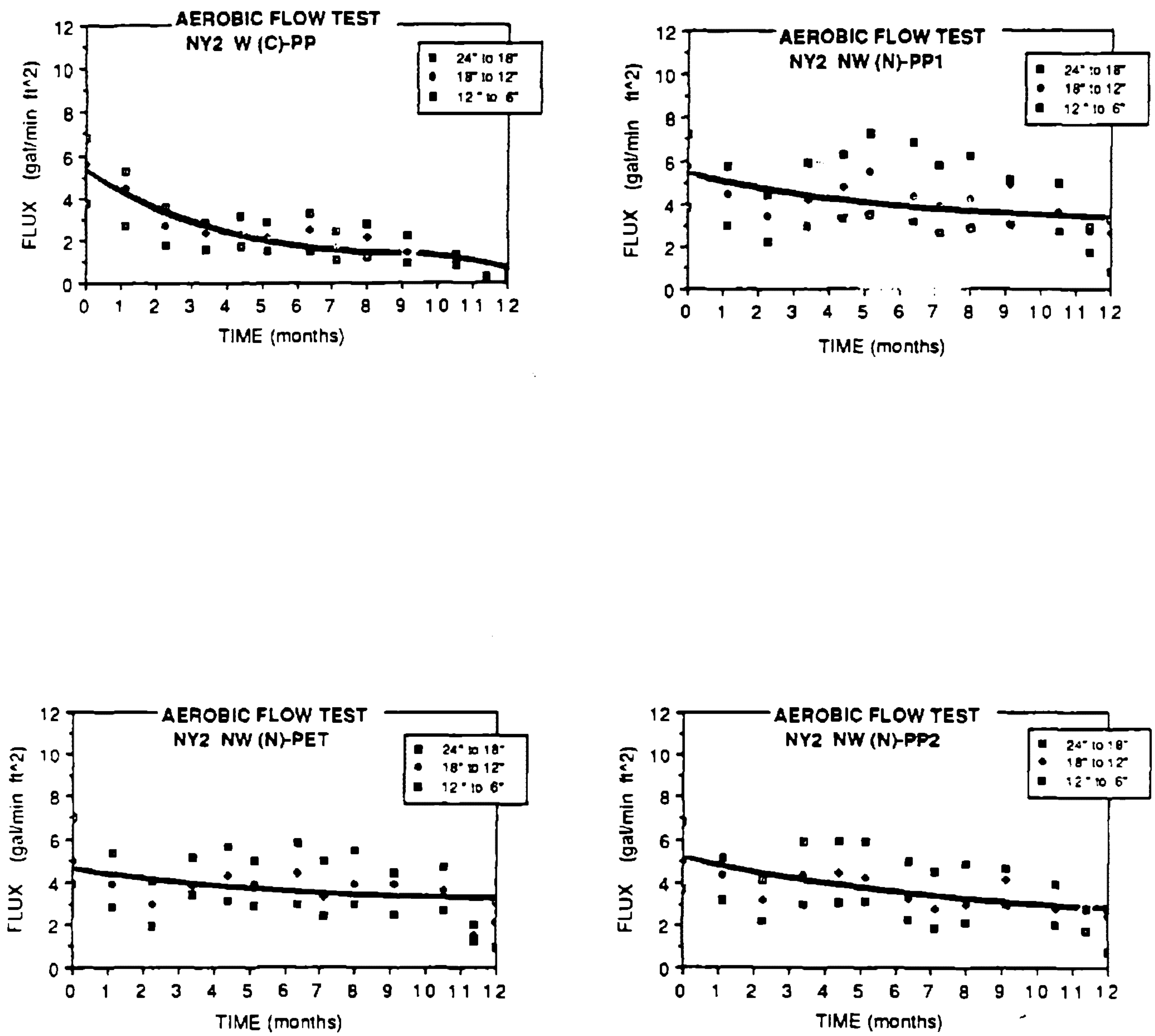


Figure 6 - Aerobic flow rate test results for all geotextiles at Site NY-2

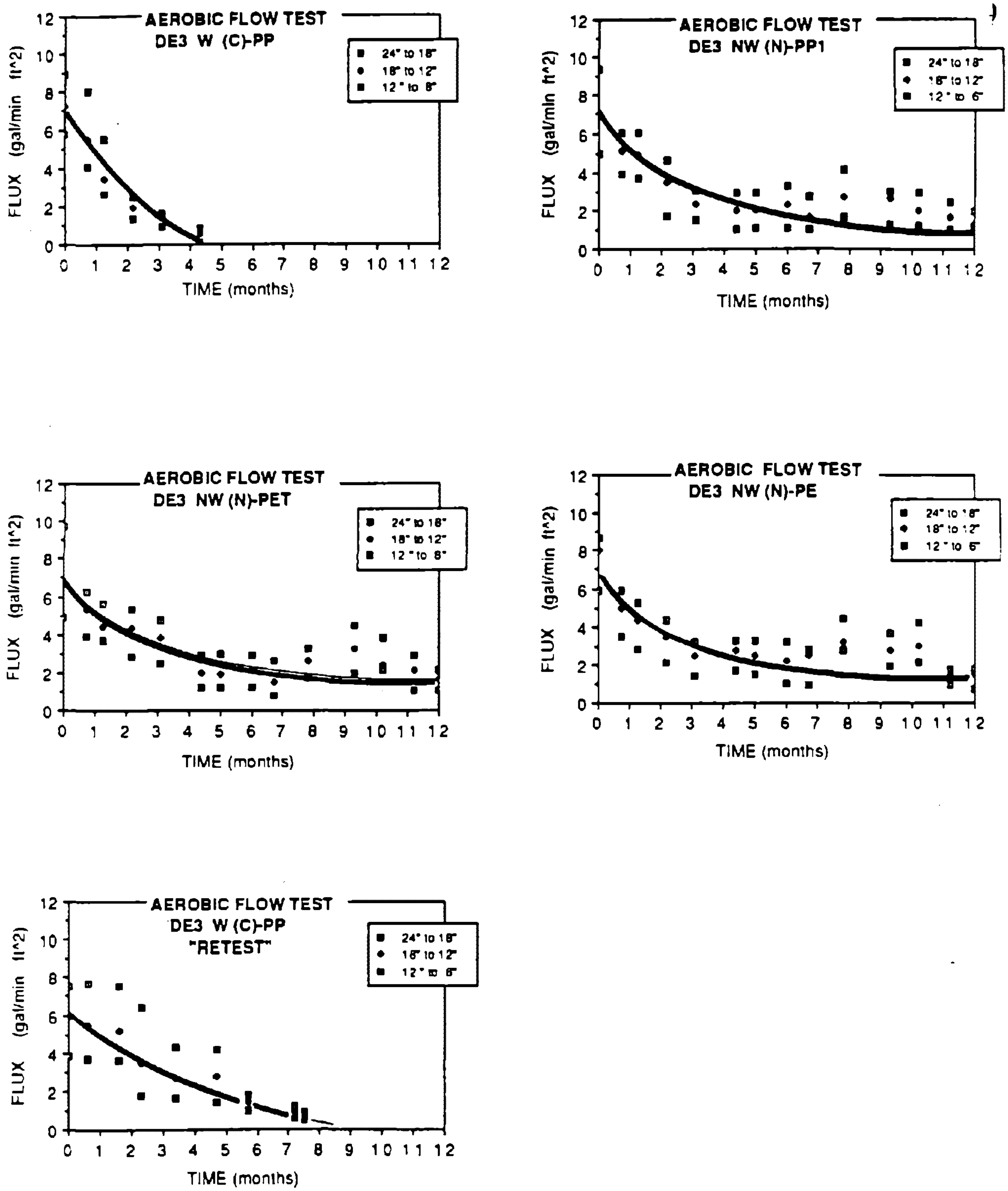


Figure 7 - Aerobic flow rate test results for all geotextiles at Site DE-3

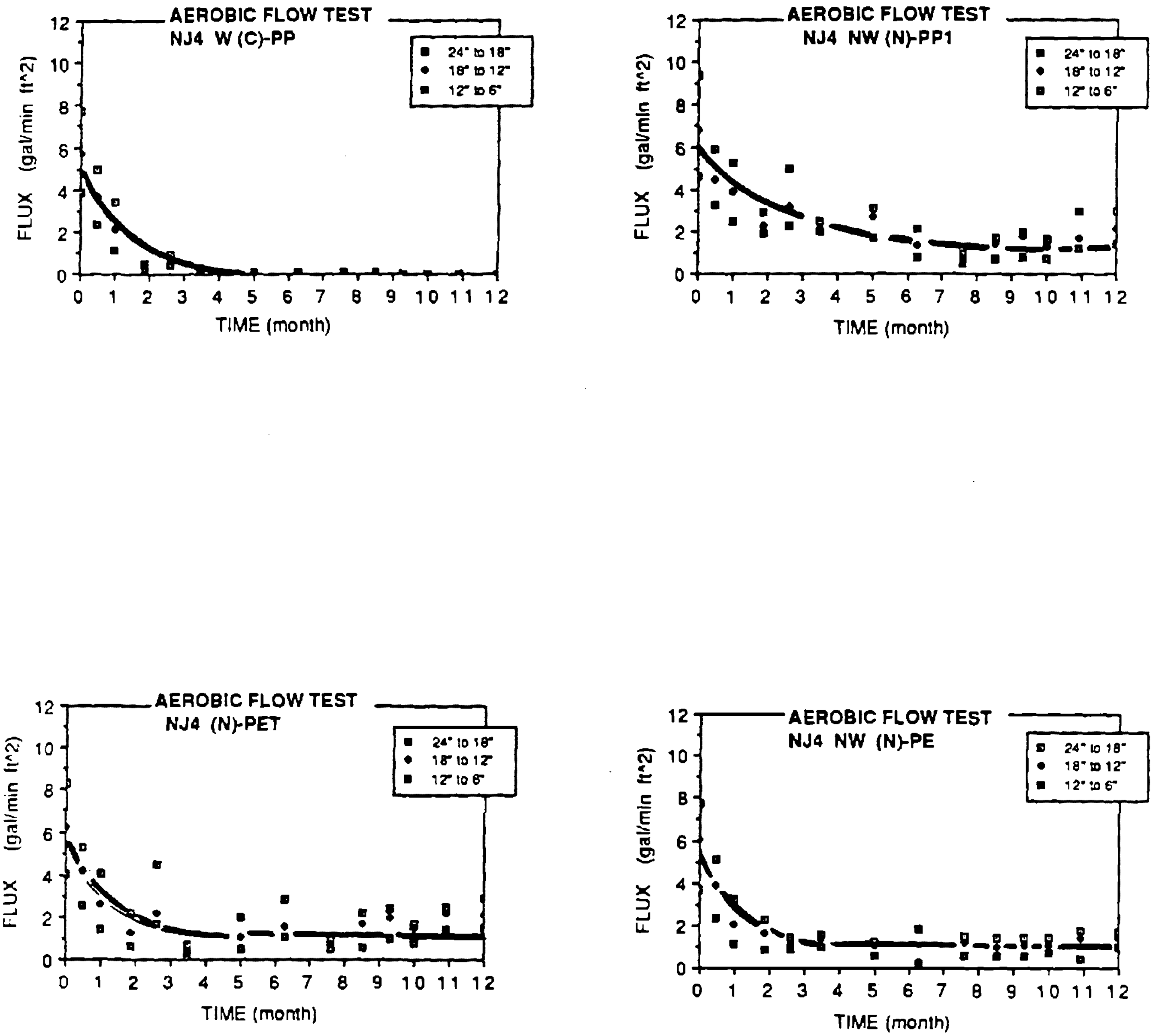


Figure 8 - Aerobic flow rate test results for all geotextiles at Site NJ-4

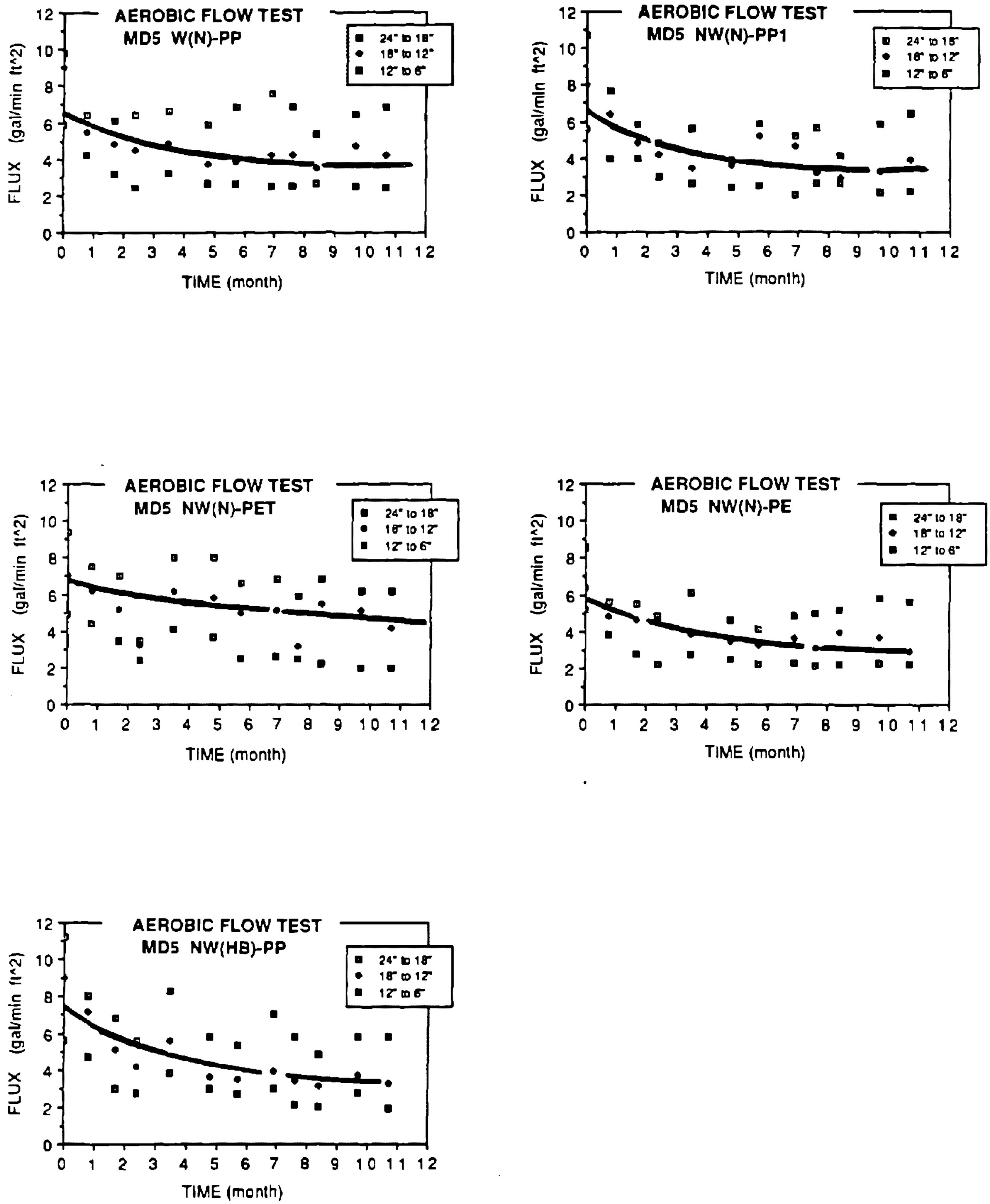


Figure 9 - Aerobic flow rate test results for all geotextiles at Site MD-5

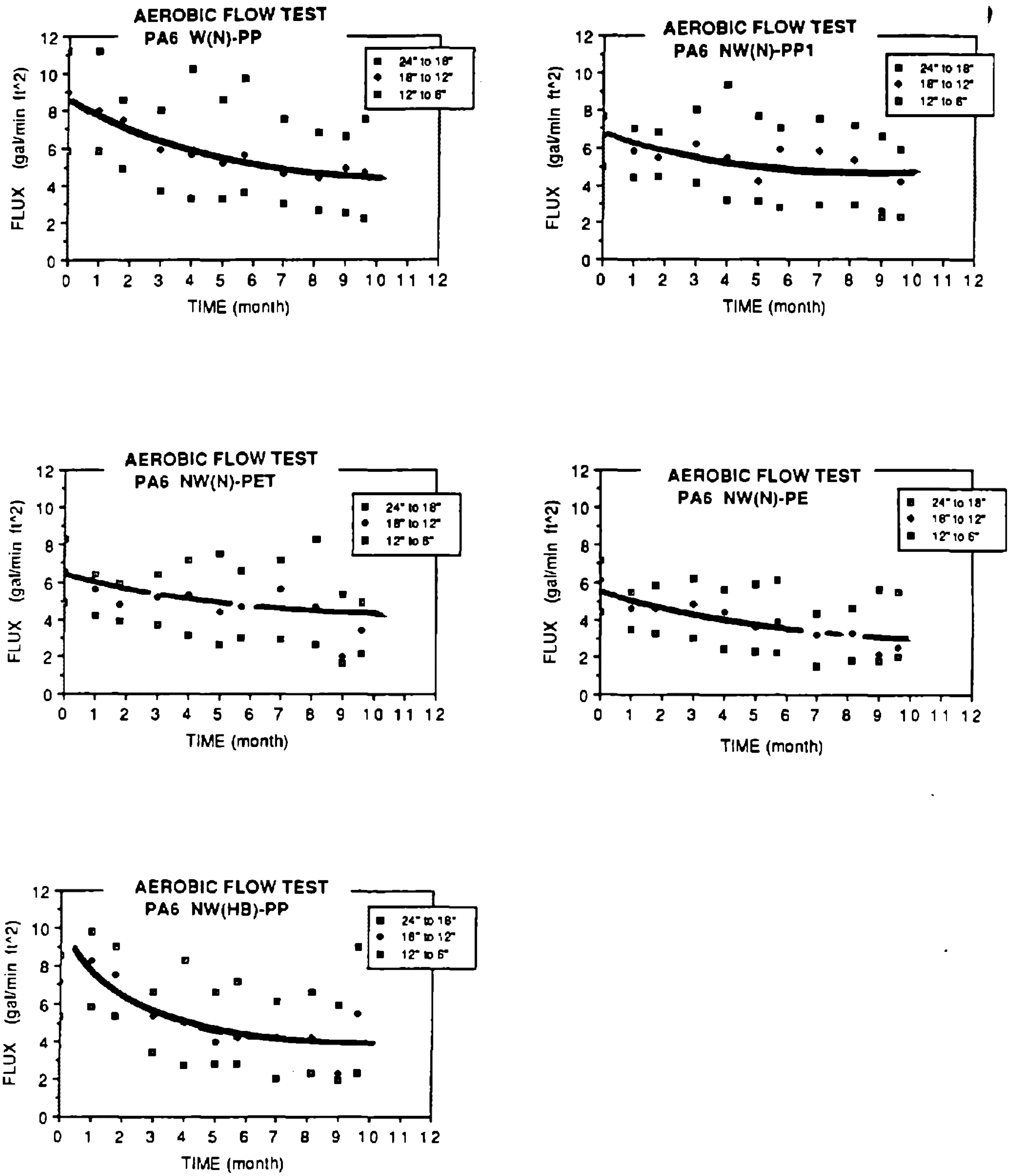


Figure 10 - Aerobic flow rate test results for all geotextiles at Site PA-6

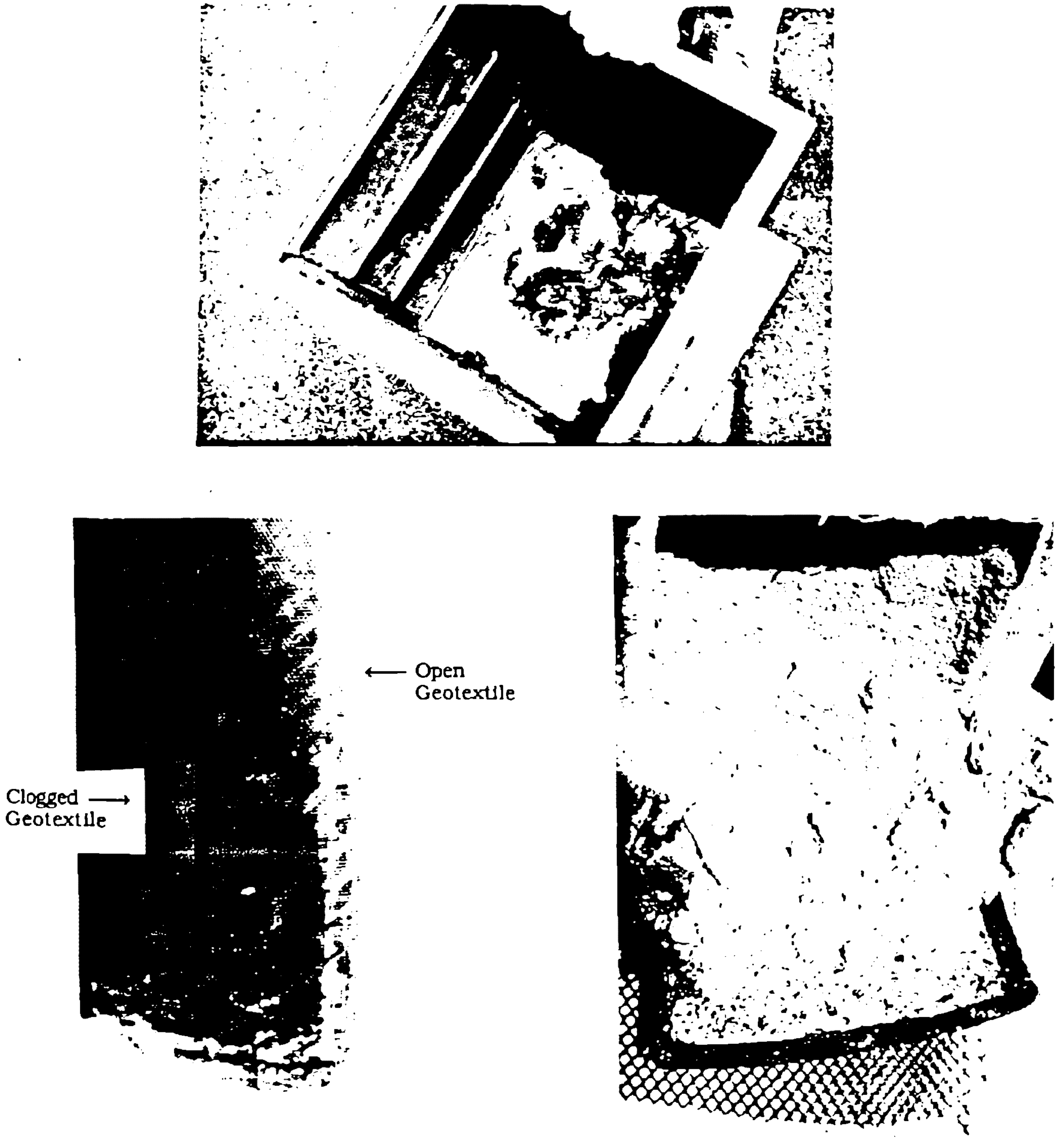


Figure 11 - Exhumed aerobic flow rate test setup showing clogged geotextile conditions (geotextile W(C)-PP at landfill site PA-1)

months was reasonable, i.e., the greater open area was effective in limiting the amount of clogging. The three needle punched nonwoven geotextiles [NW(N)-PP1, NW(N)-PET and NW(N)-PP2] performed quite similarly to one another, all gradually decreasing in flow rate over time but reaching apparent equilibrium flow conditions.

(f) Regarding landfill site NY-2, the W(C)-PP geotextile (with the 4% open area) again clogged severely, but now took the entire 12-month period to do so. The three needle-punched nonwoven geotextiles [NW(N)-PP1, NW(N)-PET and NW(N)-PP2] performed much better, and roughly equivalent to one another.

(g) Regarding landfill site DE-3 (which has a very strong leachate, recall Table 4), the flow rate decreases were quite substantial. Again, the W(C)-PP geotextile with 4% open area clogged to a degree where flow rates with our system could not be measured. After seven months the flow rates were barely readable and after 12 months they were not readable. The three needle punched nonwovens [NW(N)-PP1, NW(N)-PET, and NW(N)-PE] also showed flow rate decreases but appear to have stabilized after six months. Note that slight increases occurred between the 8th and 10th months and can only be explained as a "weaker" leachate at that particular time. Note also the addition of NW(N)-PE (which is a polyethylene geotextile) and it performs quite similarly to the polypropylene (PP) and polyester (PET) types. Thus, the type of polymer from which the geotextile is manufactured appears to have negligible significance.

(h) Regarding landfill site NJ-4, which has the "strongest" leachate, large flow rate decreases are seen for all geotextiles. As with the preceding three landfill sites, the W(C)-PP geotextile with 4% open area again clogged below detection limits, this time within eight months. The three needle punched nonwovens [NW(N)-PP, NW(N)-PET and NW(N)-PE] also had significant decreases. They behaved similarly to one another and at the end of the 12 month period appeared to have stabilized at the equilibrium values indicated.

(i) Regarding landfill site MD-5, which has the "weakest" leachate of all sites, the flow rate trends decrease but now only marginally. The W(N)-PP woven geotextile has a 10% open area and behaves significantly better than the W(C)-PP with lower percent open area used at the previous four landfill sites. Clearly, the greater opening area (from 4% to 10%) has a significant positive influence. The three needle punched nonwovens [NW(N)-PP1, NW(N)-PET and NW(N)-PE] perform similar to one another, again irrespective of polymer type. Added to this set of four geotextiles is a fifth box containing a heat-bonded nonwoven geotextile NW(HB)-PP. Its performance is slightly poorer than the needle punched geotextile types, but only nominally so. Important is that all the geotextiles in this leachate reach equilibrium values before the termination of the tests.

(j) Regarding landfill site PA-6, flow rates decrease but not significantly. The leachate at this site is not very strong so the behavior is understandable in light of the other test results and their respective leachates. Clearly, the leachate type and characteristics are seen to be of paramount importance in the geotextile clogging issue. Of the five geotextiles used at this site, the low percent open area woven W(N)-PP and heat bonded nonwoven NW(HB)-PP dropped in flow rate from their original values at a slightly greater rate than the three needle punched nonwovens [NW(N)-PP1, NW(N)-PET and NW(N)-PE]. All, however, reached a relatively high equilibrium value.

The flow rate decreases presented in this section vary according to the type of leachate and the type of geotextile filter. This begs the question as to the mechanism(s) involved. Shown in Table 4 was that all of the leachates contain very high solids content (as evidenced by the TS values) and tremendously large amounts of bacteria (as evidenced by the BOD_5 values). Thus, one could expect some amount of flow reduction as a response to the influence of two sources; sediment (particulate) matter and/or biologically oriented matter. Furthermore, the two phenomena could be interacting with one another as is well established in the literature.

In order to visually examine the cross sections of the flow boxes after the 12-month flow testing was complete, they were sampled with a 2.0 in. diameter thin-walled steel tube. This tube was driven completely through the sand, geotextile, geonet and wooden base plate. The sampling tube was then cut off even with the top of the sand, turned upside down, and the wooden box base plate was removed thereby exposing the bottom of the geonet. A low viscosity epoxy was then poured into the geonet, thereby flowing into the geotextile and then into the sand. After hardening, the entire tube (with its sand, geotextile and geonet contents) was cut along its diameter into two halves. Upon opening the two halves, the cross-sections appeared as shown in the photographs of Figure 12.

The upper photograph of Figure 12 shows the cross section of the needle punched nonwoven polyester geotextile [NW(N)-PET] at all six landfill sites after 12-months of leachate flow testing. In the two cross sections of DE-3 and NJ-4, a very clear color change midway through the sand layer can be noticed (see the lower photographs for some of this detail). The

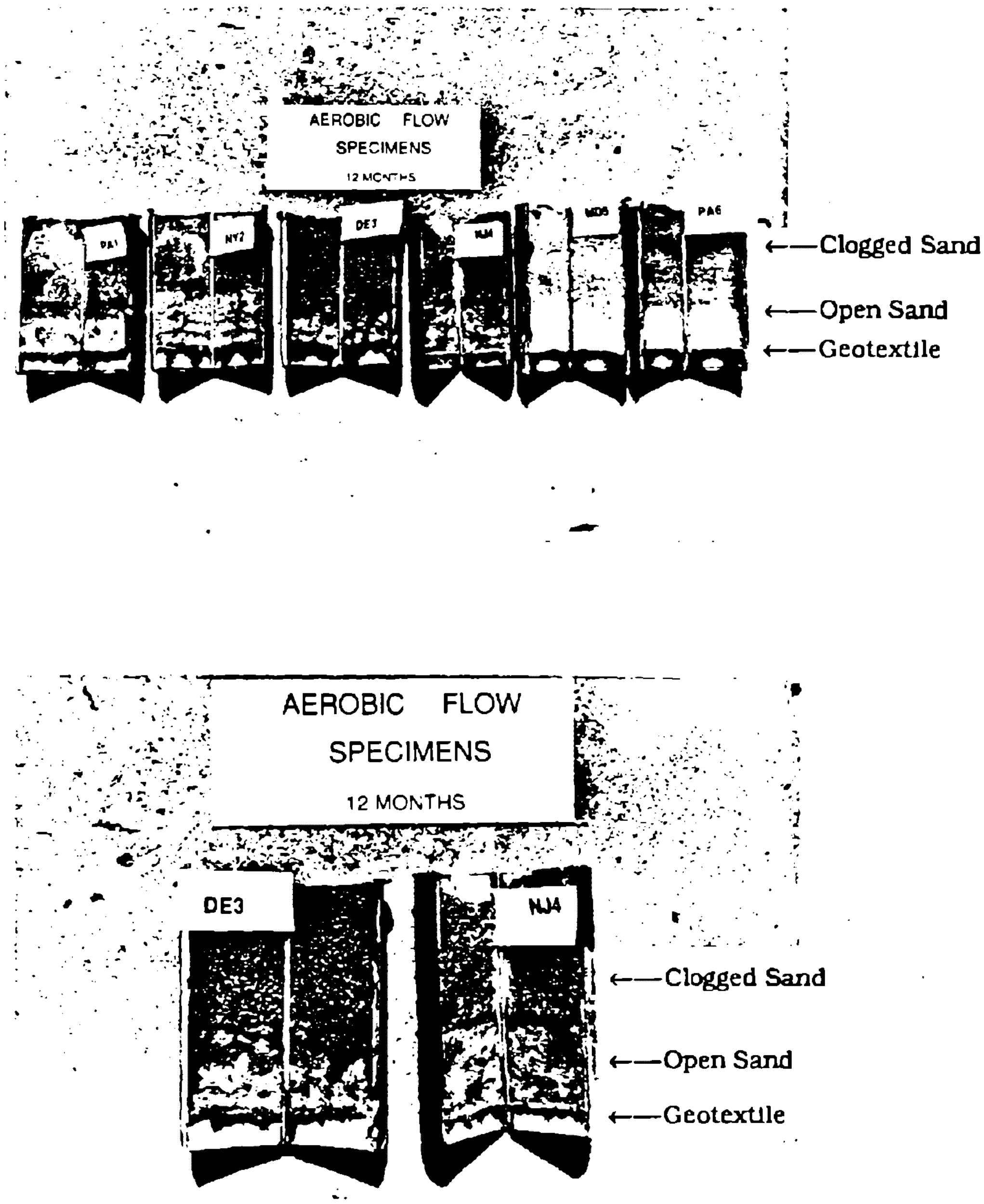


Figure 12 - Samples of the NW(N)-PET geotextiles and the overlying 6" of Ottawa sand soil from the various landfill sites after twelve months of aerobic flow testing

upper rust color is clearly indicative of iron deposits typical of bacterial activity under aerobic conditions. Note that these two sites with the major color changes had the strongest leachates of all six sites. The other four cross sections of PA-1, NY-2, MD-5 and PA-6 also show residual bacteria bonding within the sand, but without abrupt color changes. Clearly the influence of strong leachates, such as DE-3 and NJ-4, are very much in evidence through examination of these cross sections. Under high magnification, biological activity was seen to be present in all samples throughout the six inches of Ottawa sand and into the geotextile filters. *The photographs are felt to be particularly significant in that biological activity occurs in sand filters equally as much as it does in geotextile filters. Furthermore, this sand filter has the hydraulic conductivity (permeability) of some drainage layers, let alone most of the natural soils used as filter layers.*

In summarizing these aerobic flow rate tests we find that flow reduction has occurred at all six landfill sites. The relative amount, and the amount between different geotextiles varied considerably. In order to view the total data set for comparative purposes, Table 5 has been prepared. Here, the flow rate reductions are reported on the basis of their initial flow rate values compared to the final 12-month values i.e., the percent flow rate retained. Some observations concerning the aerobic flow rate results reported in this table follow:

(a) The woven geotextiles [W(C)-PP] with 4% open area had the largest flow rate decreases, in three cases below experimental detection limits. This type of tightly woven geotextile should be questioned for use as a geotextile filter for landfill leachate with respect to the design required value.

(b) Using a similar type of woven fabric [W(N)-PP] but now with a 10% open area produces reasonable and, in fact, quite good results.

(c) The trends and nominal differences between the four needle-punched nonwoven fabrics [NW(N)-PP1, NW(N)-PET, NW(N)-PP2 and NW(N)-PE] all behaved similarly and quite independently of polymer type. Thus polypropylene, polyester and polyethylene all are candidate polymers used to manufacture geotextile filters in leachate collection systems as far as flow rate behavior is concerned.

(d) Furthermore, all of the needle punched nonwoven geotextiles responded to the various leachates in approximate relationship to the severity of leachate quality, i.e. DE-3 and NJ-4 leachate, the harshest of all six landfill sites, produced the largest flow rate reductions. The other four landfill sites PA-1, NY-2, MD-5 and PA-6 with weaker leachates, resulted in lower flow rate reductions in approximate proportion to their leachate strength.

Table 5 - Results of Aerobic Flow Rate Tests After 12 Months of Evaluation in Phase I Study (Percentages Given are Flow Rates Retained Compared to the Initial or As-Received Values)

Site Designation	Time Startup	Aerobic Flow Rate Trends[1]						
		W(C)-PP	W(N)-PP	NW(N)-PP1	NW(N)-PET	NW(N)-PP2	NW(N)-PE	NW(HB)-PP
PA-1	11/18/87	0%[3,4]	80%	85%	85%	85%		
NY-2	12/10/87	10%		80%	80%	80%[2]		
DE-3	1/25/88	0%[3]		20%	20%		25%	
NJ-4	4/5/88	0%		20%	20%		10%	
MD-5	6/6/88		90%	85%	85%		80%	75%
PA-6	6/28/88		90%	85%	85%		80%	70%

Notes:
[1] flow rate tests within box (average of 24-18; 18-12; 12-6 in. falling head tests)
[2] the second PP geotextile was changed at Site #3 to PE
[3] test clogged beyond detection limits and was restarted with higher POA fabric
[4] retested

(e) The heat-bonded nonwoven fabric [NW(HB)-PP] used at landfill sites MD-5 and PA-6 showed similar flow rate reductions as the needle punched nonwoven types.

(f) The sand overlying the above mentioned geotextiles was greatly affected by the leachate. Sand clogging was contributing, to some unknown degree, throughout the tests. This important issue will be evaluated in the Phase II study, and will be presented in the conclusion portion of this report.

Anaerobic Flow and Strength Tests and Results

Soon after a landfill begins accepting appreciable quantities of solid waste, the available oxygen is depleted and the situation at the bottom of the landfill becomes anaerobic. At the level of the leachate collection system, this absence of air might even occur shortly after placement of several lifts of waste. A clear indication of anaerobic conditions is the presence of methane gas, which occurs via anaerobic microorganisms interacting with the waste. This portion of the study presents our simulation of this condition and the results of the subsequent testing program.

To evaluate the anaerobic leachate effects on various geotextile filters a completely different strategy from the previous tests was taken. In this portion of the study it was decided to immerse 14 in. wide by 12 in. long geotextile samples in 55 gallon drums filled with leachate. The geotextile test samples were placed on stainless steel racks within the drums in sets of twelve for each of the four geotextiles evaluated at each site. Thus, the total anaerobic test program consisted of 288 samples. See Figure 13 for a schematic diagram and photograph of typical incubation setup.

The leachate used for the incubation was taken from the landfill reservoir or storage tank at the start-up dates listed in Table 4(a). Leachate characteristics are those listed in this table and did not change during the course of the incubation. The drum lids were tightly sealed at all times with the exception of once per month when the samples were removed from each drum at each landfill site. These samples were sealed in plastic bags and brought to our GRI laboratory for immediate testing and evaluation. For each geotextile sample the following tests were conducted.

- three permittivity tests[10]
- three radial transmissivity tests[11]
- three Mullen burst tests[12]
- four 1.0 inch wide strip tensile tests[13]

The flow tests were performed on the retrieved samples in two different directions, i.e. flow in the cross-plane direction (or permittivity) and flow in the in-plane direction (or

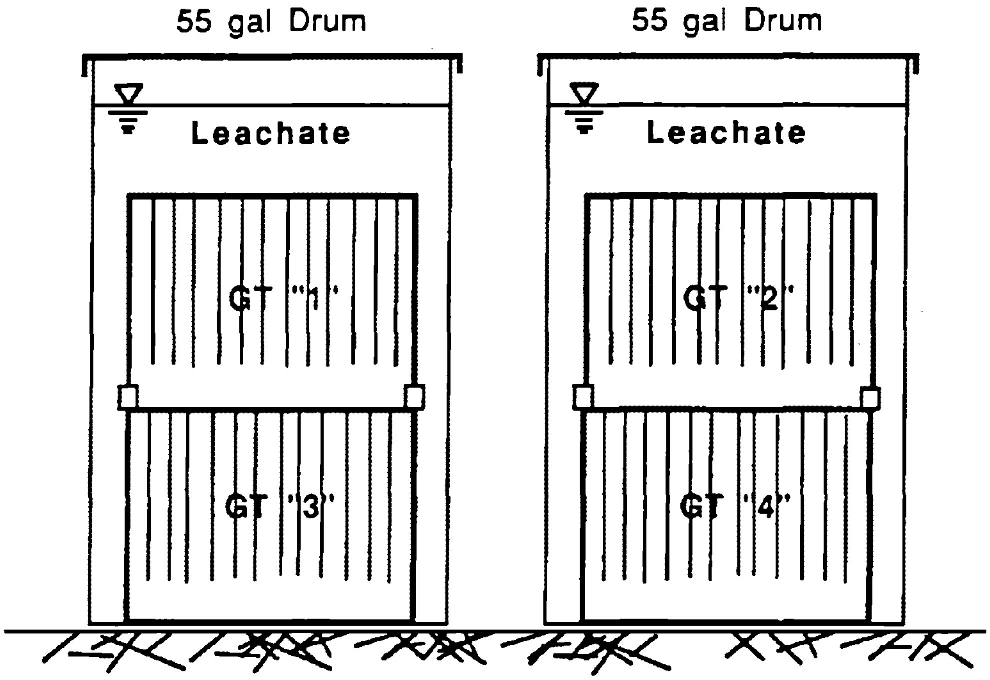


Figure 13 - Anaerobic incubation drums with geotextiles immersed in leachate in sets of twelve geotextiles of each type

transmissivity). These tests were done on the samples in their as-retrieved leachate saturated condition, however flow testing was performed with water.

The permittivity tests were done as stipulated in ASTM D-4491 with the exception of the 2 in. (50 mm) constant head. Our concern was that this value was too high and would excessively wash the biological growth out of the geotextile. Therefore we decided on use of a 0.5 in. (12 mm) constant head value. Three tests were done on each sample and the average values were obtained. The data is given in Reference 9 since it consists of numerous sets of information.

The transmissivity tests were of the radial variety because this type of test requires significantly less material than the planar test currently recommended by ASTM. The test is, however, well behaved and is established in the literature. The radial transmissivity test is performed under a constant head where liquid flows into a load bonnet and meets the inner circumference of the donut-shaped test specimen. It then flows radially in the plane of the geotextile to the outer circumference where it is collected and measured. Calculations then permit determination of the transmissivity value. The tests performed in this study were all done under a normal seating load of 43 lb/ft^2 (2.0 kPa) and a constant head of 0.5 in. (12 mm). As with the permittivity tests, the tabulated results are included in Reference 9.

A complete photo-documentation of the anaerobic clogging of the geotextiles at each site was compiled using a scanning electron microscope (SEM). This entire record is also presented in Reference 9. The biological growth took very different forms at each of the different sites. Also seen was that the biological colonies easily were detached from the fibers themselves, i.e. a chemical bonding did not appear to have occurred, see Figure 14.

The averages of the permittivity and transmissivity tests just described were further averaged with one another and are given in Table 6 following. Each landfill is listed separately along with the specific geotextiles that were incubated in that particular geotextile. From this table it is seen that:

(a) The original flow rates decreased approximately 5% to 20% for all test specimens.

(b) The stronger leachates at landfill sites DE-3 and NJ-4 were associated with the higher range of flow rate decreases.

(c) There was no particular sensitivity to geotextile type nor to polymer type.

(d) These flow rate decreases are significantly less than the aerobic test results and are lower than we suspected from viewing the exhumed geotextiles, note the condition of geotextiles removed from Site NJ-4 after 6 months incubation in Figure 14.

Table 6 - Results of Anaerobic Flow Rate Tests (Percentages Given are Flow Rates Retained Compared to the Initial or As-Received Values; N/C indicates "no change")

Site	Startup Date	W(C)PP	W(N)PP	NW(N)-PP1	NW(N)-PET	NW(N)-PP2	NW(N)-PE	NW(HB)-PP
PA-1	11/18/87	90%		95%	95%	95%		
NY-2	12/10/87	85%		90%	90%	90%		
DE-3	1/25/88	80%		90%	90%		85%	
NJ-4	4/5/88	80%		90%	90%		85%	
MD-5	6/6/88		N/C	N/C	N/C		N/C	N/C
PA-6	6/28/88		N/C	N/C	N/C		95%	95%

Note:
All tests are the average of 3 permittivity and 3 transmissivity tests

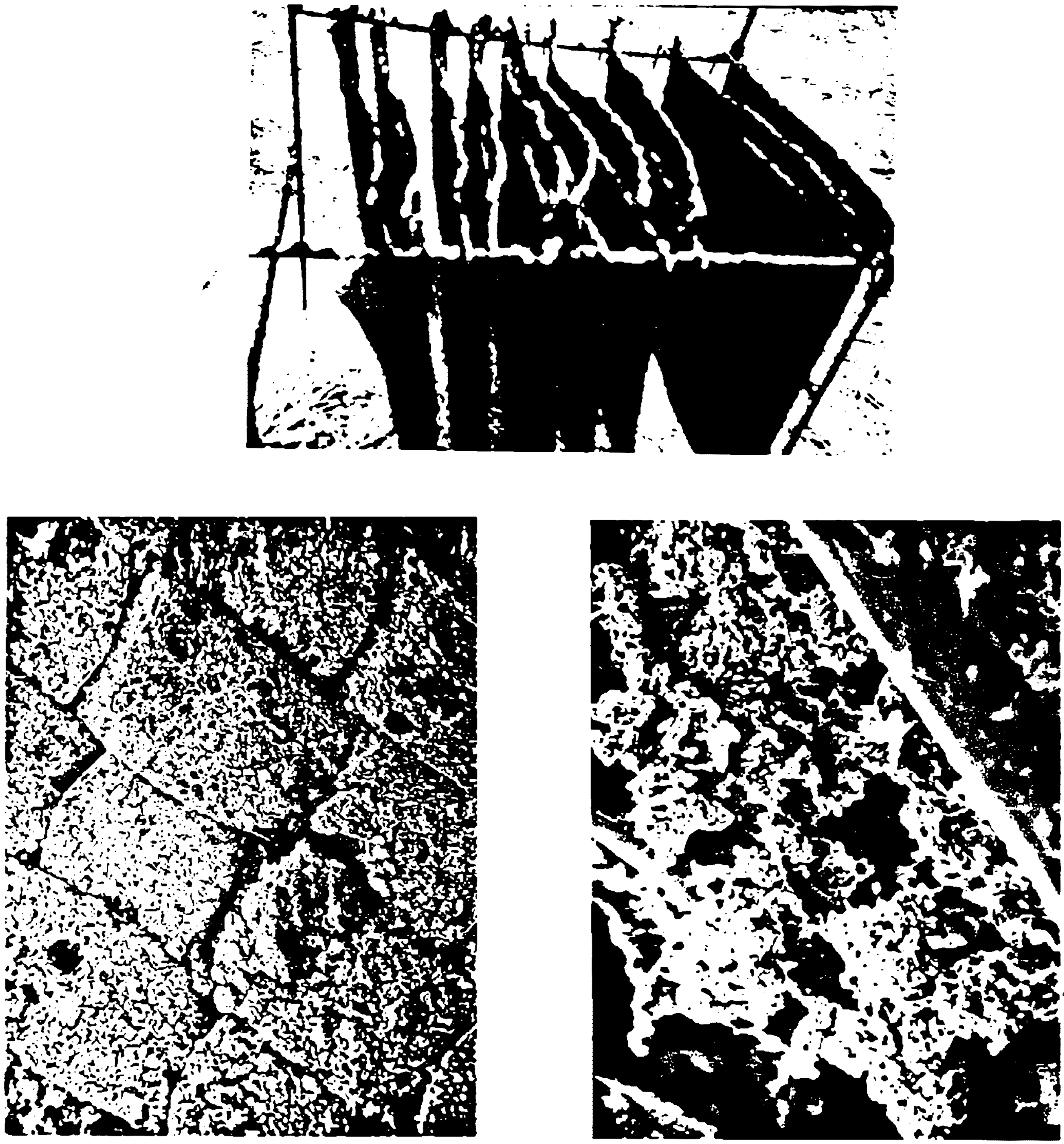


Figure 14 - Condition of geotextiles after six months of anaerobic incubation at site NJ-4. Lower photographs are scanning electron micrographs of sediment and growth on selected fibers: Left is woven fabric at 30 magnification.
Right is nonwoven fabric at 400 magnification.

(e) It is quite possible that the flow testing (with water) actually flushed some of the biological growth and fine sediments out of the geotextile. This situation was not possible for the aerobic tests discussed previously.

(f) In comparing these flow rate reductions with the aerobic test results described earlier it must be remembered that sand was not present in these tests; thus, flow rate reductions should be significantly lower, and they were.

The issue of biological *degradation, or loss of strength,* of geotextiles is often expressed by various groups, e.g., regulators, owners and designers. Envisioned are microorganisms which chemically attach themselves to the geotextile's fibers and find molecular chain endings from which degradation can occur. If such a mechanism occurs, it should be evidenced by a loss of strength and/or a loss of elongation. Since numerous leachate incubated geotextiles were available, it was decided to perform two types of strength tests; burst and strip tensile tests. The resulting information from these tests conducted on monthly exhumed geotextiles from each site are given in Reference 9. The geotextile samples brought from the sites were cut into test specimens and, for these strength tests, were air dried before testing. These results were compared to the as-received, and nonincubated, geotextiles in the same type of tests. The results are summarized in Table 7 which follows.

Table 7 indicates that loss of strength from the various geotextiles at the six landfill sites due to leachate incubation up to 12 months is a non-issue except for the nonwoven heat-bonded polypropylene fabrics at sites MD-5 and PA-6. In regard to this strength loss, it is felt that incubation within the leachate led to weakening of thermally fused fiber junctions. Thus the strength loss in this particular fabric is felt to be the result of a physical effect rather than being biologically motivated. With this exception, it appears that (within the accuracy of our testing and observations on the photomicrographs of Reference 9) neither geotextile strength nor elongation suffered from the leachate exposure.

Table 7 - Results of Anaerobic Strength Tests (Percentages Given are Strengths Retained Compared to the Initial, or As-Received Values; N/C indicates "no change")

Site	Startup	W(C)PP	W(N)PP	NW(N)-PP1	NW(N)-PET	NW(N)-PP2	NW(N)-PE	NW(HB)-PP
PA-1	11/18/87	N/C		N/C	N/C	N/C		
NY-2	12/10/87	N/C		N/C	N/C	N/C		
DE-3	1/25/88	N/C		N/C	N/C		N/C	
NJ-4	4/5/88	N/C		N/C	N/C		N/C	
MD-5	6/6/88		N/C	N/C	N/C		N/C	70%
PA-6	6/28/88		N/C	N/C	N/C		N/C	70%

Note:
All data is the average of 4-1 inch wide tensile tests and 3 Mullen burst tests

Summary of Phase I Study

The results of the Phase I (first year's) study has shown that municipal landfill leachates have tremendous numbers of biological micro-organisms present. For the six landfill leachates evaluated, the bacterial content ranged from 10^8 to 10^9 cells per milliliter with 35 to 60% viability, i.e. live cells. This, in turn, is reflected by BOD_5 levels varying from 1000 to 20,000 mg/l. Additionally, it was seen that a high total solids (TS) content (varying from 100 to 17,000 mg/l) always accompanied a high BOD content. The size of the sediment and micro-organisms in the leachate varies from 2 to 100 microns, i.e., the particulates all fall within the silt soil size range. It should be mentioned that all of the landfills evaluated in this study were codisposed with industrial waste, but the nature and degree is unknown to the authors.

With this insight as to the nature and type of the particulates in the leachates, it was decided to evaluate clogging under both aerobic and anaerobic conditions.

The *aerobic portion of the study* used 12 in. × 12 in. flow boxes, 24 in. high. The boxes were all constructed using a wooden base plate, a geonet drain, a geotextile filter and 6 in. of free draining sand. The remaining 18 in. of the boxes were empty so that falling head permeability tests could be conducted . Leachate passed through the sand and geotextile, then flowed within the geonet which was open at one end only. The time of flight for given quantities of leachate to pass through the system was measured. Each of the six sites had at least four boxes, the only difference being the type of geotextile filter. Both woven and nonwoven geotextiles were evaluated. They consisted of various polymer types and manufacturing styles.

Based on the flow rate behavior over the 12-month evaluation period at each site, the following conclusions are reached.

(a) *Flow rate decreases from original values vary considerably*. They range from full reduction (within the limits of our detection system) to 10% reduction, with many values being in the 80% to 20% reduction range.

(b) The relatively tight woven geotextile filter, with a 4% open area, performed the poorest. In each of the four different sites in which it was used, it clogged beyond our detection limit. The time periods were from 4-1/2 to 12 months.

(c) Opening up the void space of the same type of woven geotextile to a 10% open area helped considerably. Flow rates still decreased but were more in line with the needle punched nonwoven geotextile types.

(d) The needle punched nonwoven geotextiles performed equivalently. They were constructed similar to one another but were of different polymer types. Results indicate that polypropylene, polyester and polyethylene fibers do not appear to be significantly different in their flow rate response behavior.

(e) A heat-bonded nonwoven geotextile was used at two sites. Its response was somewhat poorer than the needle punched nonwovens but better than the woven geotextile with 4% open area.

(f) The Phase I study indicates that use of open woven geotextiles and each of the needle-punched nonwoven geotextiles results in steady state flow conditions after as little as 6 months, and almost always after 12 months. The flow rate reductions varied from as low as 20% of the original values (at four sites) to as large as 80% (at two sites). These reductions appeared to be related to the strength of the leachate insofar as their total solids (TS) and micro-organism content (BOD_5) is concerned. In the worst cases, flow rates are usually above 1.0 gal/min-ft^2. This is equivalent to 6.2×10^7 gal/acre-day which probably far exceeds most design requirements for leachate collection system filters.

(g) The cause of the flow reductions created somewhat of a dilemma. By cross sectioning of the boxes at the end of the 12-month period, it was clearly evident that the 6 in. of sand over the geotextile was a major source of the flow reduction. *Clearly, the experiments showed that soil clogging is every bit as serious as geotextile clogging.* Furthermore, the soil which was used was a very open graded, rounded sand (actually it was Ottawa sand) having a permeability coefficient approximately 0.02 cm/sec (0.04 ft/min). Thus, it actually meets (and exceeds) the EPA criterion for a drainage soil, let alone a filter soil.

(h) Microscopic examination of the cross sectioned soil/geotextile systems showed heavy particulate clogging in the upper half of the soil layer. Thereafter the clogging was either fibrous or consisted of very small clusters. Although not conclusively proven, we feel that the upper portion of the soil column filtered the suspended solids out of the leachate and thereafter biological activity spread throughout the remaining portion of the soil column and into the underlying geotextile. This biological activity took numerous forms including the deposition of solid precipitates in the soil and geotextile voids. Thus different geotextiles (all other things equal) responded differently to the same site's leachate.

(i) The relative amounts of flow rate reduction between leachate sediment, biological precipitates and biological growth could not be distinguished in these tests.

The *anaerobic portion of the study* was performed under completely submerged conditions in 55 gal. drums. Twelve samples of each type of geotextile were suspended on stainless steel racks and placed in the site's leachate. One sample of each type was removed for testing each month. Four geotextile types were evaluated for each of the six landfill sites. After removal of the samples they were brought to our laboratory and were tested for their retained flow capability and possible strength reduction. The general conclusions are as follows:

(a) *Relatively minor flow reductions occurred in all types of geotextiles evaluated.* The reduction values varied from 10% to 20%. Note, that these amounts are distinctly less than occurred in most of the aerobic tests. The reason for this is that sediment clogging was not initiated since flow was not occurring during the incubation periods. Furthermore, the absence of a soil column had a dramatic (but quantitatively unknown) effect in improving the flow rates.

(b) All of the exhumed geotextiles had heavy biological growth which could be easily seen and felt.

(c) Scanning electron micrographs at various times of incubation (e.g., 1, 3, 6 and 12 months), were compared to the as-received geotextiles, and were very informative.[9] Here complete growth around the individual fibers, or growth in clusters, could be seen. While difficult to quantify, the amount of growth was clearly related to the time of immersion.

(d) The micrographs also revealed that the biological growth was easily removed from the fiber's surfaces. There appeared to be no fixity or attachment to the fibers.

(e) The above observation was corroborated by various strength tests performed on the geotextiles after immersion. Within the limits of our testing, there was no strength reduction over the 12-month period. *This suggests to us that for these leachates, biological degradation of geotextiles is a nonproblem.* Phase II studies will not dwell upon the polymer degradation issue.

PHASE II - SECOND/THIRD YEAR STUDY

Building upon the results of Phase I activities, Phase II of the project was aimed at eliminating the objectionable features of the first phase and toward providing an opportunity of remediating the filtration systems by various types of backflushing. Furthermore, the focus shifted from complete geotextile filter clogging to a balance between geotextile *and soil* filter clogging. The new experimental test setups for this second phase were intended to meet the following criteria.

(a) Sand filter clogging should be distinguishable from geotextile filter clogging.

(b) Sediment clogging should be distinguishable from biological clogging.

(c) Aerobic conditions should be distinguishable from anaerobic conditions.

(d) Identical geotextiles and soils should be used at every site.

(e) The flow columns should be capable of accommodating continuous or periodic flow testing.

(f) The flow columns should use the leachate at the time of testing and not be stored for any length of time lest it change in its composition and not represent site conditions.

(g) Constant head or variable head conditions should be capable of being accommodated.

(h) The flow columns should be capable of being backflushed with liquids or gases and the results assessed.

(i) The test setup should be adaptable to include various biocide remediation attempts.

(j) Freezing of the test setups should be avoided.

(k) The flow columns should be sufficiently portable to evaluate in the sump, at the leachate storage facility or in an enclosed space.

(l) The flow columns should be inexpensive so that a large number can be constructed to test a wide variety of filtration schemes.

Incubation Columns and Testing Procedures

In order to meet the experimental test device criteria just described, incubation and flow columns as shown in Figure 15 have been developed and are used throughout the Phase II study and the biocide study which is included as Appendix "A".

The flow columns of Figure 15 are constructed from 4.0 in. diameter PVC pipe and related fittings. Most large hardware stores and swimming pool accessory supply shops have these items in stock. The containment ring is actually a pipe coupling which has a raised inner "lip" upon which the geotextile is placed and sealed. A non-water soluble adhesive is used to bond the geotextile to the lip so as to prevent edge leakage. The upper and lower tubes are both 4.0

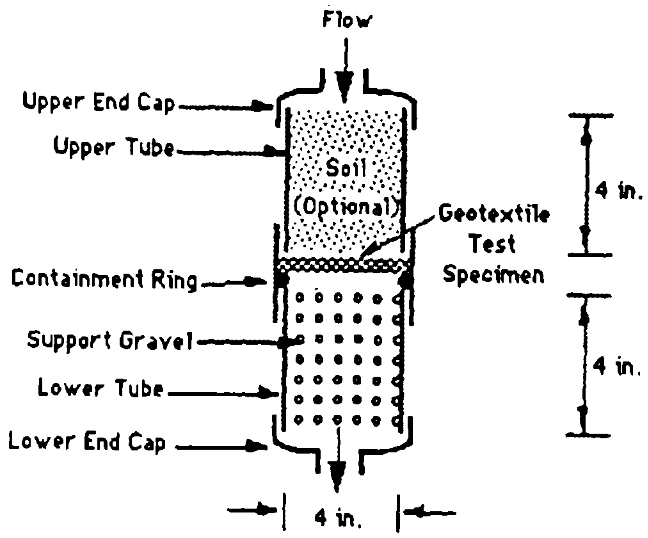


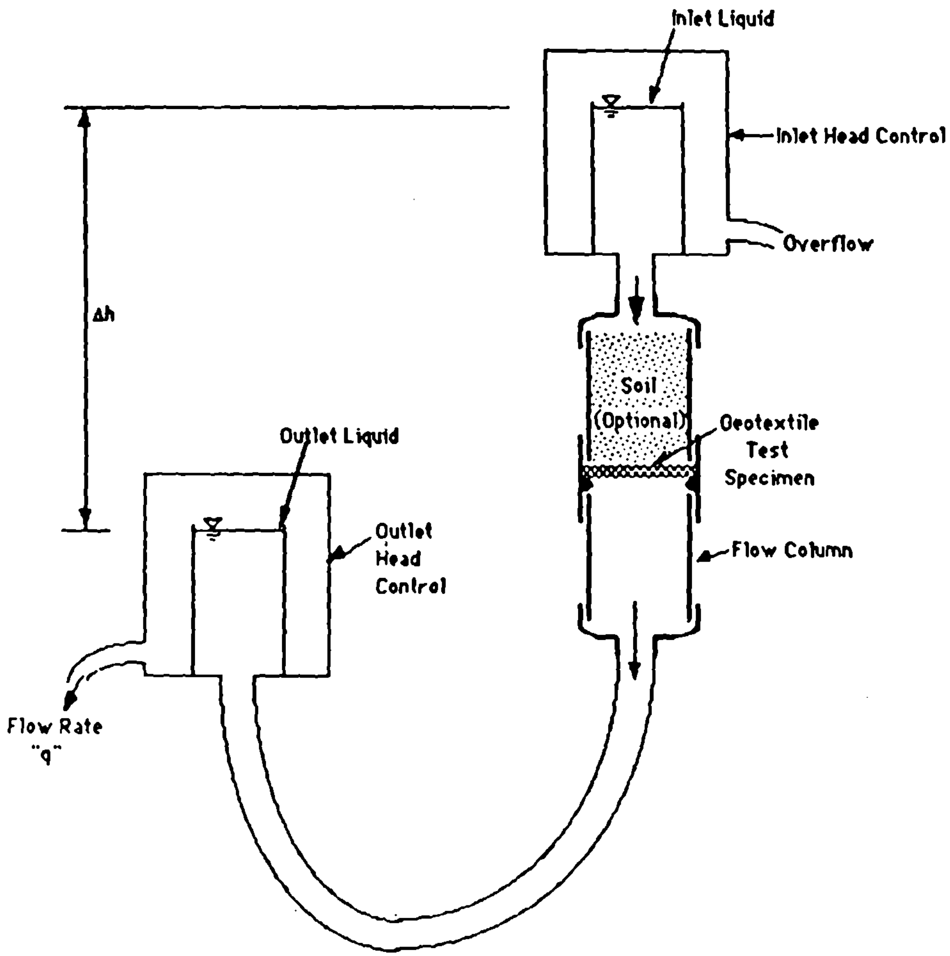
Figure 15 - Cross section of individual flow column and storage rack used to contain the flow columns when not in use at the landfill sites

inch long sections of PVC pipe. They are contained by end caps which have pre-drilled 1.0 inch holes in them that are threaded. Support gravel of 1 to 1.5 inch diameter, is placed below the geotextile prior to positioning and gluing of the lower end cap. Similarly, if soil is to be placed above the geotextile it must be done before the upper end cap is fitted to the assembly. Cap adaptors are then threaded into the end caps and fitted with 1.0 inch diameter flexible tubing (for constant head tests) or rigid clear tubing (for variable head tests). These two options are shown in Figures 16 and 17, respectively, along with photographs of the completed devices.

The experimental testing program for this second phase of study was as follows:

1. Four different geotextiles were used at each of the four landfill sites and under each set of test conditions; they are as follows:
   (a) woven monofilament geotextile of 0.21 mm average opening size and 6% open area
   (b) nonwoven heat bonded geotextile of 0.21 to 0.15 mm average opening size
   (c) lightweight nonwoven needle punched geotextile of 0.21 mm average opening size
   (d) heavyweight nonwoven needle punched geotextile of 0.15 mm average opening size
   Complete details regarding these geotextiles were given previously in Table 3.
2. Soil (uniformly graded Ottawa sand of 0.42 mm average size, see Figure 2) was placed above one set of the geotextiles, while nothing was placed above another set.
3. One set of the above mentioned columns were allowed to drain between readings (thus providing aerobic conditions), while another set was constantly immersed in leachate (thus providing anaerobic conditions).
4. All of the above variations were done at each of the six landfill sites, thus 96 ($4 \times 2 \times 2 \times 6$) flow columns of the type shown in Figure 15 are included in this study.
5. Between landfill readings (which occurred at least on monthly intervals), the test columns were stored at GRI as shown in the lower photograph of Figure 15.

Since all of the tests during the first year were performed on a monthly basis, and the distinction between fine particulate clogging versus biological clogging was never settled, a set of continuous flow tests were performed. Here the flow columns were set up in a variable head mode, as shown in Figure 17, and leachate was continuously supplied directly from a leachate sump and passed through the system. The geotextile/soil configuration was used so that flow times were long enough to be accurately measured. The results of this testing at the two sites with the harshest leachates, DE-3 and NJ-4, are shown in Figure 18. After an initial decrease which was probably a tuning of the soil/geotextile system to the flow regime and the formation of a stable flow network, the permeability of each leachate leveled off to essentially constant values. Thus, it was felt that any sediment within the leachate does not continue to build up so



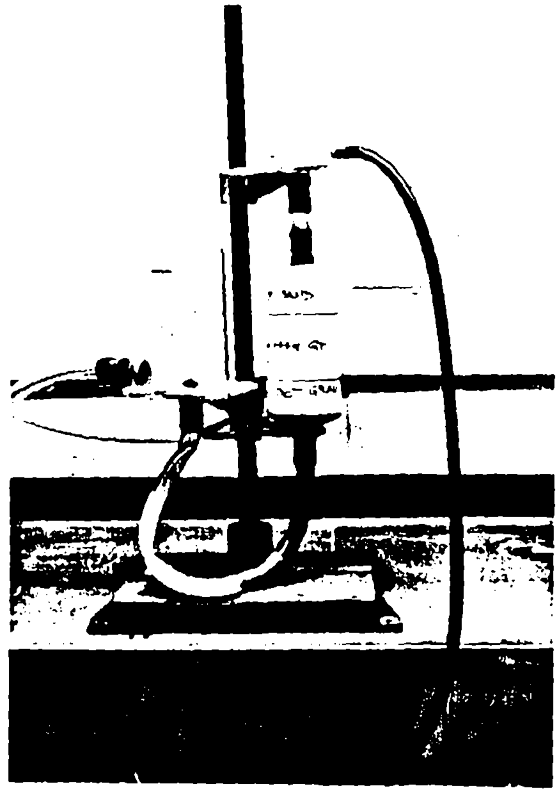
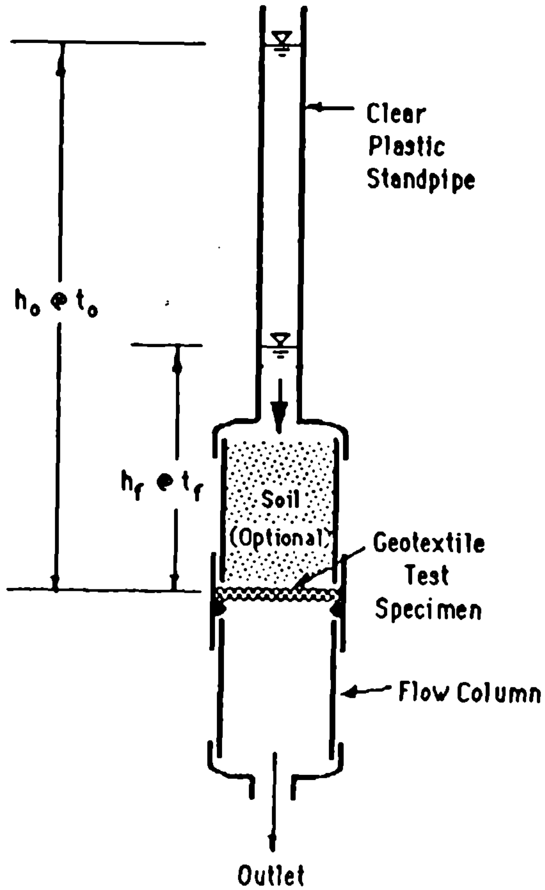


Figure 16 - Flow column and hydraulic head control devices for constant head tests



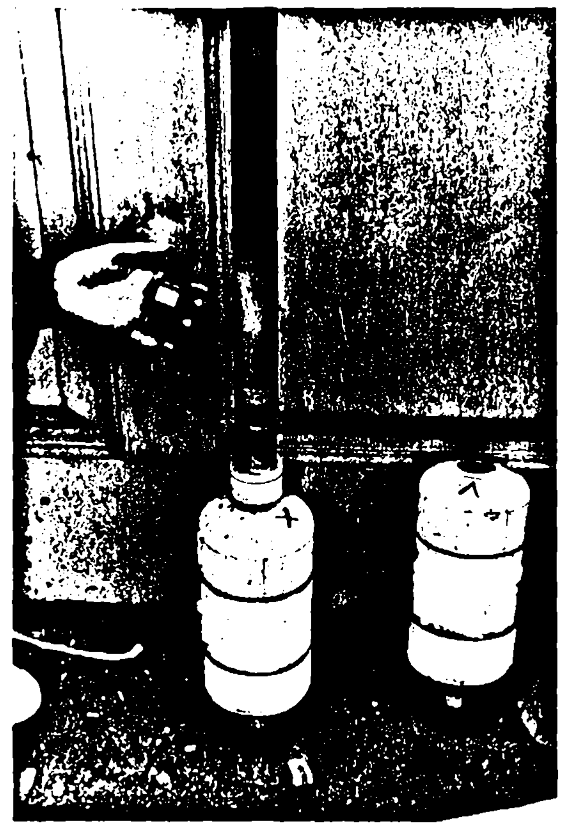


Figure 17 - Flow column and hydraulic head control devices for variable (or falling) head tests

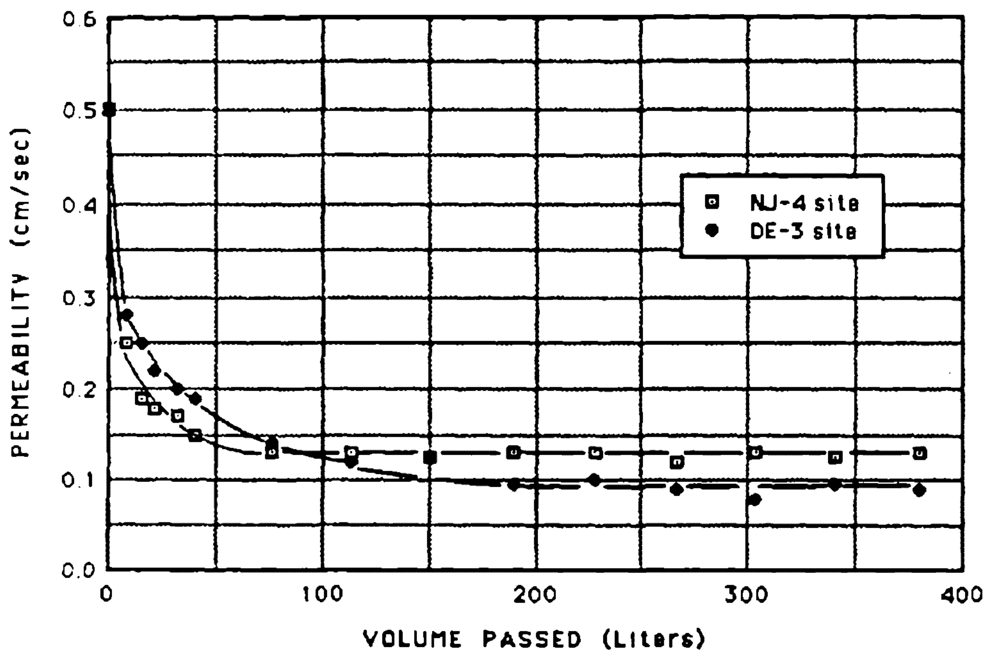


Figure 18 - Results of continuous leachate flow testing of soil/geotextile/column at DE-3 and NJ-4 sites based on variable head tests

as to stop, or even substantially decrease, the system's flow. This suggests that the short term filtration characteristics of both the soil and the geotextile are adequate to handle the indicated flow rates. It furthermore, provides a reference plane to which the long-term flow rates can be compared. Such long-term flow tests are the focus of the next section.

Flow Rates and Remediation Attempts

Long term intermittent flow rate evaluation of the columns using all six landfill leachates were undertaken. Variable head tests of the sixteen variations at each site were performed from which a "system permeability" could be calculated. The first test on each column established the base line value called "original permeability" in units of "cm/sec". From this point, flow tests were conducted on at least a monthly basis. The data to be reported was an average of at least three individual measurements per flow column.

Assuming that the flow rates would decrease as they did in Phase I testing, various remediation schemes were undertaken after the initial six months of flow rate testing. These included the following:

- leachate backflushing
- water backflushing
- nitrogen gas backflushing
- vacuum extraction

The strategy was to take flow rate readings until near-equilibrium conditions were attained, or until substantial clogging was evident, and then remediate the system by one of the above techniques. The results are given in Tables 8 through 16. These tables give flow rates in the form of system permeability (and percent reductions from the original value) for all 96 flow columns at the following stages in this Phase II portion of the project.

Table 8 - Flow rates during the initial six (6) months of evaluation

Table 9 - Flow rates after leachate backflush

Table 10 - Flow rates during the subsequent four (4) months of evaluation

Table 11 - Flow rates after water backflush

Table 12 - Flow rates during the subsequent five (5) months of evaluation

Table 13 - Flow rates after nitrogen gas backflush

Table 14 - Flow rates during the subsequent three (3) months of evaluation

Table 15 - Flow rates after vacuum extraction

Table 16 - Flow rates during the subsequent two (2) months of evaluation

The data included in these eight tables is plotted in the form of 96 separate graphs and is included as Appendix "B". These curves generally take a similar form to one another in that

Table 8 - Flow Rate Behavior and Percent Retained in Flow Rate Due to Biological Clogging During Initial Six (6) Months of Evaluation

Geotextile Type	Condition & Cover	Orig. Perm. (cm/sec)	PA-1		NY-2		DE-3		NJ-4		MD-5		PA-6	
			cm/sec	% Ret.	cm/sec	% Ret.	cm/sec	% Ret.	cm/sec	% Ret.	cm/sec	% Ret.	cm/sec	% Ret.
WM (NC)	AN/S	0.64	0.10	16	0.14	22	0.12	19	0.10	16	0.23	36	0.18	28
WM (NC)	A/S	0.64	0.16	25	0.18	28	0.088	14	0.13	20	0.18	28	0.20	31
WM (NC)	AN/W	1.3	1.3	100	0.63	48	0.63	48	0.098	8	0.25	19	0.64	49
WM (NC)	A/W	1.3	0.63	48	1.3	100	0.25	19	0.018	1	0.42	32	0.13	10
NW (HB)	AN/S	0.64	0.12	19	0.15	23	0.11	17	0.082	13	0.17	23	0.16	25
NW (HB)	A/S	0.64	0.073	11	0.17	27	0.062	10	0.013	2	0.043	7	0.20	31
NW (HB)	AN/W	1.3	0.32	25	0.016	1	0.012	1	0.0053	0	0.036	3	0.0099	1
NW (HB)	A/W	1.3	0.0016	0	0.0028	0	0.0015	0	0.0021	0	0.012	1	0.0047	0
NW (N) 16	AN/S	0.64	0.16	25	0.15	23	0.13	20	0.065	10	0.20	31	0.23	36
NW (N) 16	A/S	0.64	0.18	28	0.18	28	0.12	19	0.13	20	0.21	33	0.21	33
NW (N) 16	AN/W	1.3	0.84	65	1.3	100	0.32	25	0.21	16	0.42	32	0.42	32
NW (N) 16	A/W	1.3	0.84	65	1.3	100	0.045	3	0.25	19	0.64	49	0.11	8
NW (N) 8	AN/S	0.64	0.13	20	0.18	28	0.13	20	0.098	15	0.21	33	0.16	10
NW (N) 8	A/S	0.64	0.20	31	0.21	33	0.12	19	0.14	22	0.21	33	0.20	31
NW (N) 8	AN/W	1.3	0.84	65	1.3	100	0.42	32	0.64	49	0.64	49	0.64	49
NW (N) 8	A/W	1.3	0.84	65	1.3	100	0.066	5	0.075	6	0.64	49	0.64	49

Legend

WM = woven monofilament
NW = nonwoven
NC = non-calendered
HB = heat bonded
N = needled
AN = anaerobic
A = aerobic
S = sand over geotextile
W = without sand, i.e. geotextile alone

Summary

- 6 columns (6%) have 100 to 76% flow retained
- 4 columns (4%) have 75 to 51% flow retained
- 38 columns (40%) have 50 to 26% flow retained
- 34 columns (35%) have 25 to 6% flow retained
- 14 columns (15%) have 5 to 0% flow retained

96 100%

Table 9 - Flow Rate Behavior and Percent Retained in Flow Rates from Biological Clogging after First Treatment at Six (6) Months Duration
(Backflush was with Site Specific Leachate)

Geotextile Type	Condition & Cover	Orig. Perm. (cm/sec)	PA-1		NY-2		DE-3		NJ-4		MD-5		PA-6	
			cm/sec	% Ret.	cm/sec	% Ret.	cm/sec	% Ret.	cm/sec	% Ret.	cm/sec	% Ret.	cm/sec	% Ret.
WM (NC)	AN/S	0.64	0.15	23	0.20	31	0.17	27	0.17	27	0.25	59	0.25	59
WM (NC)	A/S	0.64	0.21	33	0.21	33	0.15	23	0.18	28	0.21	33	0.23	36
WM (NC)	AN/W	1.3	1.3	100	1.3	100	1.3	100	0.42	33	0.64	49	1.3	100
WM (NC)	A/W	1.3	1.3	100	1.3	100	1.3	100	0.64	49	0.64	49	1.3	100
NW (HB)	AN/S	0.64	0.13	20	0.23	36	0.18	28	0.13	20	0.21	33	0.21	33
NW (HB)	A/S	0.64	0.11	17	0.21	33	0.13	20	0.032	5	0.085	23	0.25	16
NW (HB)	AN/W	1.3	1.3	100	0.064	2	0.045	2	0.42	32	0.064	4	0.040	3
NW (HB)	A/W	1.3	0.004	1	0.0039	1	0.0059	1	0.0092	1	0.030	2	0.051	4
NW (N) 16	AN/S	0.64	0.18	28	0.21	33	0.15	23	0.15	23	0.20	31	0.28	44
NW (N) 16	A/S	0.64	0.21	33	0.20	31	0.16	25	0.18	28	0.23	36	0.23	36
NW (N) 16	AN/W	1.3	1.3	100	1.3	100	0.64	49	1.3	100	0.64	49	0.64	49
NW (N) 16	A/W	1.3	1.3	100	1.3	100	0.32	25	0.64	49	0.64	49	1.3	100
NW (N) 8	AN/S	0.64	0.17	27	0.25	39	0.16	25	0.14	22	0.13	20	0.21	33
NW (N) 8	A/S	0.64	0.21	32	0.23	36	0.17	27	0.16	25	0.12	19	0.25	39
NW (N) 8	AN/W	1.3	1.3	100	1.3	100	1.3	100	1.3	100	0.64	49	1.3	100
NW (N) 8	A/W	1.3	1.3	100	1.3	100	0.21	16	0.11	8	0.64	49	1.3	100

Legend

WM = woven monofilament
NW = nonwoven
NC = non-calendered
HB = heat bonded
N = needled
AN = anaerobic
A = aerobic
S = sand over geotextile
W = without sand, i.e. geotextile alone

Summary

- 23 columns (24%) have 100 to 76% flow retained
- 2 columns (2%) have 75 to 51% flow retained
- 45 columns (47%) have 50 to 26% flow retained
- 16 columns (17%) have 25 to 6% flow retained
- 10 columns (10%) have 5 to 0% flow retained

96 100%

Table 10 - Flow Rate Behavior and Percent Retained in Flow Rate from Biological Clogging Due to Four Months of Evaluation Following First Treatment (Ten Months Total Exposure)

Geotextile Type	Condition & Cover	Orig. Perm. (cm/sec)	PA-1		NY-2		DE-3		NJ-4		MD-5		PA-6	
			cm/sec	% Ret.	cm/sec	% Ret.	cm/sec	% Ret.	cm/sec	% Ret.	cm/sec	% Ret.	cm/sec	% Ret.
WM (NC)	AN/S	0.64	0.15	23	0.088	14	0.029	5	0.067	10	0.15	23	0.14	22
WM (NC)	A/S	0.64	0.17	27	0.12	19	0.038	6	0.12	19	0.031	5	0.13	20
WM (NC)	AN/W	1.3	0.64	49	0.42	32	0.36	28	0.64	49	0.079	6	0.64	49
WM (NC)	A/W	1.3	0.64	49	0.64	49	0.0043	0	0.034	3	0.25	19	0.42	32
NW (HB)	AN/S	0.64	0.17	27	0.077	12	0.065	10	0.082	13	0.14	22	0.12	19
NW (HB)	A/S	0.64	0.18	28	0.064	10	0.060	9	0.11	17	0.0049	1	0.11	17
NW (HB)	AN/W	1.3	0.64	49	0.067	5	0.0059	0	0.32	25	0.0052	0	0.0091	1
NW (HB)	A/W	1.3	0.002	0	0.002	0	0.0044	0	0.013	1	0.0072	1	0.0037	1
NW (N) 16	AN/S	0.64	0.13	20	0.094	15	0.059	9	0.13	20	0.13	20	0.13	20
NW (N) 16	A/S	0.64	0.17	27	0.11	17	0.069	11	0.094	15	0.12	19	0.13	20
NW (N) 16	AN/W	1.3	0.64	49	0.42	32	0.0097	1	0.64	49	0.36	28	0.32	25
NW (N) 16	A/W	1.3	0.32	25	0.098	8	0.0029	0	0.0059	0	0.0065	1	0.42	32
NW (N) 8	AN/S	0.64	0.12	19	0.12	19	0.069	11	0.026	4	0.11	17	0.12	19
NW (N) 8	A/S	0.64	0.32	50	0.11	17	0.079	12	0.067	10	0.14	22	0.12	19
NW (N) 8	AN/W	1.3	0.84	65	0.32	25	0.014	1	0.32	25	0.42	32	0.42	32
NW (N) 8	A/W	1.3	0.64	49	0.42	32	0.010	1	0.005	0	0.0065	0	0.18	14

Legend

WM = woven monofilament
NW = nonwoven
NC = non-calendered
HB = heat bonded
N = needled
AN = anaerobic
A = aerobic
S = sand over geotextile
W = without sand, i.e. geotextile alone

Summary

- 0 columns (0%) have 100 to 76% flow retained
- 2 columns (2%) have 75 to 51% flow retained
- 27 columns (28%) have 50 to 26% flow retained
- 46 columns (48%) have 25 to 6% flow retained
- 21 columns (22%) have 5 to 0% flow retained

96 100%

Table 11 - Flow Rate Behavior and Percent Retained in Flow Rate from Biological Clogging after Second Treatment at Ten (10) Months Duration
(Backflush was with Tap Water)

Geotextile Type	Condition & Cover	Orig. Perm. (cm/sec)	PA-1 cm/sec	PA-1 % Ret.	NY-2 cm/sec	NY-2 % Ret.	DE-3 cm/sec	DE-3 % Ret.	NJ-4 cm/sec	NJ-4 % Ret.	MD-5 cm/sec	MD-5 % Ret.	PA-6 cm/sec	PA-6 % Ret.
WM (NC)	AN/S	0.64	0.36	56	0.36	56	0.18	28	0.20	31	0.25	39	0.28	44
WM (NC)	A/S	0.64	0.42	66	0.36	56	0.21	33	0.23	36	0.10	16	0.36	56
WM (NC)	AN/W	1.3	1.3	100	1.3	100	1.3	100	1.3	100	0.64	49	1.3	100
WM (NC)	A/W	1.3	1.3	100	1.3	100	0.51	39	0.64	49	1.3	100	1.3	100
NW (HB)	AN/S	0.64	0.32	50	0.28	44	0.15	23	0.21	33	0.17	27	0.28	44
NW (HB)	A/S	0.64	0.36	56	0.21	33	0.12	19	0.23	36	0.0075	1	0.32	50
NW (HB)	AN/W	1.3	1.3	100	0.64	49	0.85	65	0.85	65	0.079	6	1.3	100
NW (HB)	A/W	1.3	1.3	100	0.11	8	0.0003	0	0.18	14	0.32	25	0.42	66
NW (N) 16	AN/S	0.64	0.32	50	0.32	50	0.21	33	0.25	39	0.20	31	0.32	50
NW (N) 16	A/S	0.64	0.25	39	0.25	39	0.17	27	0.21	33	0.51	80	0.28	44
NW (N) 16	AN/W	1.3	1.3	100	1.3	100	0.64	49	0.85	65	0.85	65	0.85	65
NW (N) 16	A/W	1.3	1.3	100	1.3	100	0.36	28	0.047	7	0.079	12	0.85	65
NW (N) 8	AN/S	0.64	0.25	39	0.28	44	0.21	33	0.085	13	0.18	28	0.32	50
NW (N) 8	A/S	0.64	0.36	56	0.32	50	0.13	20	0.085	13	0.11	17	0.25	78
NW (N) 8	AN/W	1.3	1.3	100	1.3	100	1.3	100	1.3	100	1.3	100	1.3	100
NW (N) 8	A/W	1.3	1.3	100	0.84	65	0.32	25	0.21	16	0.64	49	0.85	65

Legend

WM = woven monofilament
NW = nonwoven
NC = non-calendered
HB = heat bonded
N = needled
AN = anaerobic
A = aerobic
S = sand over geotextile
W = without sand, i.e. geotextile alone

Summary

- 25 columns (26%) have 100 to 76% flow retained
- 23 columns (24%) have 75 to 51% flow retained
- 33 columns (34%) have 50 to 26% flow retained
- 13 columns (14%) have 25 to 6% flow retained
- 2 columns (2%) have 5 to 0% flow retained

96 100%

Table 12 - Flow Rate Behavior and Percent Retained in Flow Rate from Biological Clogging Due to Five (5) Months of Evaluation Following Second Treatment (15 Months Total)

Geotextile Type	Condition & Cover	Orig. Perm. (cm/sec)	PA-1 cm/sec	PA-1 % Ret.	NY-2 cm/sec	NY-2 % Ret.	DE-3 cm/sec	DE-3 % Ret.	NJ-4 cm/sec	NJ-4 % Ret.	MD-5 cm/sec	MD-5 % Ret.	PA-6 cm/sec	PA-6 % Ret.
WM (NC)	AN/S	0.64	.14	22	.12	19	.095	15	.12	19	.050	8	.10	16
WM (NC)	A/S	0.64	.09	14	.16	25	.061	10	.14	22	.080	13	.11	17
WM (NC)	AN/W	1.3	.43	33	.87	67	.077	6	.87	67	.22	17	.44	34
WM (NC)	A/W	1.3	.66	51	.44	34	.001	0	.001	0	.069	5	.012	1
NW (HB)	AN/S	0.64	.11	17	.11	17	.042	7	.061	10	.016	3	.078	12
NW (HB)	A/S	0.64	.11	17	.08	13	.037	6	.075	12	.001	0	.11	17
NW (HB)	AN/W	1.3	.069	5	.001	0	.001	0	.001	0	.001	0	.008	1
NW (HB)	A/W	1.3	.001	0	.001	0	.001	0	.001	0	.001	0	.002	0
NW (N) 16	AN/S	0.64	.13	20	.05	8	.052	8	.091	14	.028	4	.095	15
NW (N) 16	A/S	0.64	.14	22	.06	9	.038	6	.11	17	.091	14	.13	20
NW (N) 16	AN/W	1.3	.001	0	.001	0	.001	0	.001	0	.001	0	.014	1
NW (N) 16	A/W	1.3	.001	0	.001	0	.001	0	.001	0	.001	0	.003	0
NW (N) 8	AN/S	0.64	.15	23	.095	15	.073	11	.085	13	.057	9	.08	13
NW (N) 8	A/S	0.64	.18	28	.091	14	.066	10	.098	15	.11	17	.14	23
NW (N) 8	AN/W	1.3	.43	33	.13	10	.001	0	.44	34	.001	0	.01	1
NW (N) 8	A/W	1.3	.015	1	.001	0	.001	0	.001	0	.001	0	.011	1

Legend

WM = woven monofilament
NW = nonwoven
NC = non-calendered
HB = heat bonded
N = needled
AN = anaerobic
A = aerobic
S = sand over geotextile
W = without sand, i.e. geotextile alone

Summary

- 0 columns (0%) have 100 to 76% flow retained
- 3 columns (3%) have 75 to 51% flow retained
- 7 columns (7%) have 50 to 26% flow retained
- 48 columns (50%) have 25 to 6% flow retained
- 38 columns (40%) have 5 to 0% flow retained

96 100%

Table 13 - Flow Rate Behavior and Percent Retained in Flow Rate from Biological Clogging After Third Treatment at Fifteen (15) Months Duration
(Nitrogen Gas Backflush)

Geotextile Type	Condition & Cover	Orig. Perm. (cm/sec)	PA-1 cm/sec	PA-1 % Ret.	NY-2 cm/sec	NY-2 % Ret.	DE-3 cm/sec	DE-3 % Ret.	NJ-4 cm/sec	NJ-4 % Ret.	MD-5 cm/sec	MD-5 % Ret.	PA-6 cm/sec	PA-6 % Ret.
WM (NC)	AN/S	.64	.32	50	.23	36	.23	36	.21	33	.20	31	.26	16
WM (NC)	A/S	.64	.21	33	.26	41	.21	33	.20	31	.20	31	.23	14
WM (NC)	AN/W	1.3	1.3	100	1.3	100	1.3	100	.87	67	.66	51	.87	67
WM (NC)	A/W	1.3	1.3	100	.66	51	.087	7	.08	6	.13	10	.33	25
NW (HB)	AN/S	.64	.28	44	.23	36	.18	28	.20	31	.18	28	.18	28
NW (HB)	A/S	.64	.20	31	.21	33	.13	20	.16	25	.087	14	.23	36
NW (HB)	AN/W	1.3	.87	67	.001	0	.087	67	.07	5	.001	0	.001	0
NW (HB)	A/W	1.3	.004	0	.001	0	.001	0	.001	0	.001	0	.001	0
NW (N) 16	AN/S	.64	.21	33	.26	41	.20	31	.21	33	.23	36	.23	36
NW (N) 16	A/S	.64	.21	33	.23	35	.18	28	.20	31	.21	33	.25	39
NW (N) 16	AN/W	1.3	1.31	100	.87	67	.87	6	.87	67	.001	0	.001	0
NW (N) 16	A/W	1.3	.08	6	.87	67	.066	5	.05	4	.001	0	.011	0
NW (N) 8	AN/S	.64	.21	33	.23	36	.20	31	.20	31	.21	33	.23	36
NW (N) 8	A/S	.64	.23	36	.23	36	.18	28	.17	27	.21	33	.21	33
NW (N) 8	AN/W	1.3	.87	67	.66	51	.87	67	.66	51	.001	100	.04	3
NW (N) 8	A/W	1.3	.66	51	.001	0	.001	0	.03	3	.001	100	.03	3

Legend

WM = woven monofilament
NW = nonwoven
NC = non-calendered
HB = heat bonded
N = needled
AN = anaerobic
A = aerobic
S = sand over geotextile
W = without sand, i.e. geotextile alone

Summary

- 7 columns (7%) have100 to 76% flow retained
- 16 columns (17%) have 75 to 51% flow retained
- 44 columns (46%) have 50 to 26% flow retained
- 10 columns (10%) have 25 to 6% flow retained
- 19 columns (20%) have 5 to 0% flow retained

96 100%

Table14 - Flow Rate Behavior and Percent Retained in Flow Rate from Biological Clogging Due to Three (3) Months of Evaluation Following Nitrogen Gas Backflush (18 Months Total)

Geotextile Type	Condition & Cover	Orig. Perm. (cm/sec)	PA-1 cm/sec	PA-1 % Ret.	NY-2 cm/sec	NY-2 % Ret.	DE-3 cm/sec	DE-3 % Ret.	NJ-4 cm/sec	NJ-4 % Ret.	MD-5 cm/sec	MD-5 % Ret.	PA-6 cm/sec	PA-6 % Ret.
WM (NC)	AN/S	0.64	0.11	17	0.13	20	0.075	12	0.16	25	0.015	2	0.073	11
WM (NC)	A/S	0.64	0.09	14	0.15	23	0.061	10	0.069	11	0.023	4	0.083	13
WM (NC)	AN/W	1.3	0.63	48	0.63	48	0.18	14	0.63	48	0.032	2	0.42	32
WM (NC)	A/W	1.3	0.42	32	0.31	24	0.001	0	0.001	0	0.001	0	0.037	3
NW (HB)	AN/S	0.64	0.10	16	0.07	11	0.051	8	0.060	9	0.014	2	0.064	10
NW (HB)	A/S	0.64	0.09	14	0.12	19	0.001	0	0.050	8	0.001	0	0.069	11
NW (HB)	AN/W	1.3	0.001	0	0.001	0	0.001	0	0.001	0	0.001	0	0.001	0
NW (HB)	A/W	1.3	0.001	0	0.001	0	0.001	0	0.001	0	0.001	0	0.001	0
NW (N) 16	AN/S	0.64	0.10	16	0.06	9	0.095	15	0.082	13	0.013	2	0.080	13
NW (N) 16	A/S	0.64	0.11	17	0.13	20	0.055	9	0.075	12	0.001	0	0.057	9
NW (N) 16	AN/W	1.3	0.42	32	0.001	0	0.016	1	0.63	48	0.001	0	0.001	0
NW (N) 16	A/W	1.3	0.001	0	0.001	0	0.001	0	0.001	0	0.001	0	0.001	0
NW (N) 8	AN/S	0.64	0.09	14	0.09	14	0.12	19	0.10	16	0.032	5	0.086	13
NW (N) 8	A/S	0.64	0.12	19	0.14	22	0.044	7	0.088	14	0.023	4	0.071	11
NW (N) 8	AN/W	1.3	1.26	97	0.001	0	0.001	0	0.63	48	0.001	0	0.025	2
NW (N) 8	A/W	1.3	0.001	0	0.001	0	0.001	0	0.001	0	0.001	0	0.001	0

<u>Legend</u>

WM = woven monofilament
NW = nonwoven
NC = non-calendered
HB = heat bonded
N = needled
AN = anaerobic
A = aerobic
S = sand over geotextile
W = without sand, i.e. geotextile alone

<u>Summary</u>

- 1 columns (1%) have 100 to 76% flow retained
- 1 columns (1%) have75 to 51% flow retained
- 9 columns (9%) have 40 to 26% flow retained
- 39 columns (41%) have 25 to 6% flow retained
- <u>46</u> columns (<u>48%</u>) have 5 to 0% flow retained

96 100%

Table 15 - Flow Rate Behavior and Percent Retained in Flow Rate from Biological Clogging After Fourth Treatment at Eighteen (18) Months Duration

Vacuum Extraction

Geotextile Type	Condition & Cover	Orig. Perm. (cm/sec)	PA-1 cm/sec	PA-1 % Ret.	NY-2 cm/sec	NY-2 % Ret.	DE-3 cm/sec	DE-3 % Ret.	NJ-4 cm/sec	NJ-4 % Ret.	MD-5 cm/sec	MD-5 % Ret.	PA-6 cm/sec	PA-6 % Ret.
WM (NC)	AN/S	0.64	0.21	33	0.16	25	0.16	25	0.16	25	0.064	10	0.095	15
WM (NC)	A/S	0.64	0.001	0	0.13	20	0.086	13	0.11	17	0.050	8	0.14	22
WM (NC)	AN/W	1.3	0.63	48	0.84	65	0.84	65	0.84	65	0.31	24	0.42	32
WM (NC)	A/W	1.3	0.21	16	0.31	24	0.001	0	0.032	2	0.090	7	0.25	19
NW (HB)	AN/S	0.64	0.15	23	0.12	19	0.12	19	0.14	22	0.037	6	0.071	11
NW (HB)	A/S	0.64	0.001	0	0.14	22	0.042	7	0.057	9	0.001	0	0.12	19
NW (HB)	AN/W	1.3	0.04	3	0.001	0	0.001	0	0.001	0	0.001	0	0.001	0
NW (HB)	A/W	1.3	0.001	0	0.001	0	0.001	0	0.001	0	0.001	0	0.001	0
NW (N) 16	AN/S	0.64	0.13	20	0.16	25	0.13	20	0.17	26	0.001	0	0.036	6
NW (N) 16	A/S	0.64	0.11	17	0.12	19	0.064	10	0.12	19	0.045	7	0.048	8
NW (N) 16	AN/W	1.3	0.63	48	0.001	0	0.36	28	0.84	65	0.001	0	0.001	0
NW (N) 16	A/W	1.3	0.001	0	0.001	0	0.001	0	0.001	0	0.001	0	0.001	0
NW (N) 8	AN/S	0.64	0.15	23	0.15	23	0.18	28	0.14	22	0.035	5	0.061	10
NW (N) 8	A/S	0.64	0.12	19	0.14	22	0.071	11	0.078	12	0.069	11	0.073	11
NW (N) 8	AN/W	1.3	0.63	48	0.001	0	0.001	0	0.84	65	0.001	0	0.066	5
NW (N) 8	A/W	1.3	0.001	0	0.001	0	0.001	0	0.001	0	0.001	0	0.001	0

Legend

WM = woven monofilament
NW = nonwoven
NC = non-calendered
HB = heat bonded
N = needled
AN = anaerobic
A = aerobic
S = sand over geotextile
W = without sand, i.e. geotextile alone

Summary

- 0 columns (0%) have 100 to 76% flow retained
- 5 columns (5%) have 75 to 51% flow retained
- 12 columns (13%) have 50 to 26% flow retained
- 43 columns (45%) have 25 to 6% flow retained
- 36 columns (37%) have 5 to 0% flow retained

96 100%

Table 16 - Flow Rate Behavior and Percent Retained in Flow Rate from Biological Clogging Due to Two(2) Months of Evaluation Following Fourth Treatment (20 Months Total)

Geotextile Type	Condition & Cover	Orig. Perm. (cm/sec)	PA-1		NY-2		DE-3		NJ-4		MD-5		PA-6	
			cm/sec	% Ret.	cm/sec	% Ret.	cm/sec	% Ret.	cm/sec	% Ret.	cm/sec	% Ret.	cm/sec	% Ret.
WM (NC)	AN/S	0.64	0.14	22	0.12	19	0.091	14	0.11	17	0.005	1	0.082	13
WM (NC)	A/S	0.64	0.067	10	0.13	20	0.046	7	0.058	9	0.012	2	0.075	12
WM (NC)	AN/W	1.3	0.33	25	0.33	25	0.43	33	0.33	25	0.093	7	0.008	1
WM (NC)	A/W	1.3	0.059	5	0.19	15	0.001	0	0.001	0	0.001	0	0.068	5
NW (HB)	AN/S	0.64	0.12	19	0.066	10	0.053	8	0.048	8	0.005	1	0.054	8
NW (HB)	A/S	0.64	0.10	16	0.054	8	0.005	1	0.005	1	0.005	1	0.078	12
NW (HB)	AN/W	1.3	0.001	0	0.001	0	0.001	0	0.001	0	0.001	0	0.001	0
NW (HB)	A/W	1.3	0.001	0	0.001	0	0.001	0	0.001	0	0.001	0	0.001	0
NW (N) 16	AN/S	0.64	0.13	20	0.080	13	0.058	9	0.069	1	0.005	1	0.005	1
NW (N) 16	A/S	0.64	0.12	19	0.083	13	0.013	2	0.046	7	0.005	1	0.005	1
NW (N) 16	AN/W	1.3	0.11	8	0.001	0	0.001	0	0.33	25	0.001	0	0.001	0
NW (N) 16	A/W	1.3	0.001	0	0.05	4	0.001	0	0.001	0	0.001	0	0.001	0
NW (N) 8	AN/S	0.64	0.15	23	0.071	11	0.11	17	0.066	10	0.013	2	0.045	7
NW (N) 8	A/S	0.64	0.11	17	0.098	15	0.035	5	0.075	12	0.019	3	0.040	6
NW (N) 8	AN/W	1.3	0.43	33	0.11	8	0.001	0	0.076	6	0.001	0	0.001	0
NW (N) 8	A/W	1.3	0.001	0	0.001	0	0.001	0	0.001	0	0.001	0	0.001	0

Legend

WM = woven monofilament
NW = nonwoven
NC = non-calendered
HB = heat bonded
N = needled
AN = anaerobic
A = aerobic
S = sand over geotextile
W = without sand, i.e. geotextile alone

Summary

- 0 columns (0%) have 100 to 76% flow retained
- 0 columns (0%) have 75 to 51% flow retained
- 1 columns (1%) have 50 to 26% flow retained
- 44 columns (46%) have 25 to 6% flow retained
- 51 columns (53%) have 5 to 0% flow retained

96 100%

flow rates decrease until a remediation is attempted. This remediation increases the flow rate (to varying degrees), but subsequent testing over time causes the flow rate to decrease tending toward the original, and uninterrupted behavior.

Some comments as to the remediation attempts are in order before discussing the trends appearing in Tables 8 through 16 and the corresponding graphs of Appendix "B".

Regarding leachate backflushing: our thoughts were that additional liquid would not be added to the total quantity of leachate generated at the site for an owner/operator to handle and subsequently treat. Backflushing with leachate was accomplished by reversing the flow in a constant head setup, recall Figure 16. The downstream gradient reservoir inlets leachate at the bottom of the flow column and outlets the leachate into the upstream reservoir. A pump with a controller is required to maintain a constant head in the downstream gradient reservoir and a drain connects the upstream reservoir to the sump.

The backflushing was performed at a constant head of three feet. Due to the reverse mode of flow, a geotextile and porous stone retainer was placed above the flow column to prevent the sand from liquefying and flushing into the outlet reservoir. It is interesting to note that this geotextile porous stone trap needed to be washed out or replaced after each backflushing, as it always collected sediment and bioslime after each five minutes of backflushing.

Regarding backflushing with water: this technique was also accomplished by reversing the flow on the test columns. The technique was performed in the laboratory for all ninety six columns. The base of the flow column was attached to an inlet hose. The columns containing sand were backflushed at 10 lb/sq. in. using a 100 gal/hr flow rate for a duration of one minute. The columns containing geotextiles alone were backflushed at 2 lb/sq. in. using a 100 gal/hr flow rate for a duration of one minute. Different pressures were utilized to ensure that excessive pressure would not dislodge those columns with the geotextile alone. Due to the reverse mode of flow, a geotextile and porous stone retainer were placed above the flow column to prevent the sand from liquefying and flushing into the outlet reservoir. Instead of an in-line restraint, however, the geotextile porous stone trap was hand held above the column during the backflushing process.

Regarding backflushing with nitrogen gas: the thought was not to add any liquid to the system. Nitrogen was used so as not to destroy anaerobic conditions in those test columns which were constantly saturated. Backflushing with nitrogen was accomplished by reversing the flow in the columns. The technique was performed in the laboratory for all ninety six columns. The test column was attached to an inlet hose. The columns were first saturated with leachate for 24 hours. The columns were then hooked up to the nitrogen tank and pressurized in a reverse mode. All of the columns were backflushed at 30 lb/in^2 using a 100 gal/hr flow rate for a duration of one minute. Backflushing with a gas produced a very different response from that of backflushing with a liquid. In this case, no geotextile nor porous stone retainer was needed because only bubbles and leachate emerged from the top of the columns. Only minor amounts of solids were transported in the froth which was emitted from the top of each column.

Regarding vacuum extraction; our thoughts were that we could relieve the clogging by sucking the bioslime and sediment down-gradient instead of trying to force it up-gradient as in the other three remediation attempts. This method, like backflushing with nitrogen, would not generate any additional liquid and might be relatively easy to implement in the field. Vacuum extraction was performed in the laboratory for all ninety six columns. The permeameter base was attached to an inlet hose. The columns were first saturated with leachate for 240hours. The columns were then attached to the vacuum system and 500 ml of leachate was drawn through each column. The vacuum was maintained at 10 inches of mercury during this time. Due to the different degrees of clogging some columns relinquished this quantity of fluid quickly while others needed considerable time.

As mentioned previously, Tables 9, 11, 13 and 15 are the results of the leachate backflush, water backflush, nitrogen backflush and vacuum extraction, respectively. Tables 8, 10, 12, 14 and 16 represent the flow rate behavior preceding and following each of these remediation schemes.

Summary of Phase Two Study

The flow rate trends observed in Phase I were again noticed in this Phase II study. We feel that the Phase II data, however, is much more authoritative due to the greatly improved test devices. Appendix "C" gives details of the ASTM Test Method which has been modeled and developed on the basis of this testing program. It will be available as ASTM D1987-91, as of May 1, 1991. Also it was noted that both the sand/geotextile combined systems and the geotextile by itself are candidates for clogging. *Regarding the first six months of flow testing, i.e., before the first remediation, the following comments apply.*

- The columns with sand above the geotextiles clogged considerably more than those with the geotextile alone; i.e., 23% flow was retained for sand/geotextiles vs. 34% flow retained for geotextiles alone. Note that, if the heat-bonded nonwoven fabrics are eliminated from the geotextile group, the flow rate retained by the geotextile group is 45%, suggesting that geotextiles can certainly clog less than natural soil filters.
- Of the four geotextiles evaluated, the highest retained flow was with the lightweight needled nonwoven (38.0%), with the heavyweight needled nonwoven (34.2%) and woven monofilament (31.9%) slightly behind. The nonwoven heat-bonded fabric had the lowest retained flow of only 10.0% after 6 months of evaluation.
- Of the various landfill leachates, the lowest retained flow rate was using the NJ-4 (14%) and DE-3 (17%) leachates. Recall from Table 4 that these are the leachates with the highest TS and BOD_5 concentrations. The other four landfill leachates and their percentages of flow retained after six months of testing were PA-6 (26%), MD-5 (29%), PA-1 (38%) and NY-2 (41%).

In order to assess the overall performance of the remediation attempts, and their relative performance in contrast to one another, the data of Tables 9, 11, 13 and 15 were analyzed with respect to their percent of flow rate improvement. These values were actually scaled directly from the 96 curves of Appendix "B". The results for percent recovery, or removal efficiency, are given in Table 17. The data indicates the following trends:

- Backflushing of geotextiles by themselves is more efficient than backflushing of geotextile/sand systems. The average recovery efficiencies are 29% and 13%, respectively.
- With sand overlying a geotextile there is no measurable difference from one type of geotextile to another.
- With the geotextile acting alone, remediation is most effective with the woven monofilament geotextiles (38% recovery efficiency), slightly less effective with the

Table 17 - Flow Rate Recovery with Respect to Various Remediation Attempts

(a) Flow Columns with Sand Overlying Geotextile

Geotextile Type	Condition	Recovery Efficiency (%) Leachate	Water	Nitrogen	Vacuum	Averages		
woven,	anaerobic	15	26	17	8	17	15	13%
monofilament	aerobic	7	27	14	7	14		
nonwoven,	anaerobic	8	20	21	7	14	13	
heat-bonded	aerobic	9	18	16	6	12		
nonwoven,	anaerobic	11	20	19	6	14	12	
needled-light	aerobic	6	19	14	2	11		
nonwoven,	anaerobic	6	25	24	8	16	14	
needled-heavy	aerobic	5	25	19	3	13		
Average		8	23	18	6			

(b) Flow Columns with Geotextile Alone

Geotextile Type	Condition	Recovery Efficiency (%) Leachate	Water	Nitrogen	Vacuum	Averages		
woven,	anaerobic	45	60	45	18	42	38	29%
monofilament	aerobic	58	56	20	7	35		
nonwoven,	anaerobic	19	51	23	1	23	16	
heat-bonded	aerobic	2	35	0	0	9		
nonwoven,	anaerobic	44	74	45	12	44	31	
needled-light	aerobic	20	38	19	0	19		
nonwoven,	anaerobic	35	44	51	10	35	30	
needled-heavy	aerobic	35	42	29	0	26		
Average		32	50	29	6			

nonwoven needled lightweight (31%) and heavyweight (30%) geotextiles, and relatively ineffective with the nonwoven heat bonded geotextiles (16%).

- For the cases where sand is placed over the geotextile, there is no difference between anaerobic and aerobic remediation schemes.
- For the geotextile acting by itself, remediation was slightly better under anaerobic conditions than with aerobic conditions.
- For the cases where sand is placed over the geotextile, the remediation recovery efficiency rankings were:

  water > nitrogen > leachate > vacuum

- For the cases where the geotextile is acting alone, the remediation recovery efficiency rankings were:

  water > leachate > nitrogen > vacuum

CONCLUSIONS

Recognition of past research concerning biological clogging of landfill drainage systems has led to a simulated field oriented project focused on geotextile filter clogging using a number of domestic landfill leachates. The filter was singled out (versus the geonet drain, drainage stone or perforated pipe) since it has the smallest openings and is likely to become clogged before other components. Geotextiles were emphasized because they are relatively new materials for this particular application.

Phase I of the study, which lasted for 12 months, caused a reorientation of our initial goals since the granular soils covering the filters were clogging before the geotextiles. Furthermore, sediments, and/or particulates, were a major factor in the flow reductions which appeared to be synergistic with the biological clogging. Clearly, partial filter clogging was occurring with a gradual reduction of flow rate over time. These trends were common to all six (6) landfills that were under observation. All of the landfills were domestic (Subtitle "D") facilities; but were very different in their waste stream, volume of waste deposited and liquid management schemes. It was recognized early in this Phase I activity that remediation attempts would be a necessary part of the overall study, but the experimental setup could not accommodate such activities. New, and different, test devices would be necessary if such attempts were to be made. What was concluded, however, from Phase I activities were the following:

- Filter clogging (as indicated by flow rate reductions) over the 12-month test period varied widely. The range was between 10% and 100% (i.e., to the limit of our capability).
- A geotextile filter must be relatively open in its pore structure if it is to limit the amount of clogging, i.e., the geotextile must be capable of passing the sediment, or particulates, along with the associated micro-organisms into the down-gradient drainage system.
- The polymer type (polypropylene, polyester or polyethylene) comprising the geotextile fibers appears to be a non-issue.
- Both anaerobic and aerobic conditions promote clogging, the relative amounts, however, were not capable of being identified because of differing test setups.
- The strength of the geotextiles was not adversely effected by the 12-month exposure to the various leachates. This finding, coupled with numerous micrographs which showed no chemical attachment of bacteria to the fibers, leads us to conclude that *biological degradation of polymeric based geotextiles does not occur.*

Phase II of the study, which lasted for 24 months, saw the development of a new, and vastly improved, test device for flow rate evaluation. The four inch diameter flow columns which were developed during this project have the following capabilities:

- All types of cross sections can be evaluated; geotextiles by themselves, soil/geotextile systems, soil/geotextile/geonet systems, or soil/geotextile/gravel systems.
- Anaerobic, or aerobic, conditions can be maintained.
- Flow rates can be evaluated using a falling head or a constant head measurement approach.
- The devices are relatively small and quite portable. Therefore, they can be stored indoors and taken to a site for evaluation, or stored at the site, or even within the leachate storage tank or sump.
- Various types of remediation of clogged systems can be evaluated.
- The test devices and their measurement protocol have recently been adopted as an ASTM Test Method, see Appendix "C". The test method designation is D1987-91 and will be available May 1, 1991.
- The test devices, and their contents, can be epoxy-set and cut in half to visually observe the conditions existing within the cross section.
- Since all parts of the device consist of PVC plumbing and swimming pool accessories, they are readily available, easily sealed by chemical wipes, and low in cost. Current cost for all components necessary to build one flow column is approximately $30.

Ninety-six (96) of the above described test columns were constructed and used for the duration of this Phase II study. There were four geotextiles, with and without soil above them, anaerobic and aerobic conditions, and all were used at six landfills ($4 \times 2 \times 2 \times 6 = 96$). They were evaluated for an initial six months; from which flow reductions were seen to replicate the results of the Phase I study. Thus, the first remediation, a leachate backflush, was attempted. It resulted in an improved flow rate but to varying amounts between the 96 different columns. After four months of continued flow testing the flow rates decreased allowing for a second remediation. This remediation used a water backflush. Again flow rates were increased but over the next five months they again decreased. The third remediation was a nitrogen gas backflush. It improved flow rates, but three months later they were once again reduced. The fourth, and last, remediation was vacuum extraction which only nominally improved flow rates when it was performed. Thereafter, the flow rate again decreased. The overall average behavior of the 96 columns is shown in Figure 19. It visually describes the decreasing flow rate trends between remediations and the rapid increase in flow rates immediately following

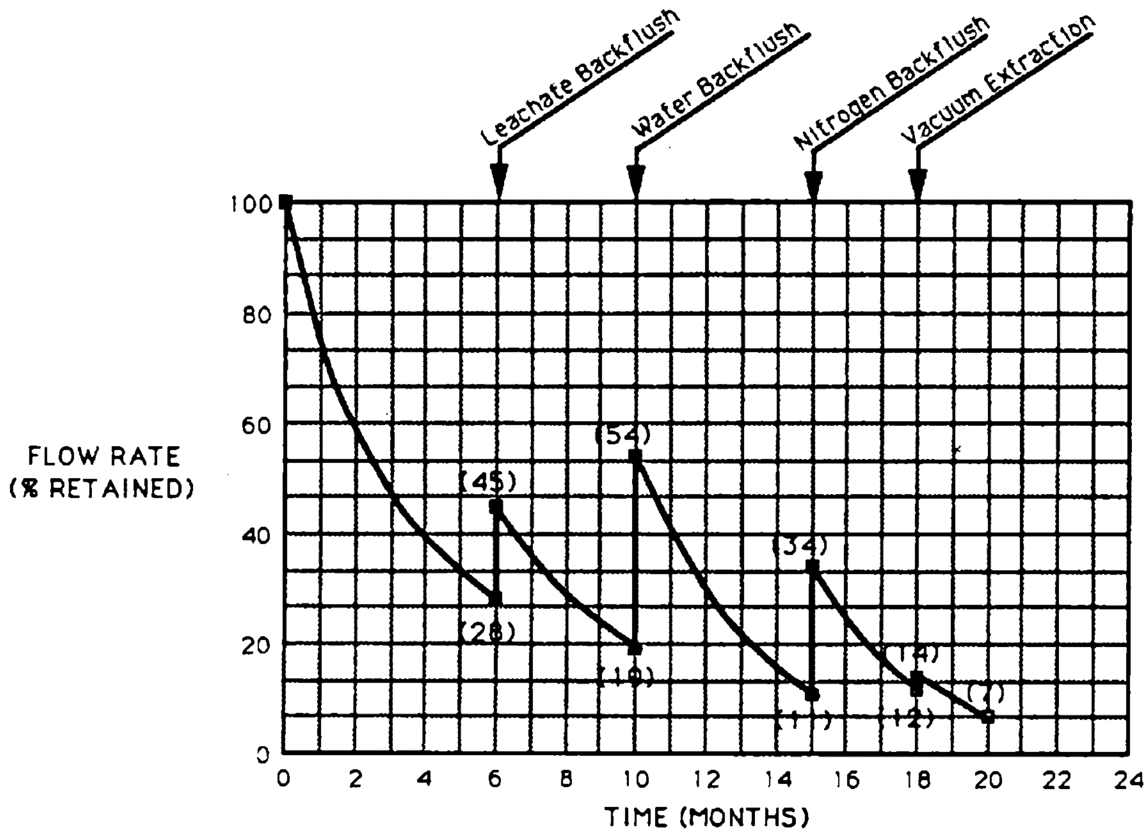


Figure 19 - Average response of ninety-six flow rate colmns from Phase II Activities

remediation. The individual curves for each of the 96 test columns are given in Appendix "B".

The conclusions reached from this Phase II study are as follows:

- Flow rate reductions were similar to the Phase I results and the conclusions drawn earlier have been substantiated.
- If geotextile and/or soil filters are to be used in leachate collection systems they must have sufficiently open voids to pass the sediment, or particulates, along with the micro-organisms contained in the leachate into the downstream drainage system.
- The limiting, or equilibrium, flow rate retained must be compared to the site specific design requirement to see if it is adequate, or not. If flow rates over time are not adequate, remediation is necessary. It was found that the water backflush technique gave the best results (35% improvement), nitrogen gas backflush (23%) and leachate backflush (17%) methods were next, and the vacuum extraction gave only nominal improvement (2%), i.e., it was the least effective.
- The periodicity of backflushing to open up a clogged, or semi-clogged, filter system appears to be approximately six (6) months.

Early in the overall study it was suggested that the incorporation of biocides into the geotextile (or geonet) polymer structure might be effective in keeping the flow system open. The concept was to add various amounts of a time-released biocide into the polymer compound as the product is manufactured, which would essentially diffuse to the surface of the fibers during its service life. Upon contact, it would subsequently kill the viable micro-organisms in the leachate. In the tests that were conducted on 16 separately built flow columns there was some experimental evidence that 2% and 4% biocide was partially effective. However, the remains of the dead bacteria must be permitted to pass through the system. This apparently could not happen for our particular tests setups. Thus, the idea of a very open filter system was further reinforced. This biocide study is presented in its entirety as Appendix "A".

RECOMMENDATIONS

As far as recommendations are concerned; it is very clear to us that landfill filters are not, and cannot, be designed identically as soil filters in geotechnical applications. *Leachate is a turbid, micro-organism laden liquid which behaves very differently than water.* Recognizing this feature leads us to our recommendations concerning landfill drainage/filtration systems.

- The focus of attention should be placed on the filter with respect to long-term flow rate capability. Note that the drainage component (gravel, geonet or pipe) can then be designed based on the long-term flow rate capability of the filter.
- The filter, either geotextile or natural soil, must be sufficiently open so as to pass the majority of the sediment and micro-organisms contained in the leachate into the downstream drain in a steady-state (i.e., equilibrium) manner.
- The required quantity of leachate flowing through the filter is a site-specific design consideration which has not been considered in this project.
- The drain beneath the filter must be capable of accepting this flow rate (along with the associated sediment and micro-organisms) and of transmitting it to the downgradient sump for collection, removal and proper treatment.

These comments underscore the importance of the design-by-function concept of engineering design. For a landfill filter, this involves comparing an allowable flow rate with a required flow rate for a design value of factor-of-safety. This project gave insight as to allowable flow rates for a variety of possible geotextile and natural soil filter conditions. The required flow rate must come from a site-specific design. In this regard additional research should be considered.

An additional project, with a focus on design considerations, is recommended. Clearly, the HELP model[4] would be involved in such an effort, but other water balance methods might also be considered. In fact, the entire liquids management strategy of landfilling should probably be investigated in light of current practice, e.g., current trends toward leachate recirculation practices. In such a proposed effort, field exhuming of abandoned landfills, or exhuming sites-of-oportunity which have open leachate collection systems, should be carefully examined for their behavior and performance. By so doing, feed-back into either the allowable flow rates or the required flow rates can be re-evaluated and appropriately modified.

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Appendix "A"

BEHAVIOR OF BIOCIDE TREATED GEOSYNTHETICS

APPENDIX "A"

BEHAVIOR OF BIOCIDE TREATED GEOSYNTHETICS

A-1 Introduction

In light of the relatively large flow rate decreases that were observed in the course of this study, an attempt at using biocides in the flow system was undertaken. This was done under the assumption that the biocide would kill the micro-organisms that came into contact with it and that the non-viable (i.e., dead) matter would pass through the system in much the same way that fine particles or sediment moves through any other drainage system. Furthermore, the introduction of the biocide was felt to be best achieved when delivered on a long-term basis rather than as one bulk dosage. Thus, biocide was added to the polymer compound during fabrication of the respective geonets or geotextiles. The reasoning for this approach was that the biocide would time release, via molecular diffusion, through the polymer structure and migrate to the surface of the ribs or fibers over a long period of time. If the approach is seen to be of value, calculations can then be made as to the long-term time release behavior. This Appendix to the report describes our attempts at increasing flow rates of landfill leachate filters and drainage systems using biocide treated geosynthetics.

A-2 Type of Biocide

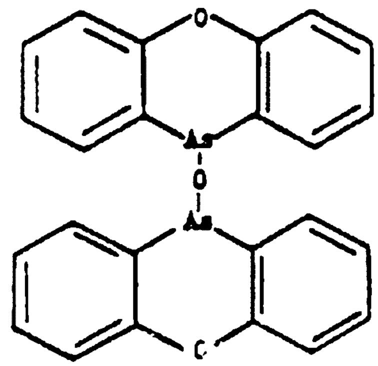
The biocide used in this study is Vinyzene® SB-1 PR manufactured by Morton Thiokol, Inc. of Danvers, Massachusetts. Vinyzene SB-1 PR is a concentrate of 10, 10' -oxybisphenoxarsine (OBPA) in a polypropylene resin carrier. The product, is supplied as a homogeneous solid in pelletized form measuring approximately 3.5 mm by 2.5 mm. It is recommended for use in polyolefins and other polymeric compositions requiring preservation against fungal and bacterial deterioration. The manufacturer states that "low levels of Vinyzene SB-1 EEA (a similar product but in an ethylene acrylic acid copolymer resin carrier) will provide long term preservation against fungal and bacterial attack and will help prevent surface growth, permanent staining, embrittlement and premature product failure." Vinyzene can be incorporated into the polymer compound at any convenient stage of the manufacturing process. The product can be fed into an extrusion operation in much the same way as pelletized color concentrates.

In 1976, EPA placed OBPA on its list of suspect pesticides that might be hazardous to human health. EPA's review of animal and other studies on OBPA, however, indicated that it is not as hazardous as originally suspected. On May 4, 1979 the U.S. Environmental Protection Agency decided that the pesticide, OBPA, which is used in a wide variety of plastic consumer products to protect them from fungal and bacterial damage, does not pose a threat to human health or the environment if used in accordance with label instructions. This decision means that OBPA has been restored to its former place on EPA's list of currently registered pesticides.

Materials containing OBPA include swimming pool liners, wall coating, vinyl roofs on cars, marine upholstery, awnings, industrial fabric, and caulking for tubs, sinks, weatherstripping and gutter repair. The EPA registration number for Vinyzene® is 2829-115 and Morton Thiokol's patent number is 4,086,297.

Some selected physical and chemical properties of 10, 10'-oxybisphenoxarsine (OBPA) are as follows.

Molecular Formula:	$C_{24}H_{16}As_2O_3$
Molecular Weight:	502.2
Structural Formula:	



Specific Gravity:	1.40 - 1.42
Appearance:	White to off-white crystalline solid
Melting Point:	185 - 186°C.
Vapor Pressure:	$< 10^{-6}$ torr @ 21°C
	$< 10^{-6}$ torr @ 100°C
	1.0×10^{-3} torr @ 150°C
	3.0×10^{-3} torr @ 200°C
	8.5×10^{-3} torr @ 250°C
Thermal Decomposition Range:	300 – 380°C
Solubility	5 ppm in H_2O 2.75 gm/100 gm of 95% ethanol 2.30 gm/100 gm of isopropanol 2.78 gm/100 gm of xylene

A-3 Incorporation of the Biocide into Different Geosynthetics

The biocide was shipped to the respective geosynthetic fabrication facility for its inclusion into the candidate geonet or geotextile. After the dosage was decided upon (it varied from 1 to 8% by weight), it was added to the standard compound, suitably mixed and extruded into ribs (for geonets) or fibers (for geotextiles).

In the first series of tests, either 1, 2 or 4% biocide was introduced into the compound to produce a 250 mil thick, high density polyethylene (HDPE) geonet. For control purposes, the same type of geonet was produced without the addition of any biocide. The cross section of the columns for these tests consisted (from the top down) of sand/geotextile/geonet/gravel and they were coded as Series "A", see Table A-1. Tests were conducted both saturated at all times (labeled anaerobic) and allowed to air dry between readings (thus aerobic). All tests in this series were run for 444 days duration.

The next series of tests, i.e. Series "B", utilized the biocide in the geotextile and did not use a geonet. The cross section consisted of sand/geotextile/gravel. The geotextile was of the nonwoven, needle-punched polypropylene variety and it contained either 2% or 4% biocide. The biocide was introduced at the fabrication facility along with the manufacturers standard compound of resin, carbon black (or other antidegradant) and processing package. As seen in Table A-1, there were also geotextiles included with no biocide so as to act as the control columns. Tests were conducted under both constantly saturated conditions (labeled anaerobic) and intermittently saturated, then air dried condition (thus aerobic). All tests in this series were performed for 444 days.

Test Series "C" consisted of biocide treated geotextiles and no geonets; but unlike the previous series, three different types of geotextiles were evaluated. The geotextiles were nonwoven needle punched (as before) and also two types of woven monofilament fabrics with different opening sizes, see Table A-1. The tests were also different in that gravel was used above the geotextile instead of sand. Thus the flow column consisted of gravel/geotextile/gravel, with the geotextiles treated with 2, 4 or 8% biocide. Again, the biocide was introduced at the manufacturing facility. In this series, which lasted 121 days, all tests were kept saturated, thus anaerobic.

Table A-1 - Conditions Within Flow Columns for Biocide Study

Coding (1)	Soil (2) Above	Geotextile (3) Type	Geotextile Size (mm)	Geotextile AOS Sieve	Geotextile Amt. Biocide	Geonet (4) Amt. Biocide	Soil (5) Below	Condition
A0-AN	Sand	N-N-PP	0.15	100	0	0	Gravel	Anaerobic
A0-A	Sand	N-N-PP	0.15	100	0	0	Gravel	Aerobic
A1-AN	Sand	N-N-PP	0.15	100	0	1	Gravel	Anaerobic
A1-A	Sand	N-N-PP	0.15	100	0	1	Gravel	Aerobic
A2-AN	Sand	N-N-PP	0.15	100	0	2	Gravel	Anaerobic
A2-A	Sand	N-N-PP	0.15	100	0	2	Gravel	Aerobic
A4-AN	Sand	N-N-PP	0.15	100	0	4	Gravel	Anaerobic
A4-A	Sand	N-N-PP	0.15	100	0	4	Gravel	Aerobic
B0-AN1	Sand	N-N-PP	0.15	100	0	-	Gravel	Anaerobic
B0-AN2	Sand	N-N-PP	0.15	100	0	-	Gravel	Anaerobic
B0-A1	Sand	N-N-PP	0.15	100	0	-	Gravel	Aerobic
B0-A2	Sand	N-N-PP	0.15	100	0	-	Gravel	Aerobic
B2-AN	Sand	N-N-PP	0.15	100	2	-	Gravel	Anaerobic
B2-A	Sand	N-N-PP	0.15	100	2	-	Gravel	Aerobic
B4-AN	Sand	N-N-PP	0.15	100	4	-	Gravel	Anaerobic
B4-A	Sand	N-N-PP	0.15	100	4	-	Gravel	Aerobic

Notes

(1) Test Series "A" and "B" lasted 444 days; Test Series "C" lasted 121 days.
(2) Sand is a #40 Sieve Subrounded Ottawa Sand in a 4.0 inch thick layer above the geotextile
(3) N-N-PP = nonwoven needle punched polypropylene
    W-M-PP1 = woven monofilament polypropylene AOS = 70
    W-M-PP2 = woven monofilament polypropylene AOS = 40
(4) Geonet is a 250 mil HDPE
(5) Gravel is a 1" to 1.5" Subrounded Gravel

Table A-1 - Continued

Coding (1)	Soil (2) Above	Geotextile (3) Type	Geotextile Size (mm)	Geotextile AOS Sieve	Geotextile Amt. Biocide	Geonet (4) Amt. Biocide	Soil (5) Below	Condition
C1-0-AN1	Gravel	N-N-PP	0.15	100	0	-	Gravel	Anaerobic
C1-0-AN2	Gravel	N-N-PP	0.15	100	0	-	Gravel	Anaerobic
C1-2-AN1	Gravel	N-N-PP	0.15	100	2	-	Gravel	Anaerobic
C1-2-AN2	Gravel	N-N-PP	0.15	100	2	-	Gravel	Anaerobic
C1-4-AN1	Gravel	N-N-PP	0.15	100	4	-	Gravel	Anaerobic
C1-4-AN2	Gravel	N-N-PP	0.15	100	4	-	Gravel	Anaerobic
C1-8-AN1	Gravel	N-N-PP	0.15	100	8	-	Gravel	Anaerobic
C1-8-AN2	Gravel	N-N-PP	0.15	100	8	-	Gravel	Anaerobic
C2-0-AN1	Gravel	N-N-PP	0.15	100	0	-	Gravel	Anaerobic
C2-0-AN2	Gravel	N-N-PP	0.15	100	0	-	Gravel	Anaerobic
C2-2-AN	Gravel	N-N-PP	0.15	100	2	-	Gravel	Anaerobic
C2-4-AN	Gravel	N-N-PP	0.15	100	4	-	Gravel	Anaerobic
C3-2-AN	Gravel	W-M-PP-1	0.21	70	2	-	Gravel	Anaerobic
C3-4-AN	Gravel	W-M-PP-1	0.21	70	4	-	Gravel	Anaerobic
C4-2-AN	Gravel	W-M-PP-2	0.42	40	2	-	Gravel	Anaerobic
C4-4-AN	Gravel	W-M-PP-2	0.42	40	4	-	Gravel	Anaerobic

A-4 Field Testing and Evaluation Procedures

Flow rate testing for each of the columns with biocide treated geosynthetics were placed within the four inch diameter incubation and test columns depicted in Figure A-1. As indicated in Table A-1 there were 8 columns in Series "A", 8 columns in Series "B" and 16 columns in Series "C". Series "A" and "B" were evaluated over a 444 day duration and Series "C" was evaluated for 121 days duration.

All of the tests in this biocide study used leachate from landfill site DE-3. This particular leachate has the highest concentration of COD, TS and BOD_5 of the six landfill leachates which were evaluated during the course of the project. The approximate properties of the leachate are as follows:

- pH = 5.8
- COD = 40,000 mg/l
- TS = 17,000 mg/l
- BOD_5 = 24,000 mg/l

Fresh leachate was used for each test since it was taken directly out of the sump at the low elevation of the landfill or from the nearest underground storage tank.

The tests were of the falling head variety which measures the time of flight for a high head of leachate to reach a lower value. The protocol for the test itself is included as Appendix "B" to this report. Calculations allow for the determination of a "system" hydraulic conductivity, or permeability coefficient which is in the units of cm/sec. This unit is the conventional one used in EPA reports and manuals. Note, however, that the permeabiliy being measured is the permeability of the composite system including each component which may retard flow. In this Appendix, the "permeability" value will be used on a comparative basis, with the original value being the highest that the system can possibly achieve.

Figure A-1 - Photograph of Field Incubation and Test Column

A-5 Results of Test Series "A"

As indicated in Table A-1, this test series consisted of a sand/geotextile/geonet/gravel cross section with the biocide having been introduced into the geonet. The biocide levels were at 0, 1, 2 and 4% and tests were conducted under both anaerobic and aerobic conditions.

The system hydraulic conductivity, or simply "permeability", results for test Series "A" are shown in Figures A-2 and A-3 representing anaerobic and aerobic conditions, respectively. Separate curves are for the control and each biocide level in the geonet. Comparison of these two figures indicates that there is essentially no difference in the flow characteristics from the anaerobic to the aerobic state. Within the curves of each figure a nominal improvement in permeability from using 2 or 4% biocide in the geonet was evidenced at the conclusion of the test period of 444 days. However, because the improvement in flow is nominal at the end of testing and flow improvement is not evidenced throughout the entire testing period, statistical variation in the data may influence the behavioral trends. One general feeling is that using biocide in the geonet is simply not logical since the flow rate in the geonet is relatively high. Thus the biocide probably did not have adequate residence time to be effective.

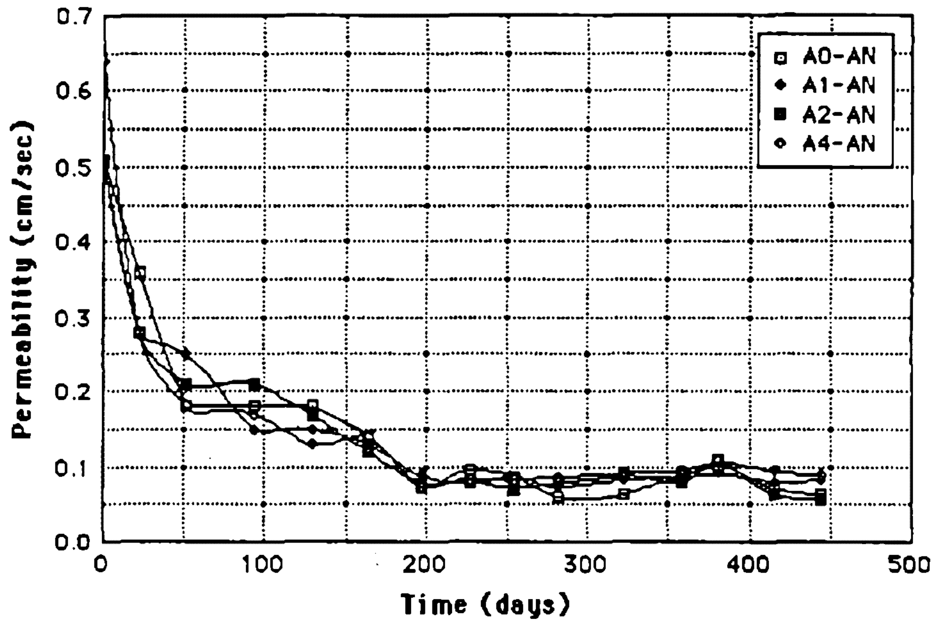


Figure A-2 - Effect of Geonet Biocide Content on System Permeability under Anaerobic Conditions (Test Series "A")

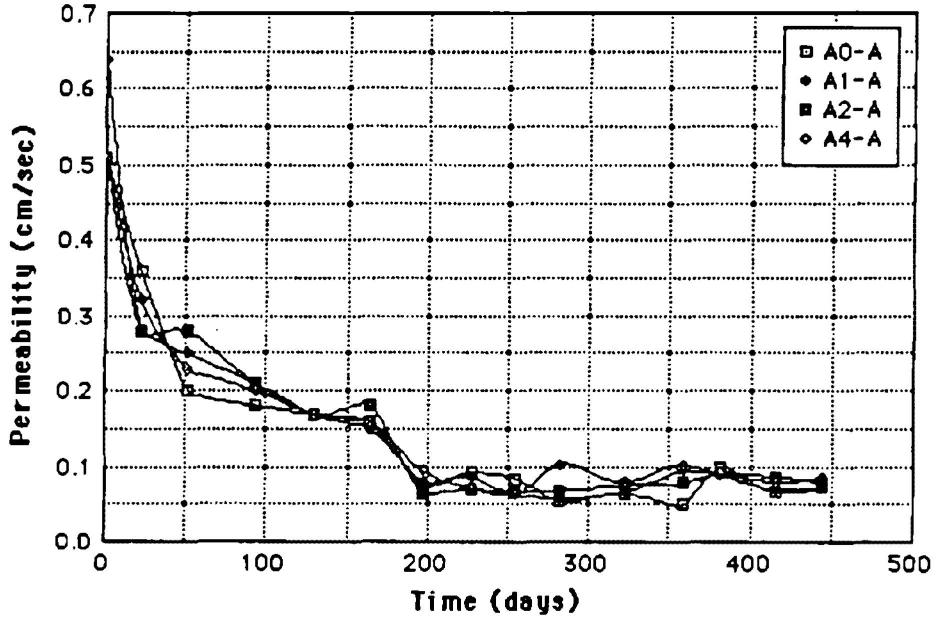


Figure A-3 - Effect of Geonet Biocide Content on System Permeability under Aerobic Conditions (Test Series "A")

A-6 Results of Test Series "B"

As indicated in Table A-1, this test series consisted of a sand/geotextile/gravel cross section with the biocide having been introduced into the geotextile. The biocide levels were at 0, 2, and 4% and tests were conducted under anaerobic and aerobic conditions. The rational for this change from the previous test series is that flow in the geotextile would be much lower than in the geonet due to its much smaller void spaces. The greatly decreased flow rate in the geotextile would possibly allow for the biocide to have a greater contact time with the micro-organisms in the leachate and hence be more effective.

Figures A-4 and A-5 provide a comparison of anaerobic and aerobic conditions. A replicate for the geotextile with 0% biocide was provided for each condition and the data was averaged for plotting. A comparison of these figures reveals little difference in flow characteristics from anaerobic to aerobic conditions. This same trend was seen previously with the geonet tests. Generally, the geotextile with 4% biocide provided slightly higher flow rates with the exception of the anaerobic state in which the geotextile clogged severely beyond 400 days. As with Series "A" tests, statistical variation is bound to play a significant role. Two test specimens in Series "B", B0-AN1 and B4-A, were resin set and dissected to visually determine the extent of clogging. In each specimen, as shown in Figure A-6, it appears as though the Ottawa sand has clogged within the upper 1 to 2 inches of the specimen. Note the closeup photograph of Column B4-A where the upper layer of soil was completely bonded together while the soil above the geotextile was loose. The biofilm apparently did not reach the level of the geotextile indicating that either the biocide is too far from the biofilm itself or that the grain size distribution of the sand is sufficiently small to create its own clogged layer.

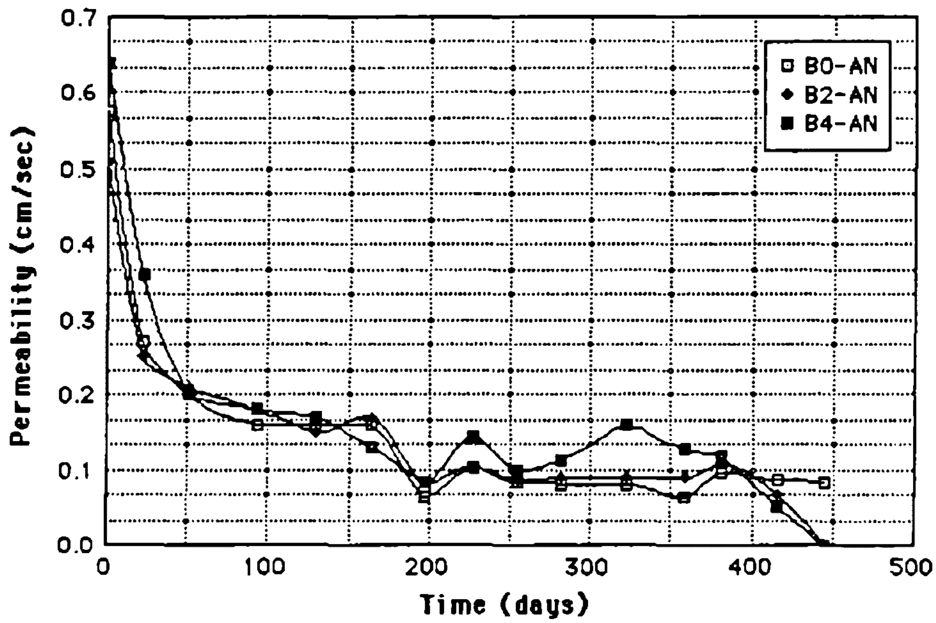


Figure A-4 - Effect of Geotextile Biocide Content on System Permeability under Anaerobic Conditions (Test Series "B")

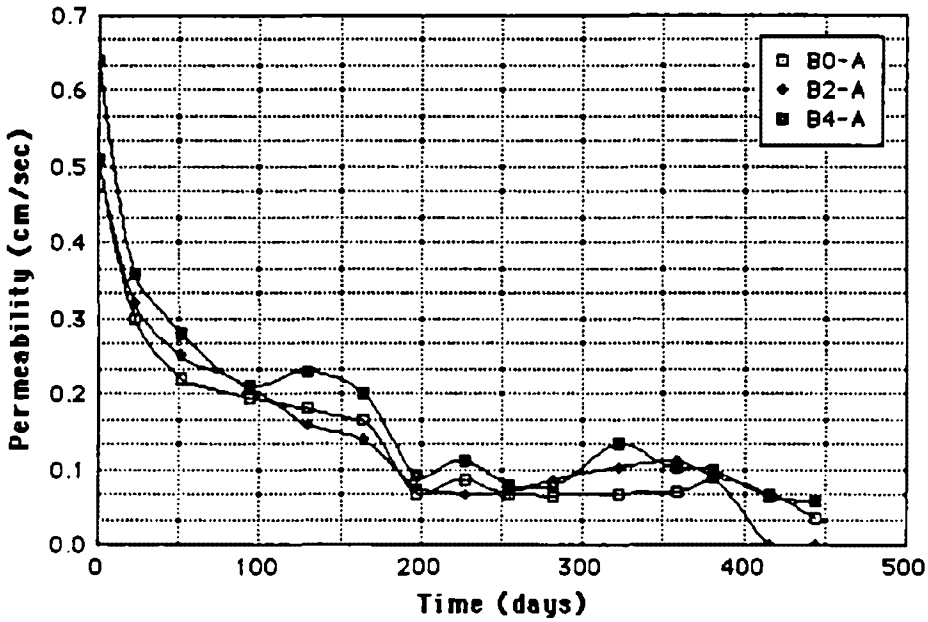


Figure A-5 - Effect of Geotextile Biocide Content on System Permeability under Aerobic Conditions (Test Series "B")

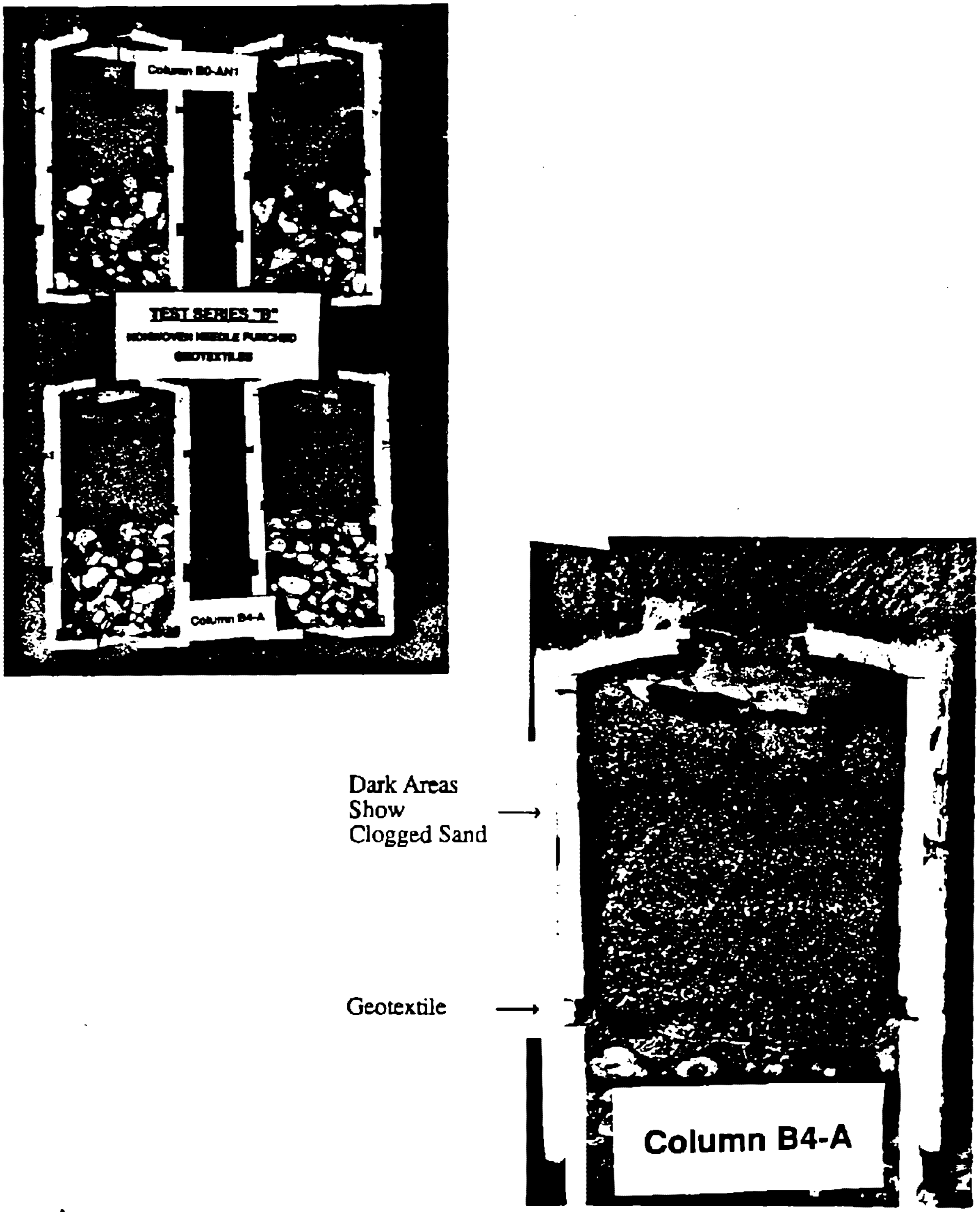


Figure A-6 - Photographs of Resin Set Columns of Test Series "B" Split in Half at the End of 444 Days of Testing

A-7 Results of Test Series "C"

After evaluating the flow columns of Test Series "A" and "B" for 323 days, it was apparent that a clearly defined flow improvement resulting from biocide activity was not being observed. It was considered likely that the biofilm layer was occurring in the upper portion of the sand, hence the biocide in the geonet (Series "A") or in the geotextile (Series "B") was too far away from the clogged layer to be effective. Thus, it become necessary to assemble an additional series of 16 columns without sand, which is the thrust of Series "C".

Series "C" columns consist of a cross section of gravel/geotextile/gravel. The gravel is 1.0 to 1.5 inch size and does little insofar as retarding flow is concerned. The geotextiles are treated with varying amounts of biocide, from 0 to 8% (recall Table A-1) and all columns were evaluated in the anaerobic condition. This latter decision was made since there was little difference in the anaerobic and aerobic flow rates in the previous tests and anaerobic conditions are felt to better simulate landfill leachate conditions. The geotextiles in this series varied considerably. Those used were the following.

- nonwoven needle-punched with an opening size of 0.15 mm
- woven monofilament with a opening size of 0.21 mm
- woven monofilament with an opening size of 0.42 mm

The first part of Series "C" tests consists of the nonwoven needle punched polypropylene geotextile with 0, 2, 4 and 8% biocide within the fabric. A replicate set was constructed so that the values used in graphing are averages of the two data sets. An evaluation of varying biocide contents is displayed in Figure A-7. There appears to be little difference in flow at the onset of testing, however there is an improvement in flow with 8% biocide at the completion of testing 121 days later. The use of 8% biocide, however, may affect the strength characteristics of the fabric and currently the EPA has restricted biocide content of this type in other media to 4%. As with the other test series, statistical scatter is significant.

In the second part of Series "C" testing, a different manufacturers nonwoven needle punched polypropylene geotextile with 0, 2 and 4% biocide was used. A replicate was constructed for the control, i.e., 0% biocide, and graphs were plotted using the average of data sets. To compare the two different products, Figure A-8 was plotted. In the first month of testing, there is little difference in flow rates. As the test progresses, the 2 and 4% biocide geotextiles tend to give better

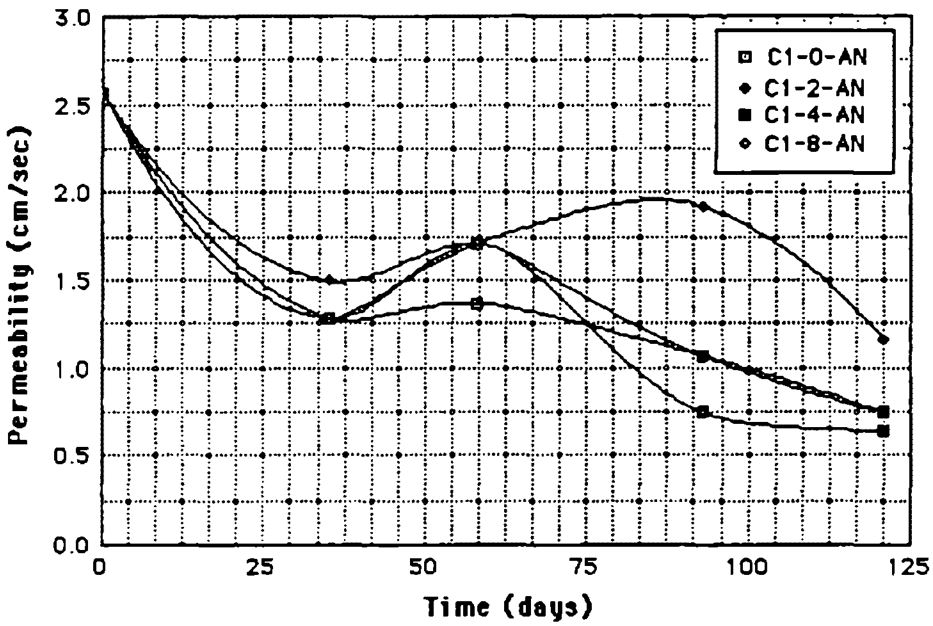


Figure A-7 - Nonwoven Needle-Punched Effect of Geotextile Biocide Content on System Permeability (Test Series "C")

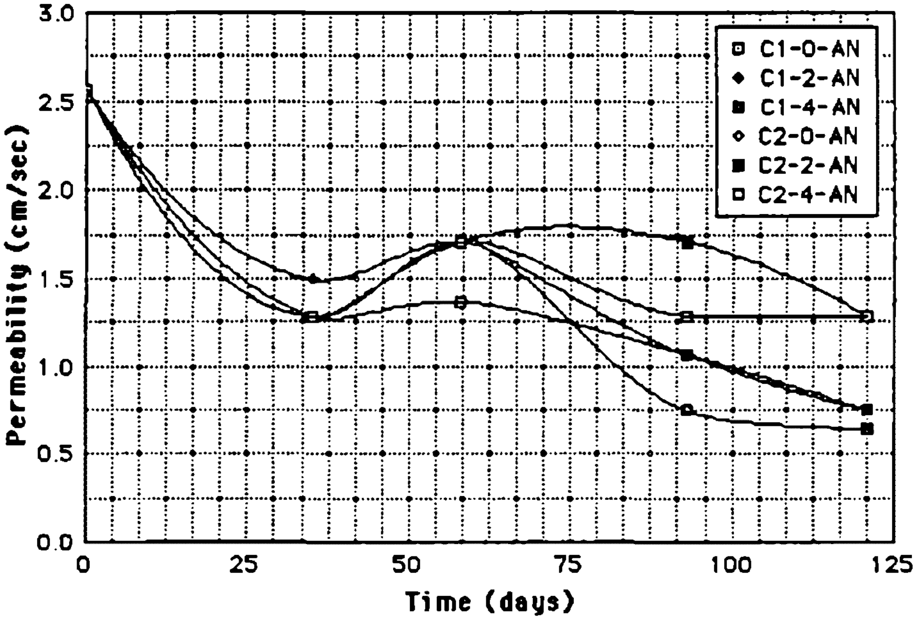


Figure A-8 - Comparison of Two Nonwoven Needle-Punched Geotextiles with Varying Biocide Content (Test Series "C") flow rates with a large improvement in flow at 121 days. Statistical scattering of the data and the short duration of the testing are concerns with respect to the significance of the data.

Two woven monofilament polypropylene geotextiles were used for the third part of the Series "C" tests. The apparent opening sizes and other relevant test conditions are provided in Table A-1. Each fabric was tested with 2 and 4% biocide content. A control with 0% biocide, was not constructed for this test set. To compare the effects of opening size on clogging Figure A-9 was prepared. From the graph it is seen that the larger opening size geotextile provides a measurable increase in flow rate with the 4% biocide content giving better results in general. The smaller opening size fabric with 4% biocide clogged severely two months into the test. The four samples in this series were then epoxy resin set and dissected in the same manner as the Series B specimens. Photographs are given as Figure A-10. While difficult to see on the photographs, it was obvious that the larger opening size (0.42 mm) allowed more epoxy to flow through the geotextile indicating that it was indeed providing better flow than the 0.21 mm opening size geotextile.

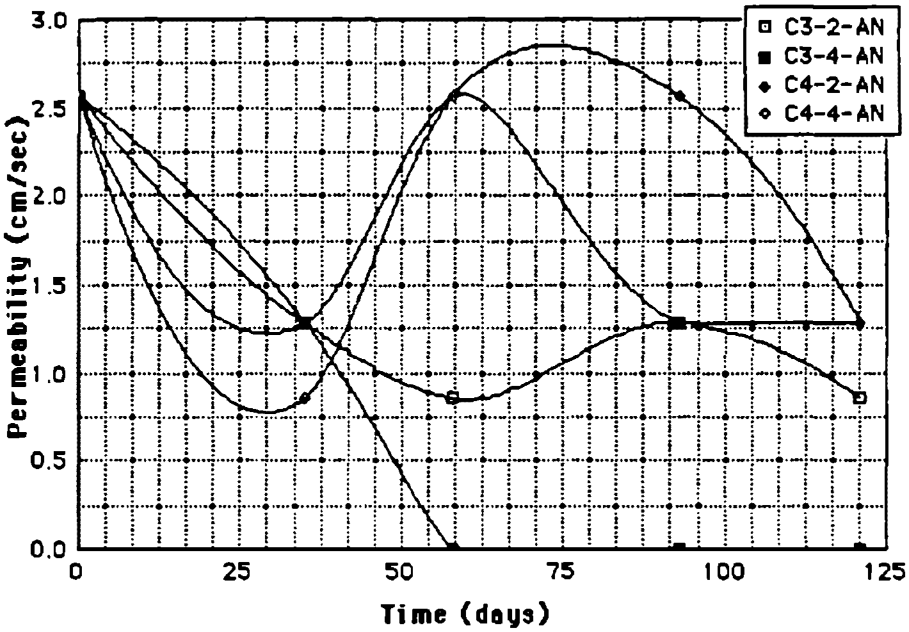


Figure A-9 - Comparison of Woven Monofilament Geotextile Opening Size with Varying Biocide Content (Test Series "C")

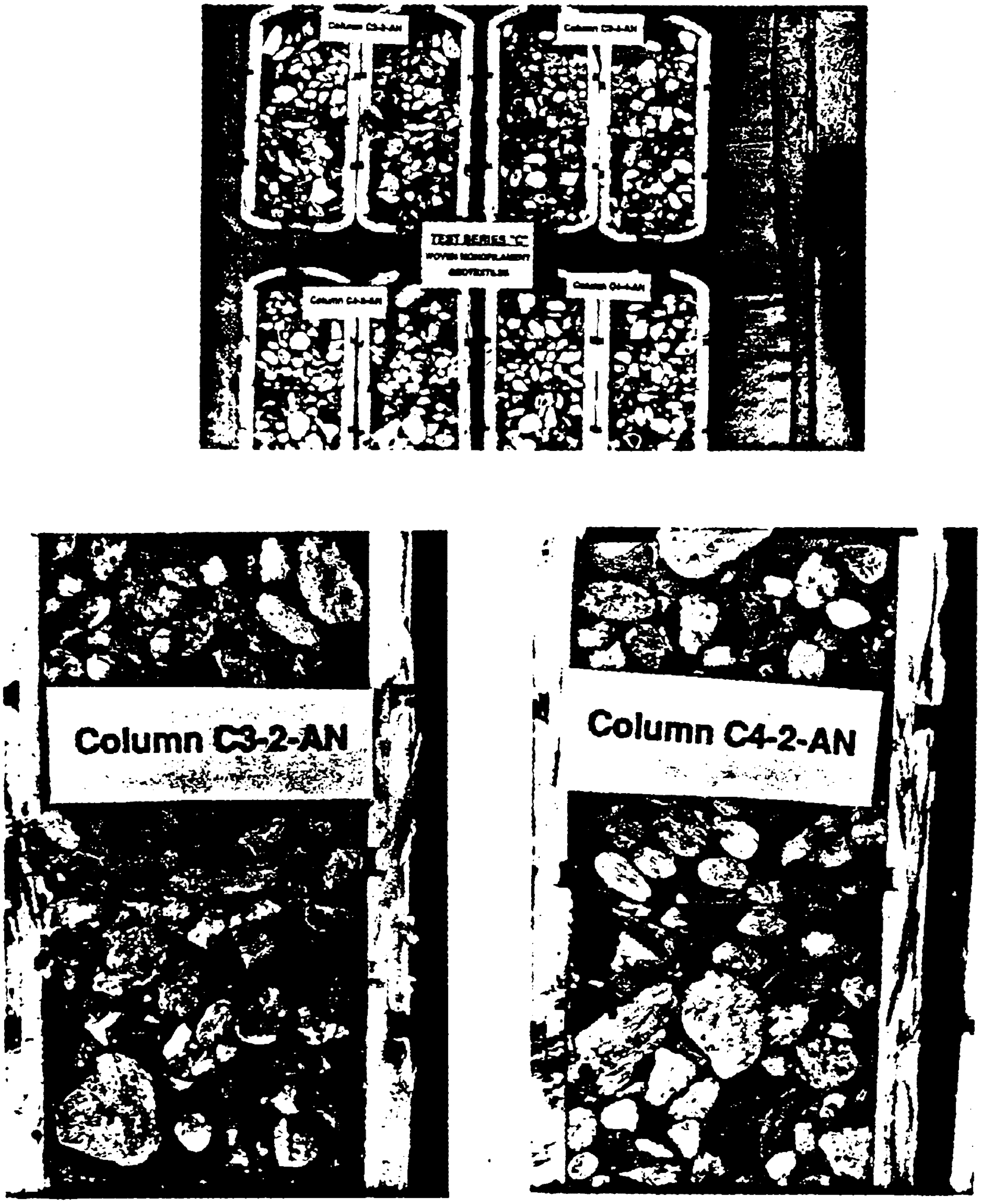


Figure A-10 - Photographs of Resin Set Columns of Test Series "C" Split in Half at the End of 121 Days of Testing

A-8 Conclusions of Biocide Study

From the results of the Series "A" tests (biocide in geonets) and Series "B" tests (biocide in geotextiles) it was concluded that the location of the biocide vis-a-vis the initial formation of a biofilm layer is critical. This conclusion was tentatively reached after 323 days of conducting these tests. It was confirmed at the termination of the 444 day tests after setting the test columns with epoxy and cutting them apart. Clearly the biofilm layer was occurring at the top of the sand column some 2 to 3 inches above the biocide treated geosynthetics, recall Figure A-6. While there may have been some flow rate improvement due to high concentrations of biocide, it was very subtile (at best) and was masked by the inherent scatter in the test data. There was essentially no difference between flow rates in anaerobic versus aerobic conditions.

These findings led to Series "C" tests which contained no sand above the biocide treated geosynthetic and forced the leachate to interface directly with the biocide. Rather than use a single type of geotextile, three different types of geotextiles were utilized. They had opening sizes varying from 0.15 mm (the nonwoven needle-punched styles used in test Series "B"), to 0.21 mm (a woven monofilament), to 0.42 mm (another woven monofilament). Quite clearly, the flow rates through the largest opening size geotextiles, i.e. the 0.42 mm, were the highest. This suggests to us that micro-organisms (dead or alive) must be able to pass through the system. Whenever these micro-organisms reside on, or within, the small pores of a filter (either natural soil or a geotextile) there is a possibility of partial, or even complete, clogging.

Appendix "B"

INDIVIDUAL TEST COLUMN RESULTS
OF PHASE II STUDY

(All 96 Columns in Phase II are Included in this Appendix along with Each of the Four Remediation Attempts)

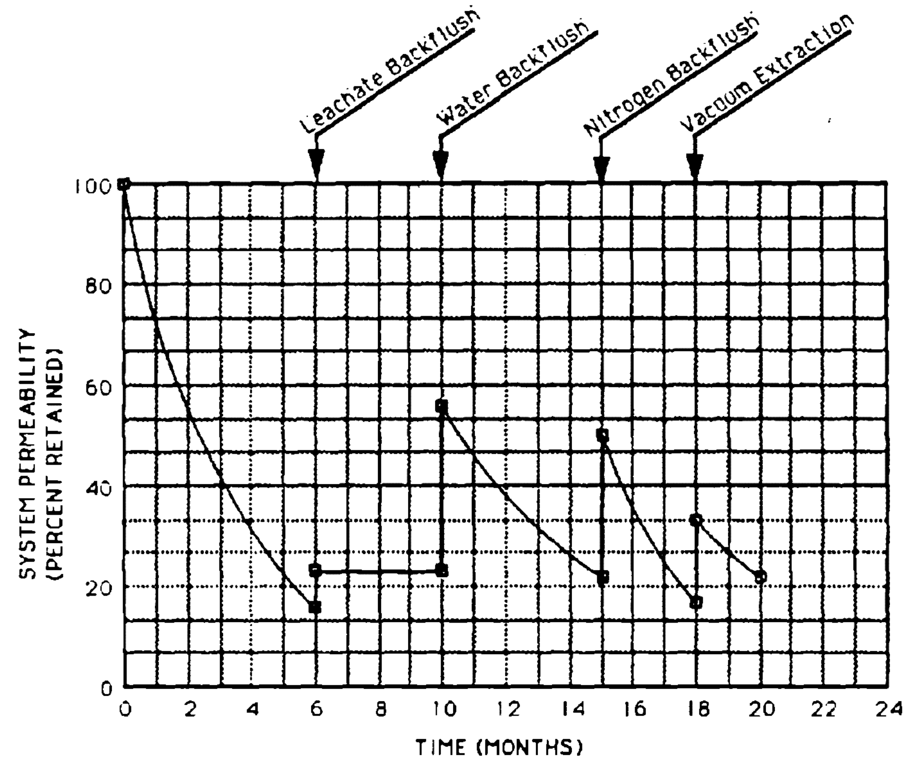


Figure 1 - System Permeability Retained and Various Remediation Attempts for Landfill PA-1 and Flow Test Column WM (NC) AN/S

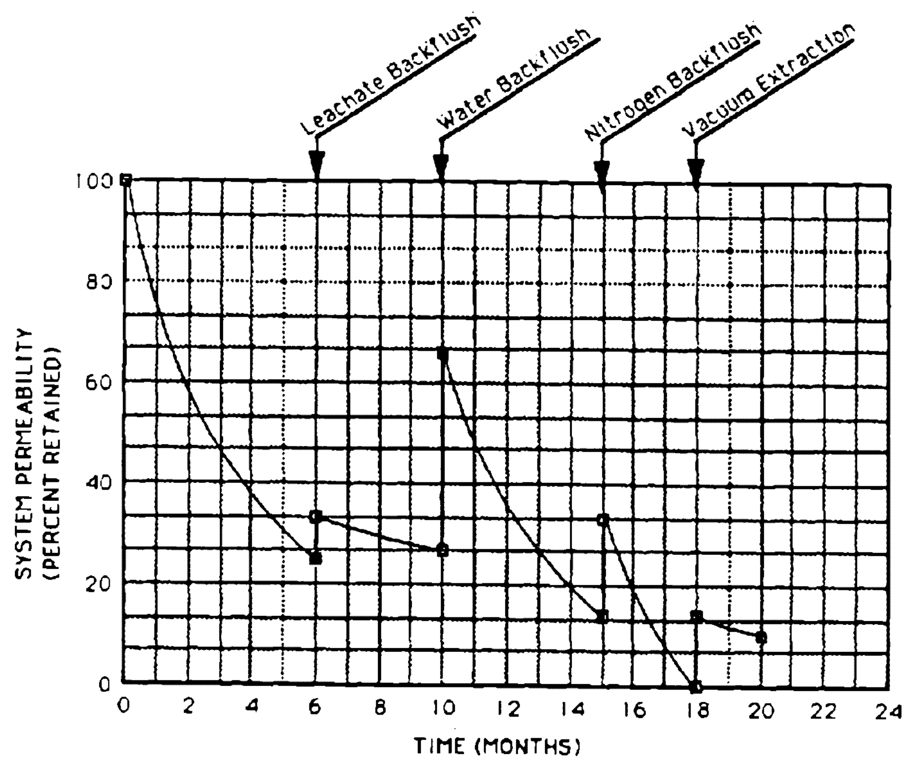


Figure 2 - System Permeability Retained and Various Remediation Attempts for Landfill PA-1 and Flow Test Column WM (NC) A/S

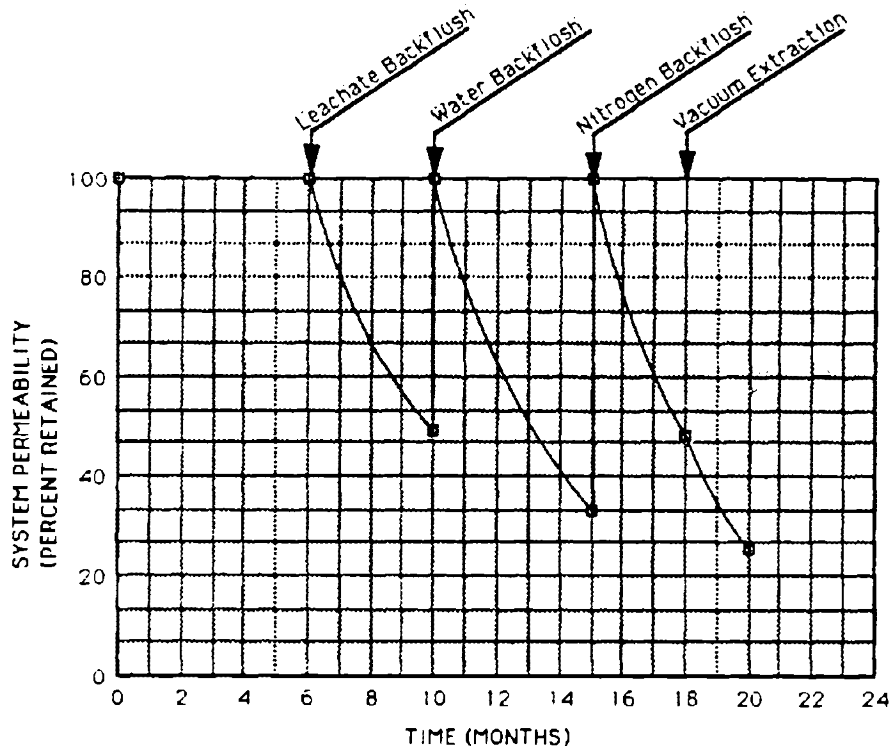


Figure 3 - System Permeability Retained and Various Remediation Attempts for Landfill PA-1 and Flow Test WM (NC) AN/W

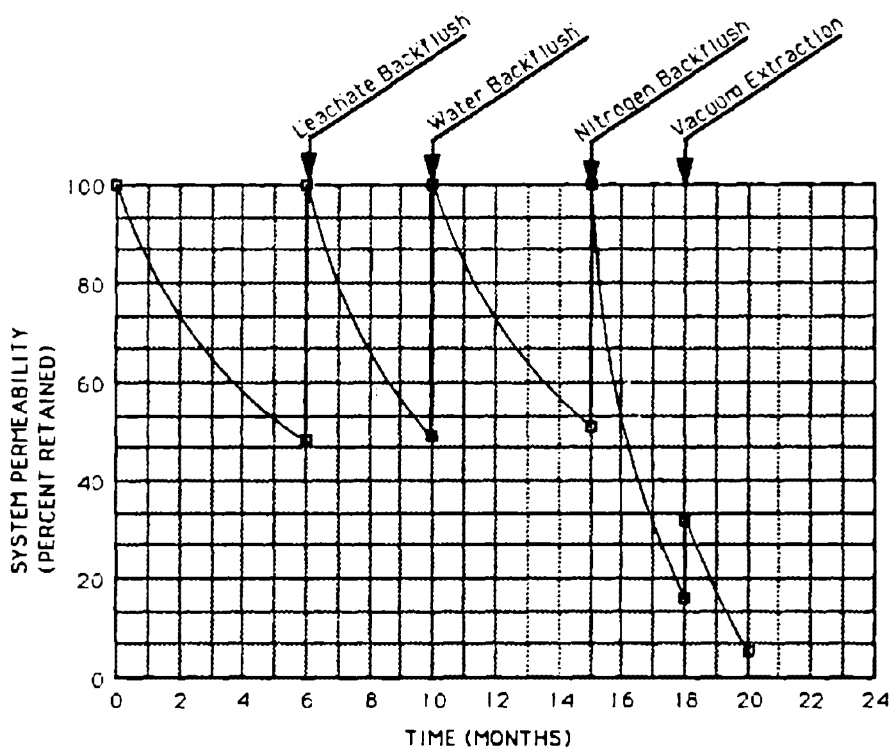


Figure 4 - System Permeability Retained and Various Remediation Attempts for Landfill PA-1 and Flow Test Column WM (NC) A/W

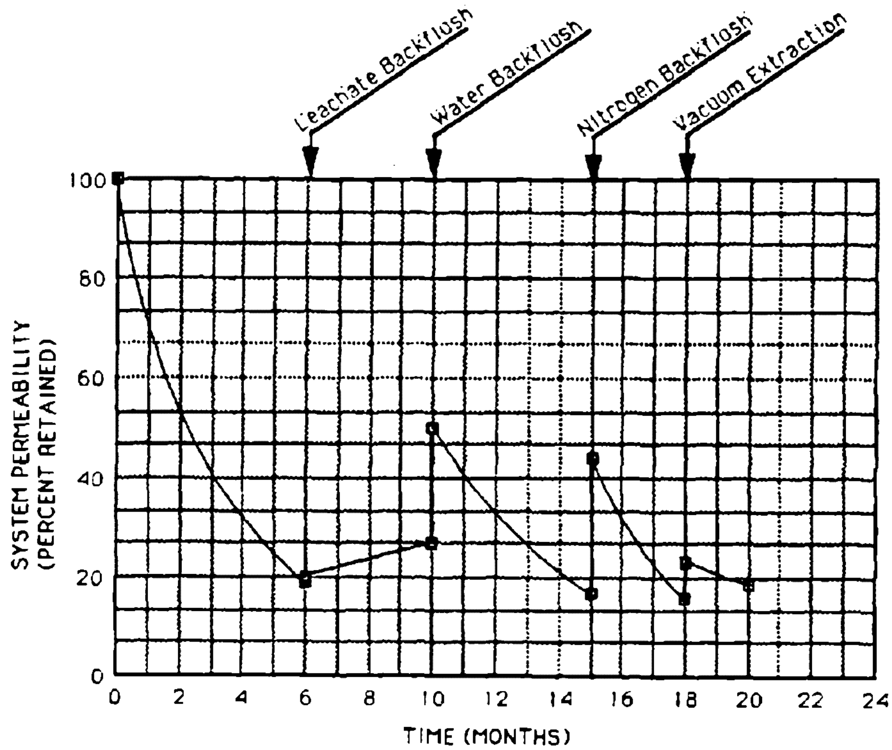


Figure 5 - System Permeability Retained and Various Remediation Attempts for Landfill PA-1 and Flow Test Column NW (HS) AN/S

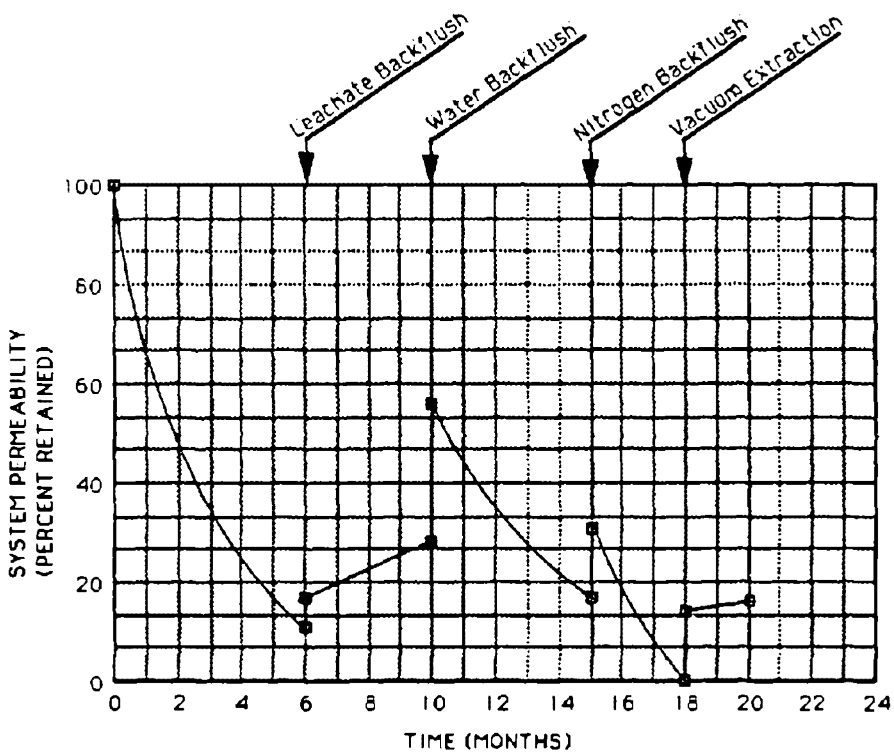


Figure 6 - System Permeability Retained and Various Remediation Attempts for Landfill PA-1 and Flow Test Column NW (HS) A/S

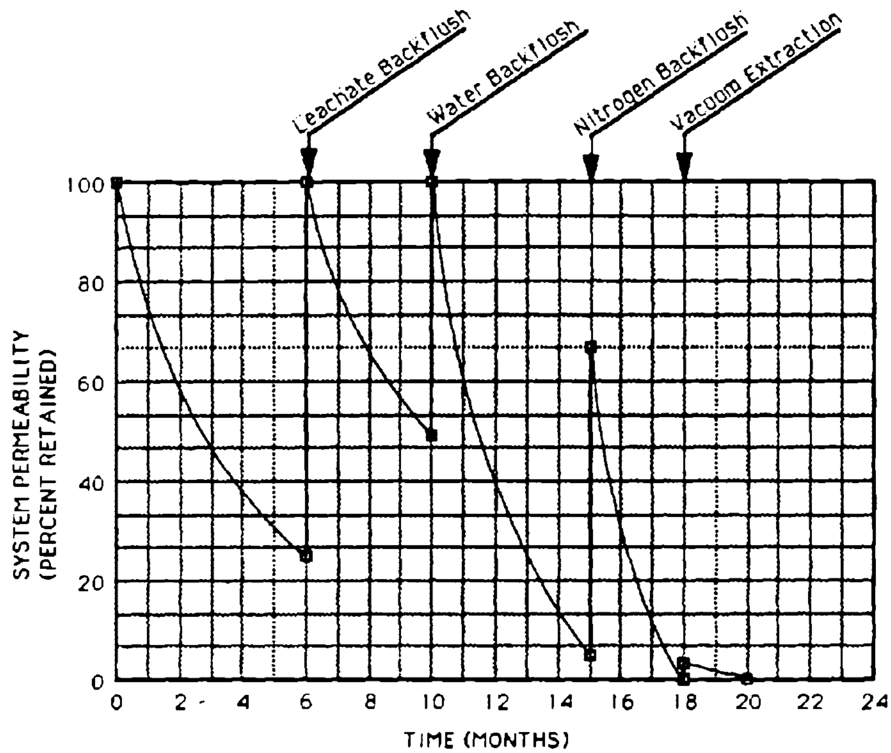


Figure 7 - System Permeability Retained and Various Remediation Attempts for Landfill PA-1 and Flow Test Column NW (HS) AN/W

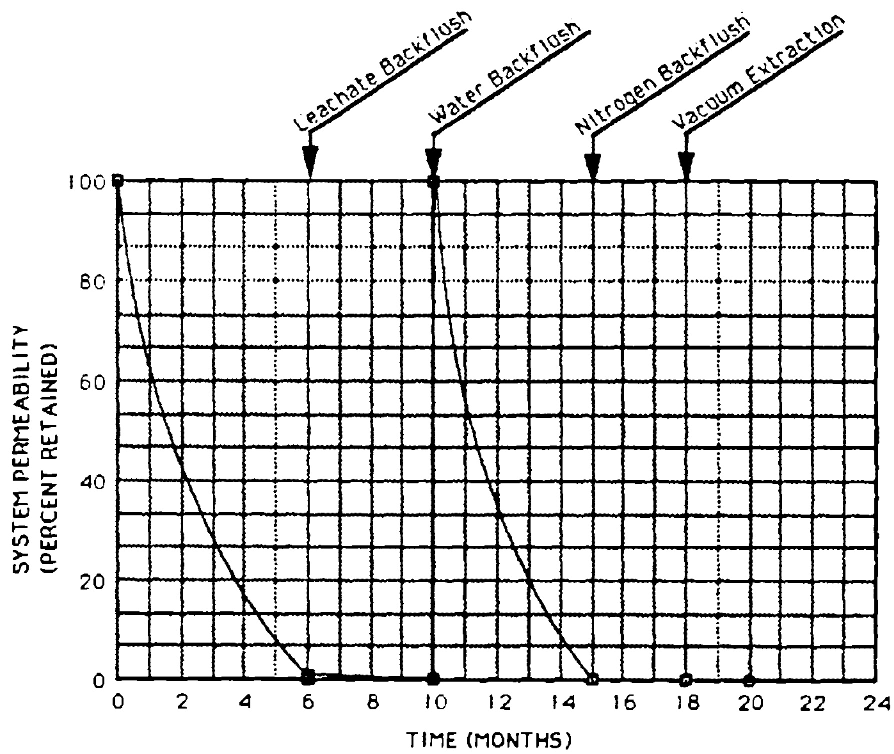


Figure 8 - System Permeability Retained and Various Remediation Attempts for Landfill PA-1 and Flow Test Column NW (HS) A/W

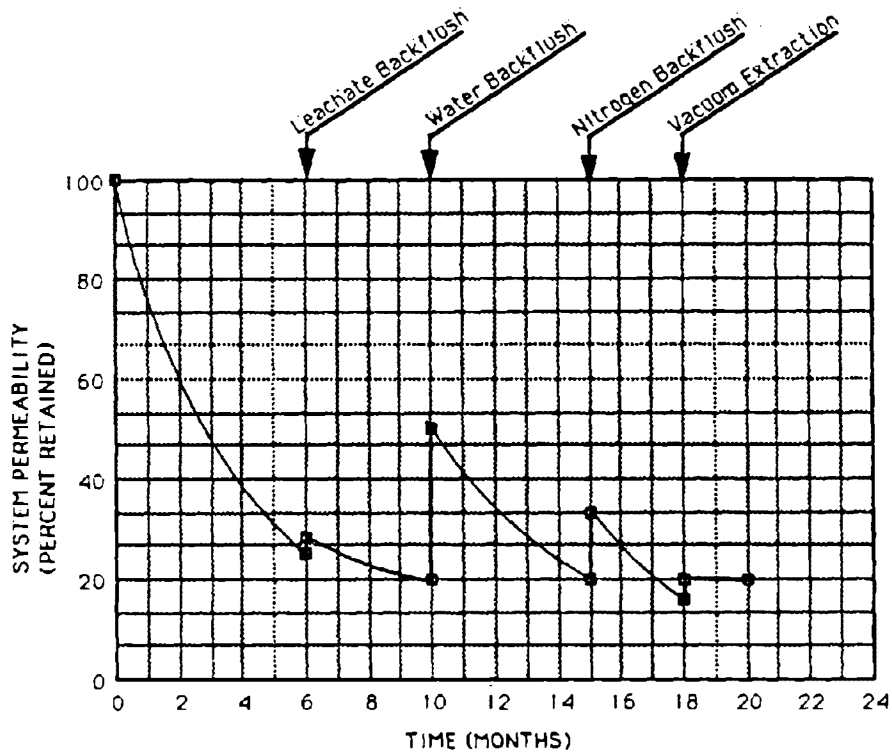


Figure 9 - System Permeability Retained and Various Remediation Attempts for Landfill PA-1 and Flow Test Column NW (N) 16 AN/S

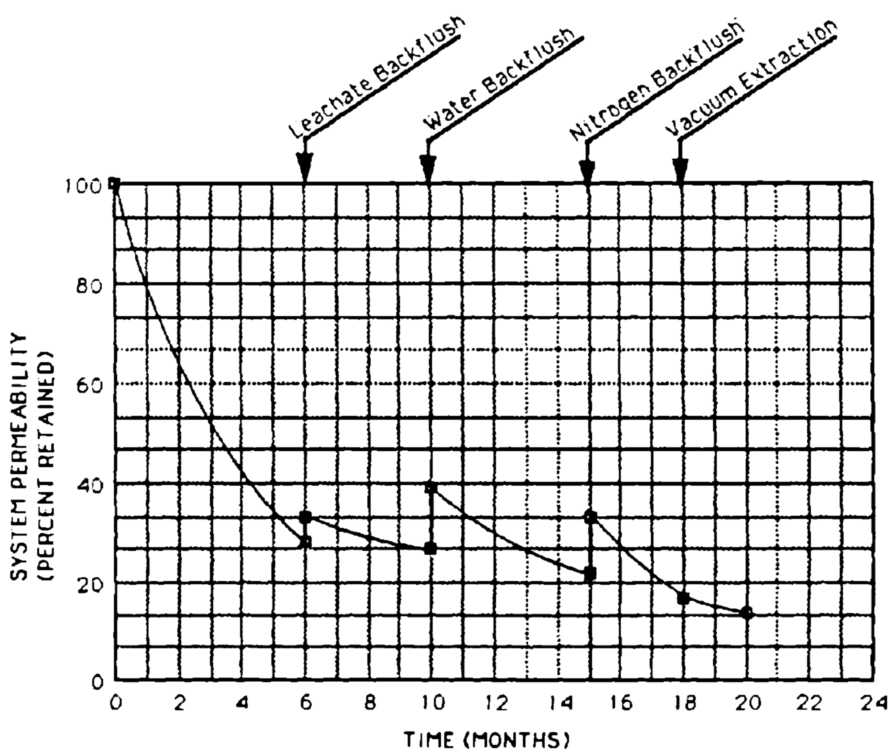


Figure 10 - System Permeability Retained and Various Remediation Attempts for Landfill PA-1 and Flow Test Column NW (N) 16 A/S

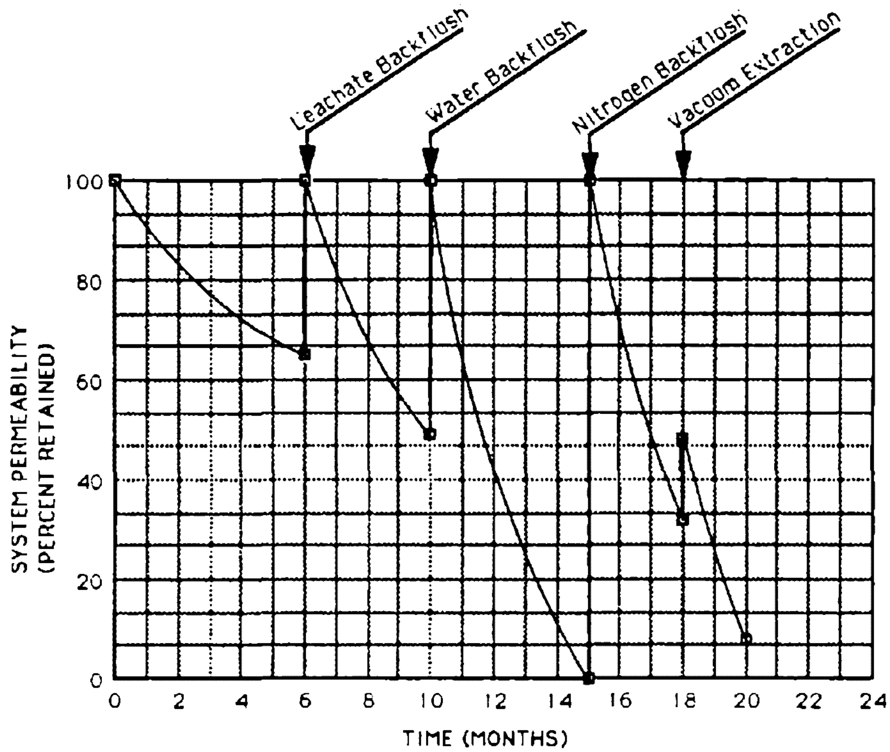


Figure 11 - System Permeability Retained and Various Remediation Attempts for Landfill PA-1 and Flow Test Column NW (N) 16 AN/W

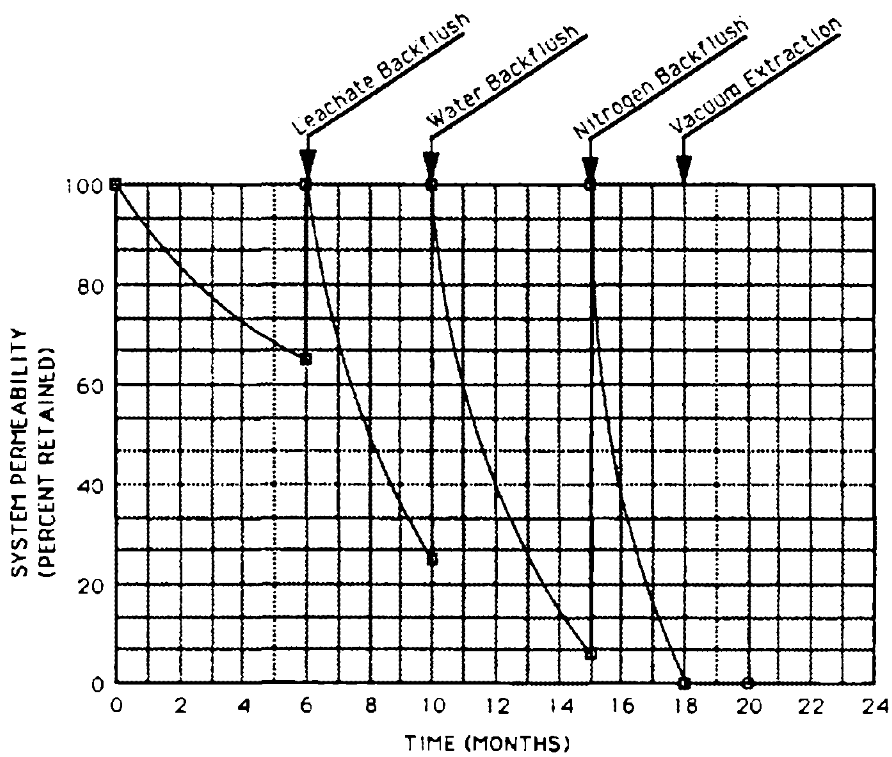


Figure 12 - System Permeability Retained and Various Remediation Attempts for Landfill PA-1 and Flow Test Column NW (N) 16 A/W

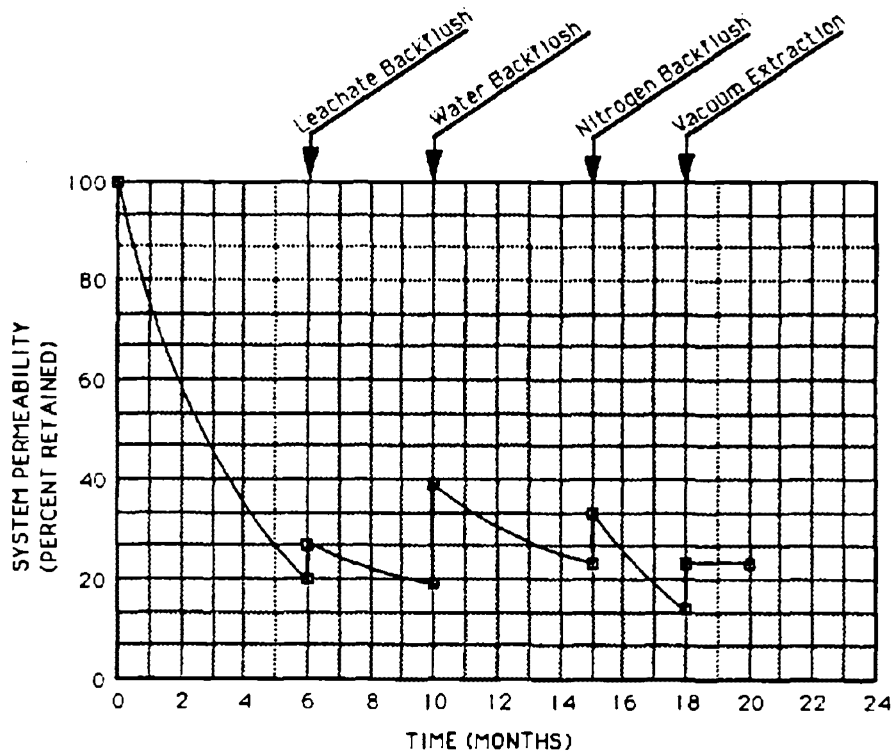


Figure 13 - System Permeability Retained and Various Remediation Attempts for Landfill PA-1 and Flow Test Column NW (N) 8 AN/S

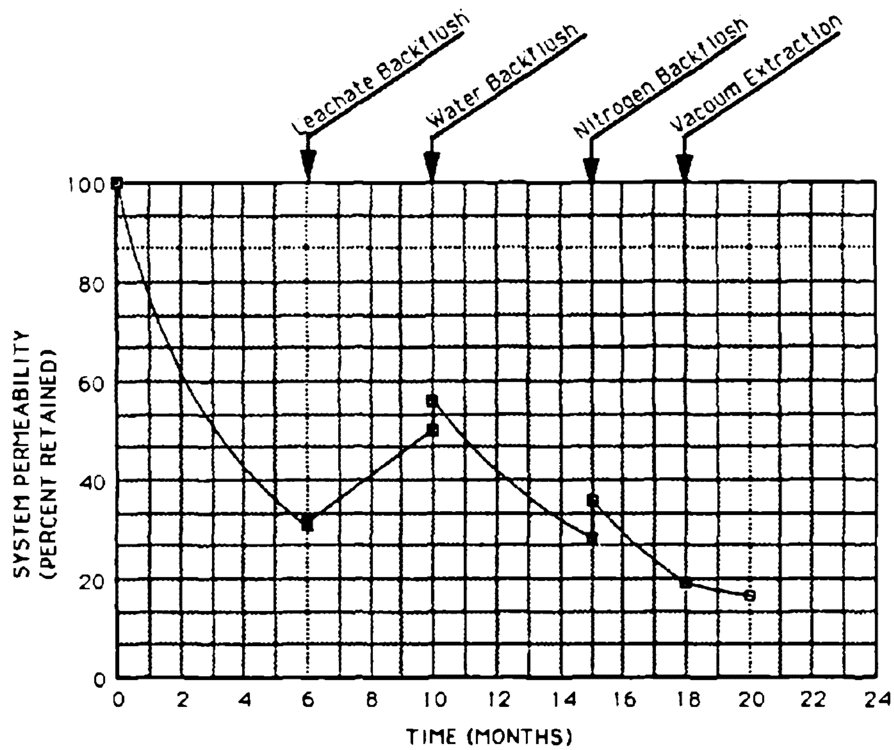


Figure 14 - System Permeability Retained and Various Remediation Attempts for Landfill PA-1 and Flow Test Column NW (N) 8 A/S

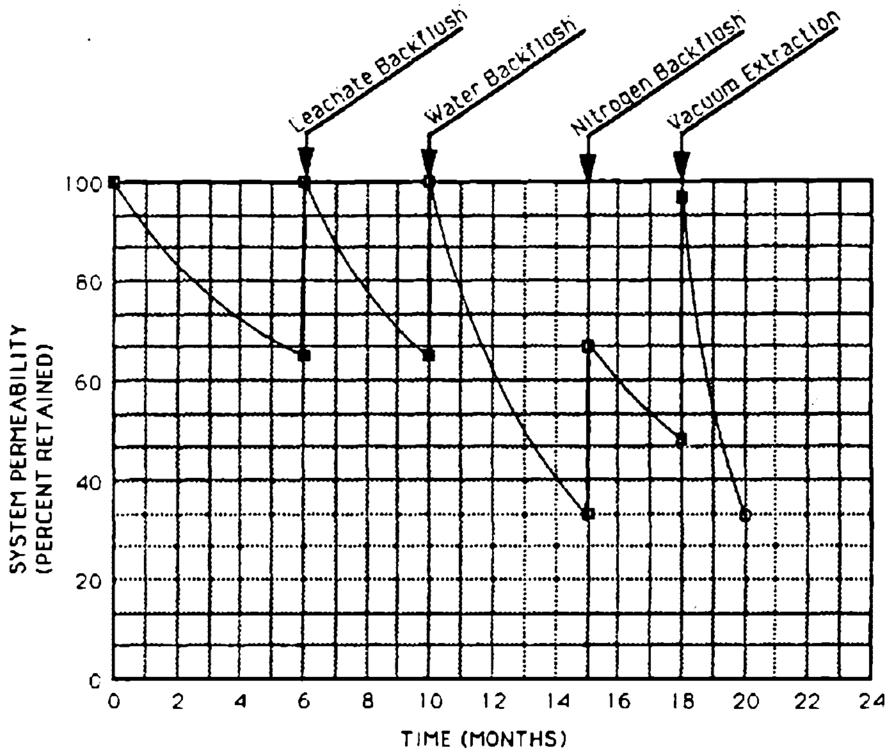


Figure 15 - System Permeability Retained and Various Remediation Attempts for Landfill PA-1 and Flow Test Column NW (N) 8 AN/W

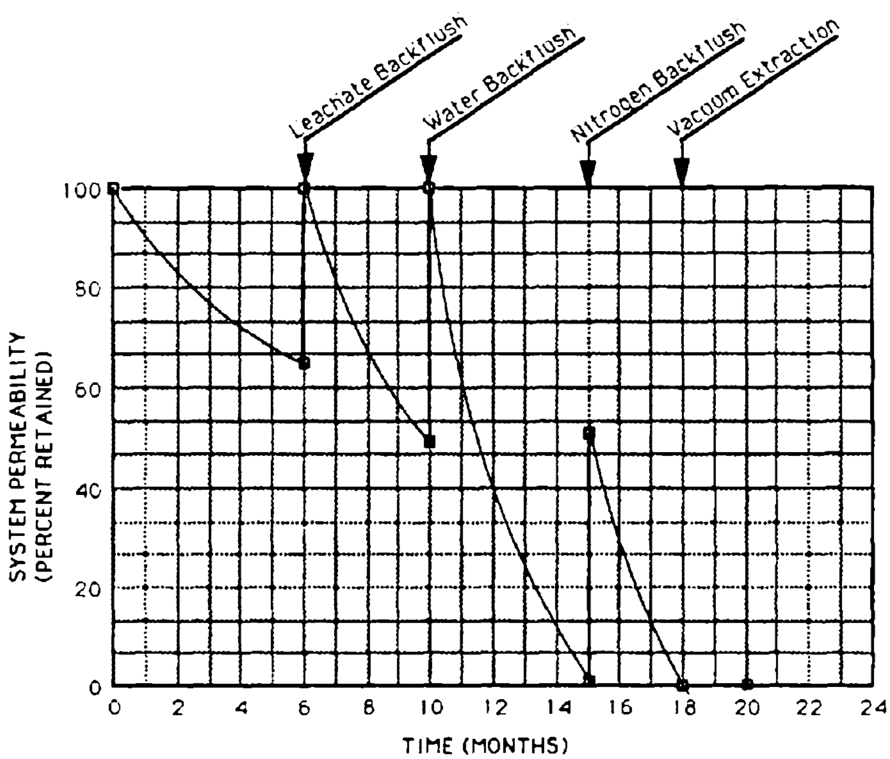


Figure 16 - System Permeability Retained and Various Remediation Attempts for Landfill PA-1 and Flow Test Column NW (N) 8 A/W

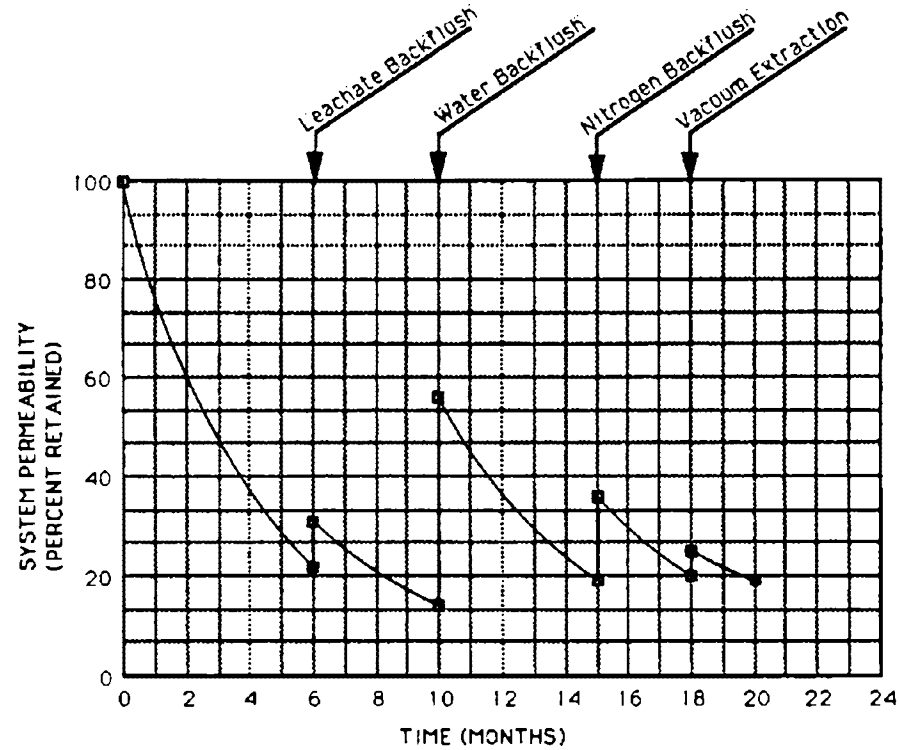


Figure 17 - System Permeability Retained and Various Remediation Attempts for Landfill NY-2 and Flow Test Column WM (NC) AN/S

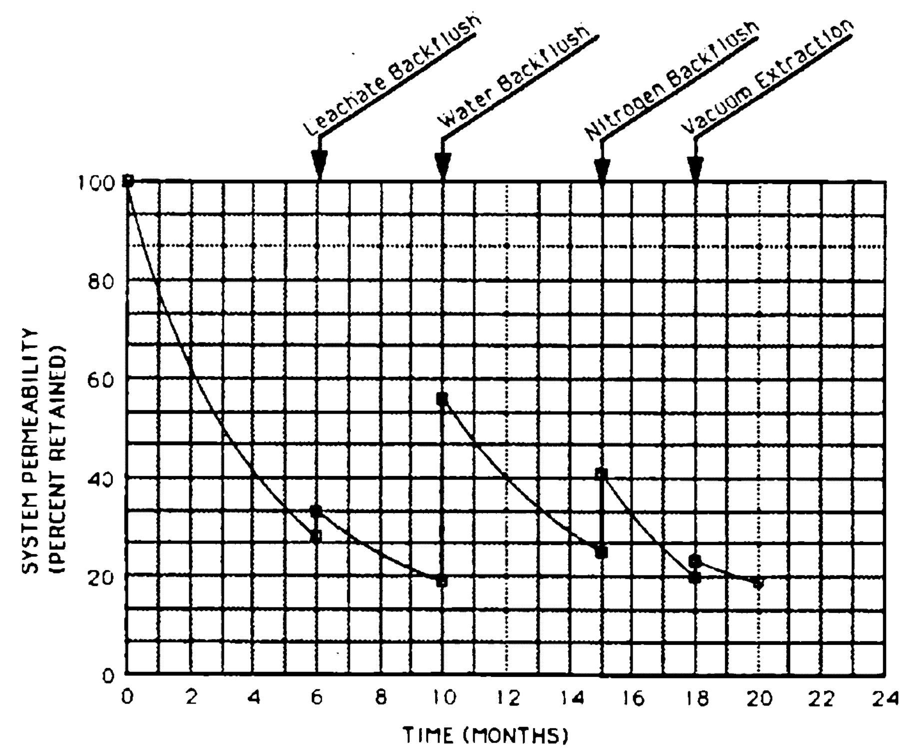


Figure 18 - System Permeability Retained and Various Remediation Attempts for Landfill NY-2 and Flow Test Column WM (NC) A/S

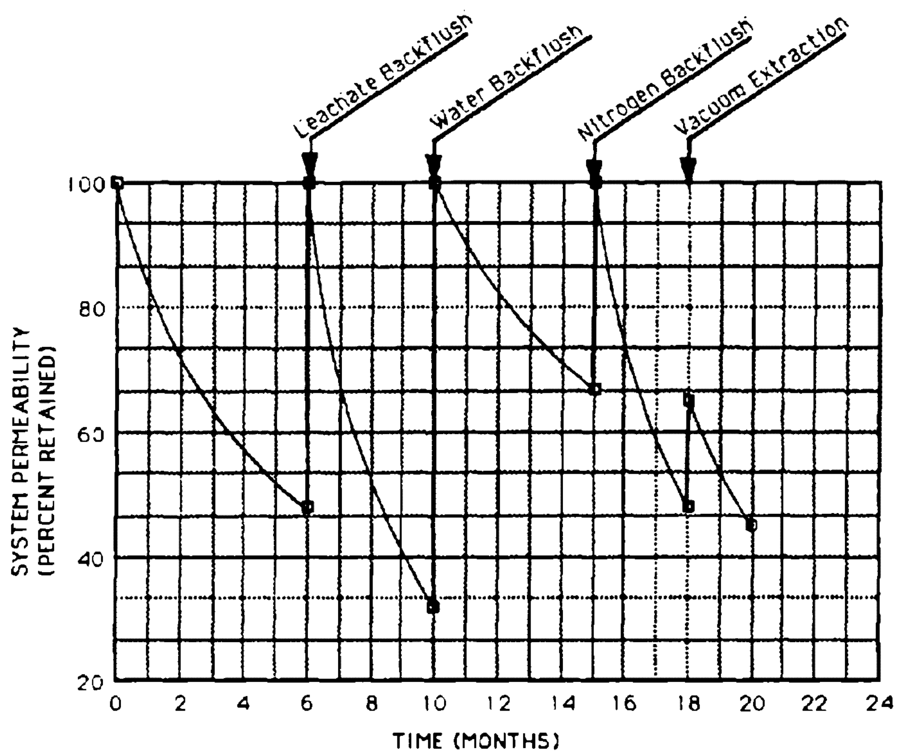


Figure 19 - System Permeability Retained and Various Remediation Attempts for Landfill NY-2 and Flow Test Column WM (NC) AN/W

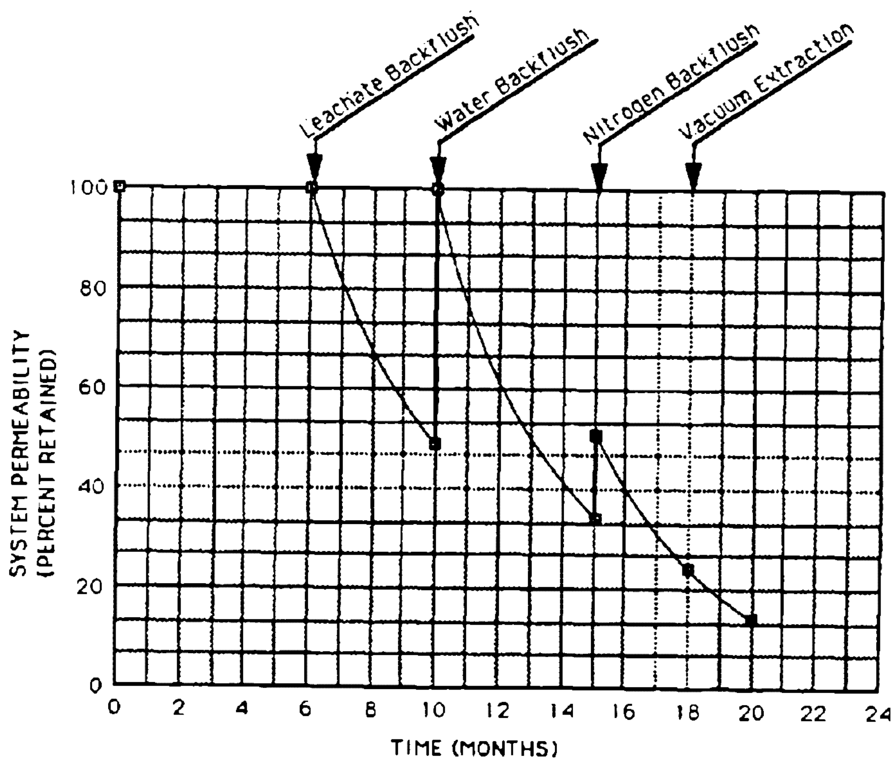


Figure 20 - System Permeability Retained and Various Remediation Attempts for Landfill NY-2 and Flow Test Column WM (NC) A/W

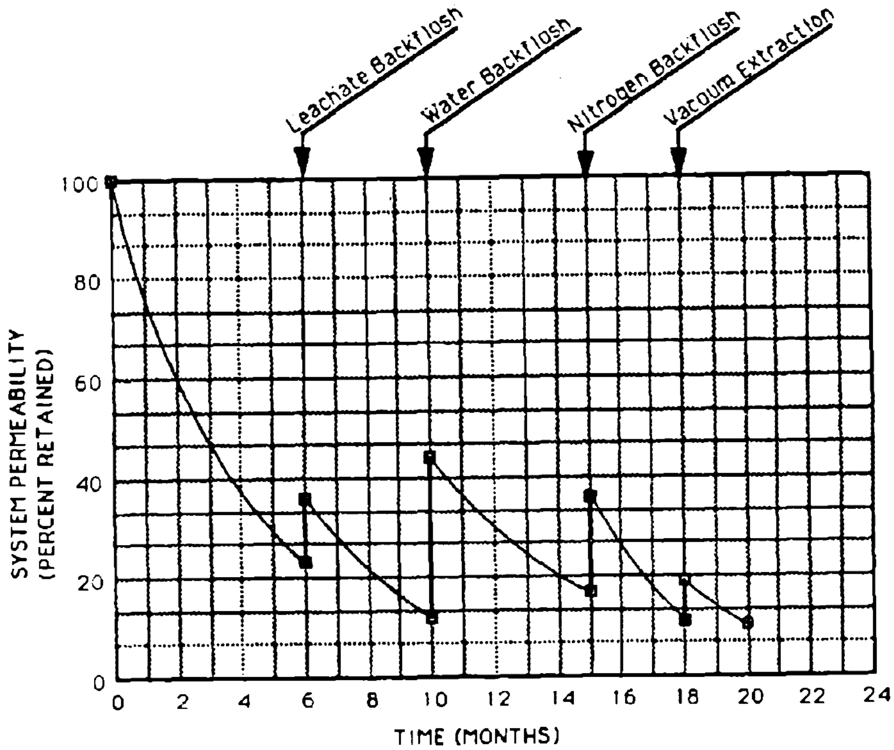


Figure 21 - System Permeability Retained and Various Remediation Attempts for Landfill NY-2 and Flow Test Column NW (HS) AN/S

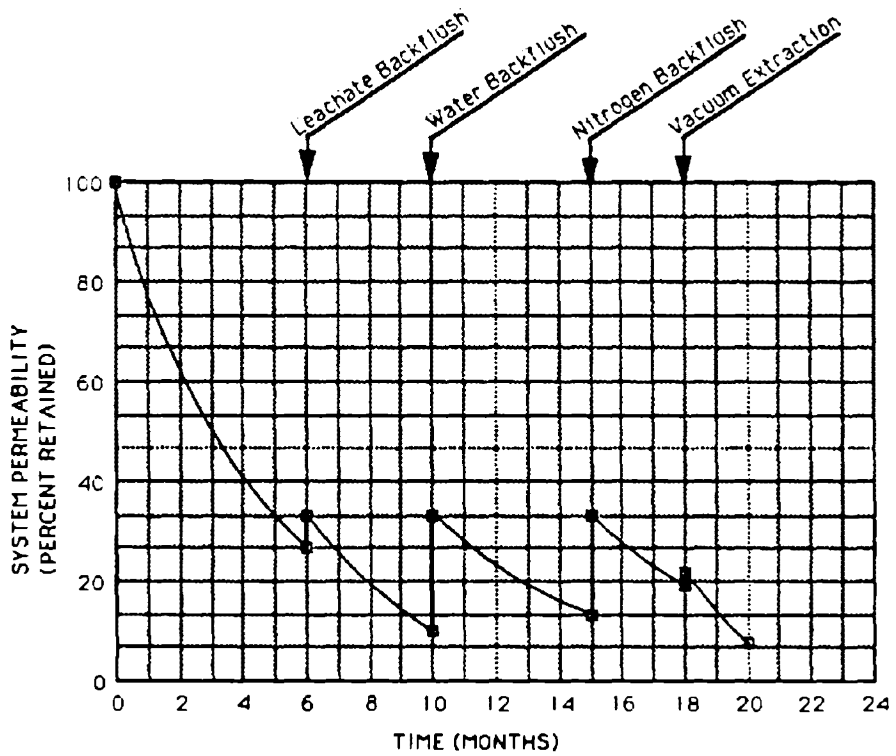


Figure 22 - System Permeability Retained and Various Remediation Attempts for Landfill NY-2 and Flow Test Column NW (HS) A/S

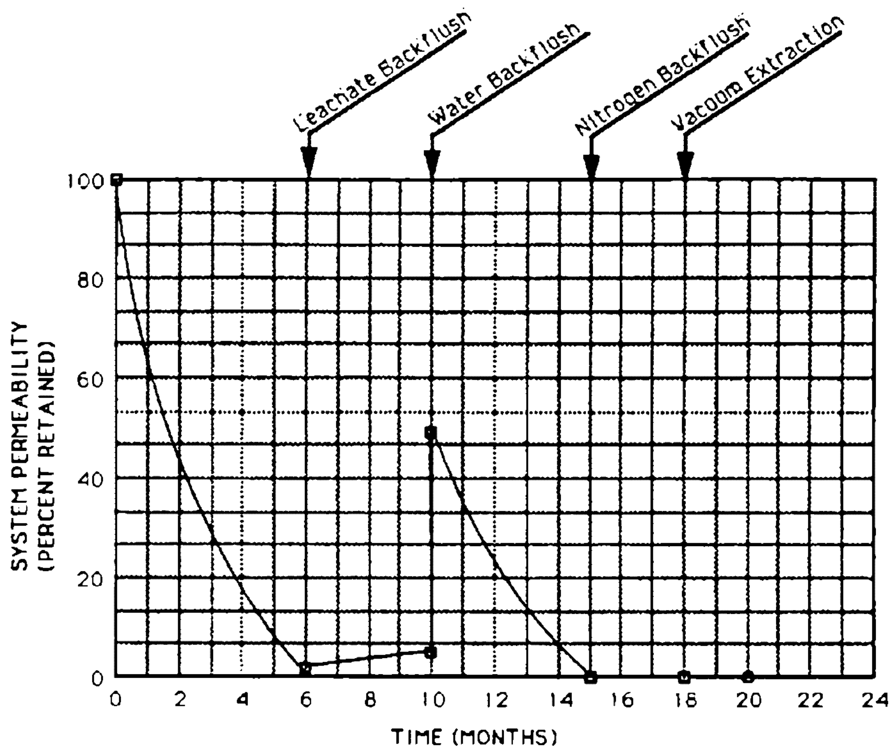


Figure 23 - System Permeability Retained and Various Remediation Attempts for Landfill NY-2 and Flow Test Column NW (HS) AN/W

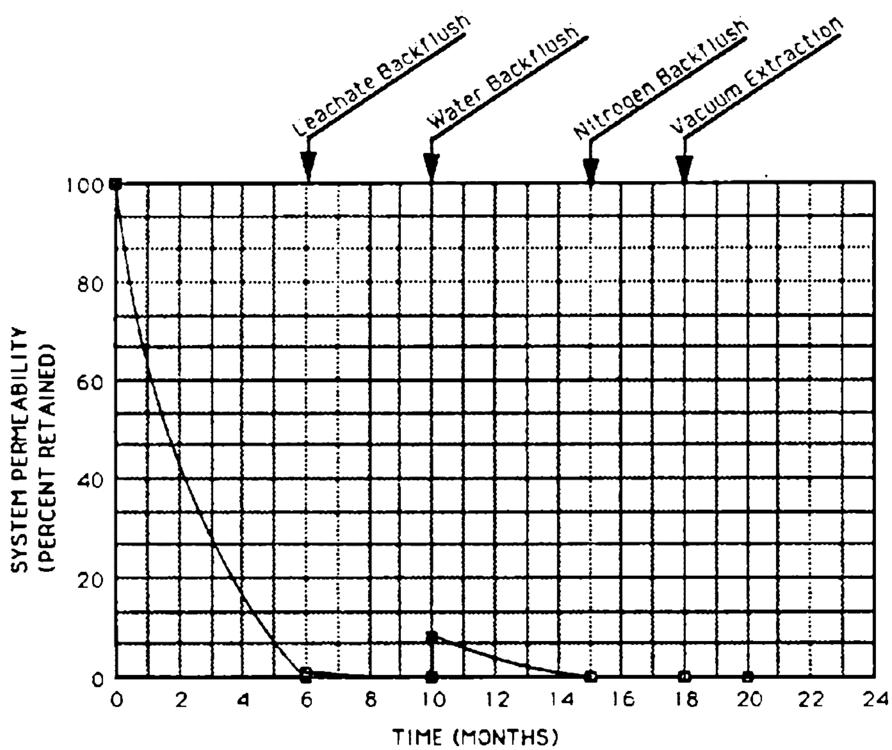


Figure 24 - System Permeability Retained and Various Remediation Attempts for Landfill NY-2 and Flow Test Column NW (HS) A/W

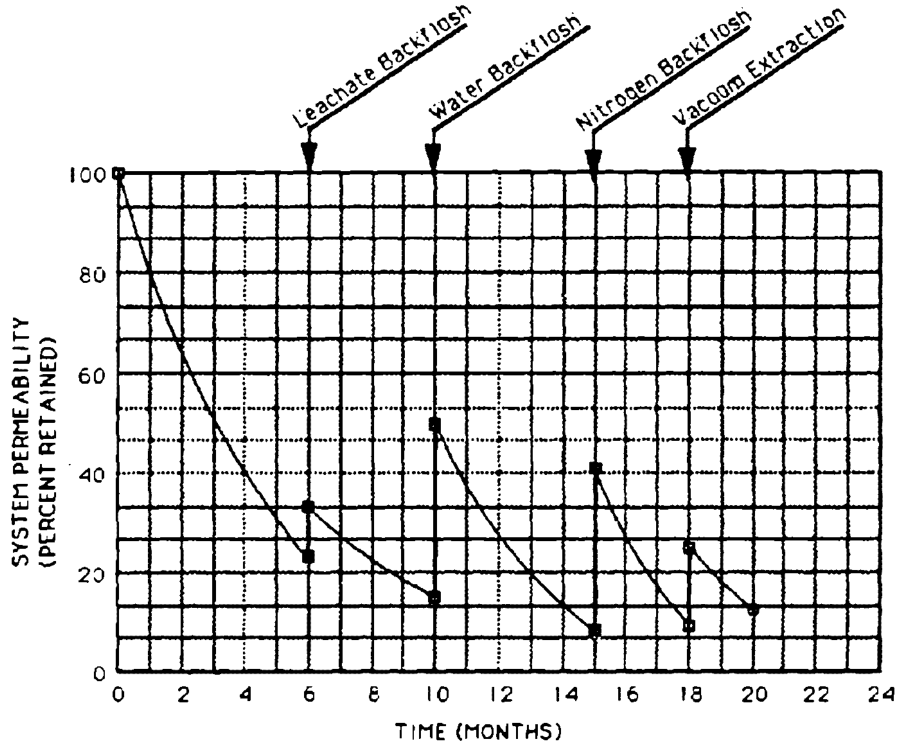


Figure 25 - System Permeability Retained and Various Remediation Attempts for Landfill NY-2 and Flow Test Column NW (N) 16 AN/S

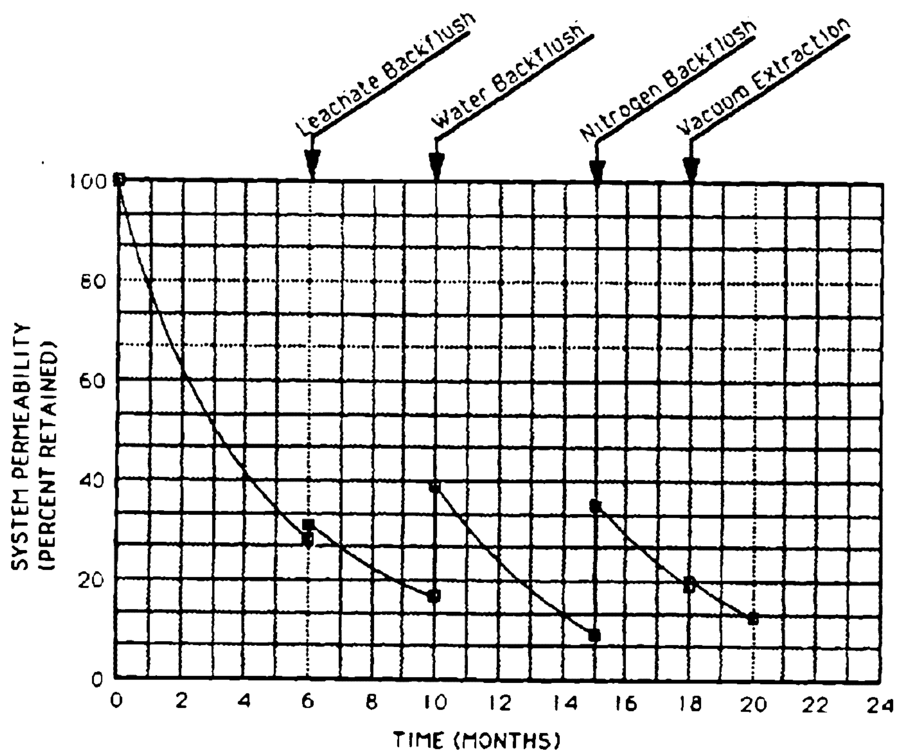


Figure 26 - System Permeability Retained and Various Remediation Attempts for Landfill NY-2 and Flow Test Column NW (N) 16 A/S

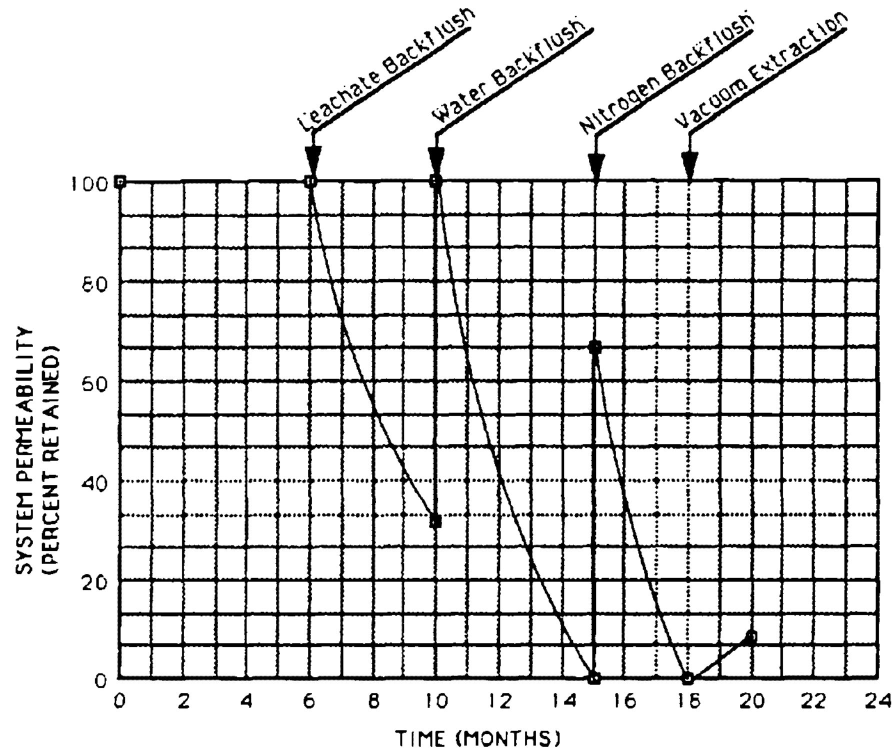


Figure 27 - System Permeability Retained and Various Remediation Attempts for Landfill NY-2 and Flow Test Column NW (N) 16 AN/W

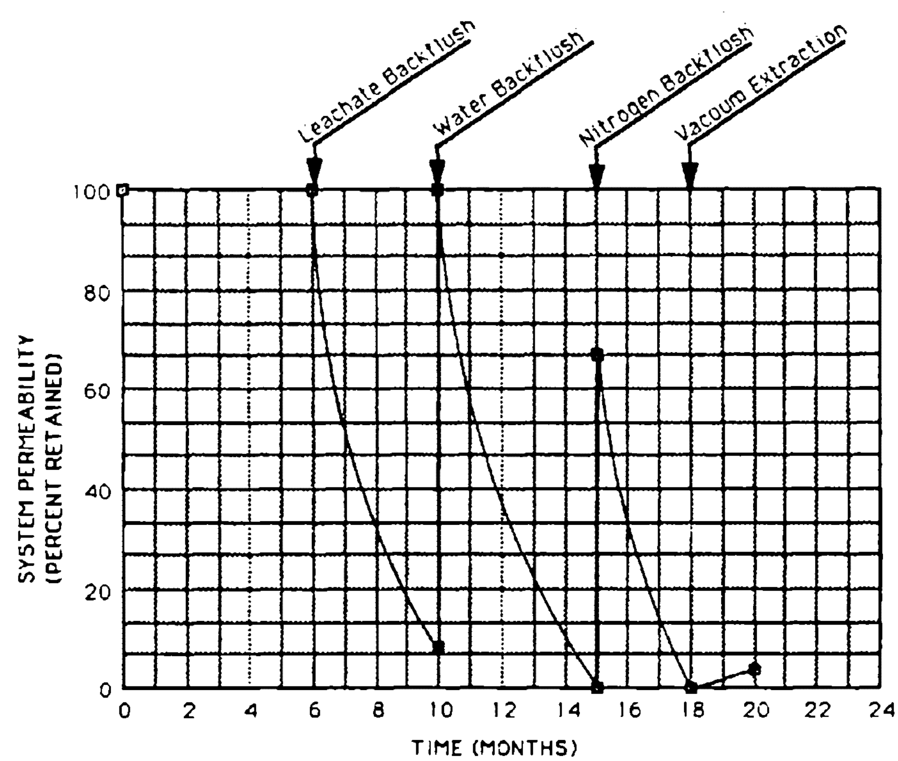


Figure 28 - System Permeability Retained and Various Remediation Attempts for Landfill NY-2 and Flow Test Column NW (N) 16 A/W

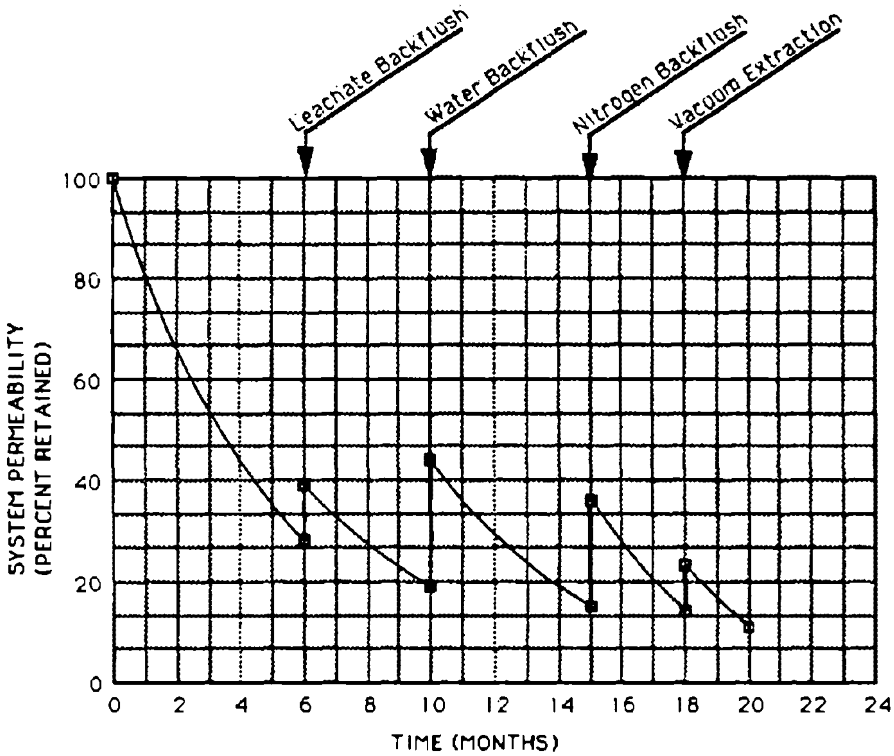


Figure 29 - System Permeability Retained and Various Remediation Attempts for Landfill NY-2 and Flow Test Column NW (N) 8 AN/S

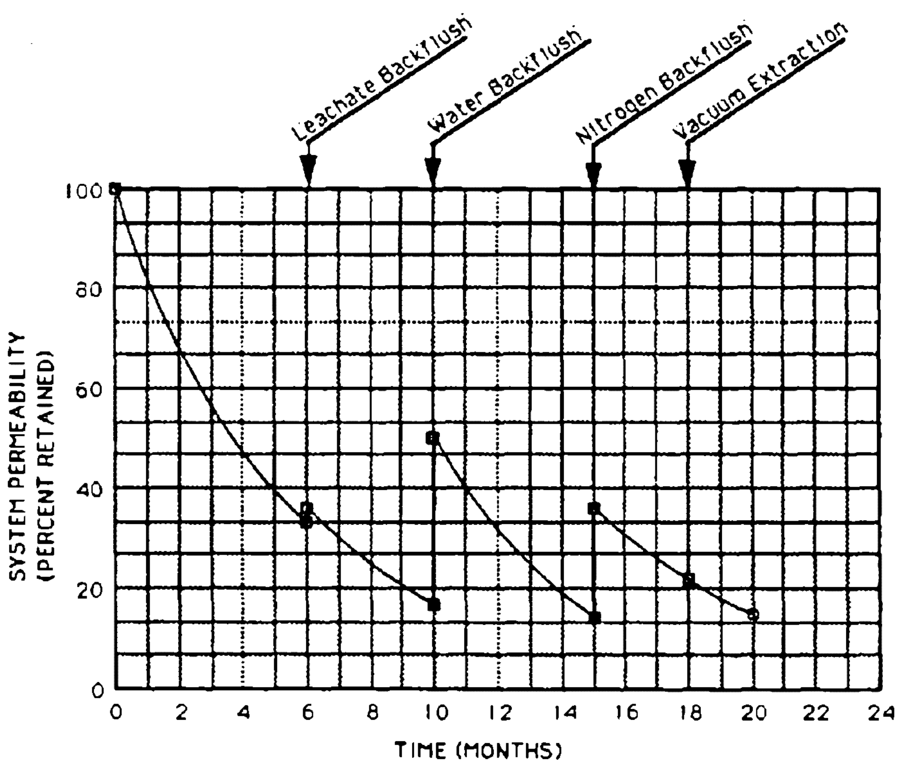


Figure 30 - System Permeability Retained and Various Remediation Attempts for Landfill NY-2 and Flow Test Column NW (N) 8 A/S

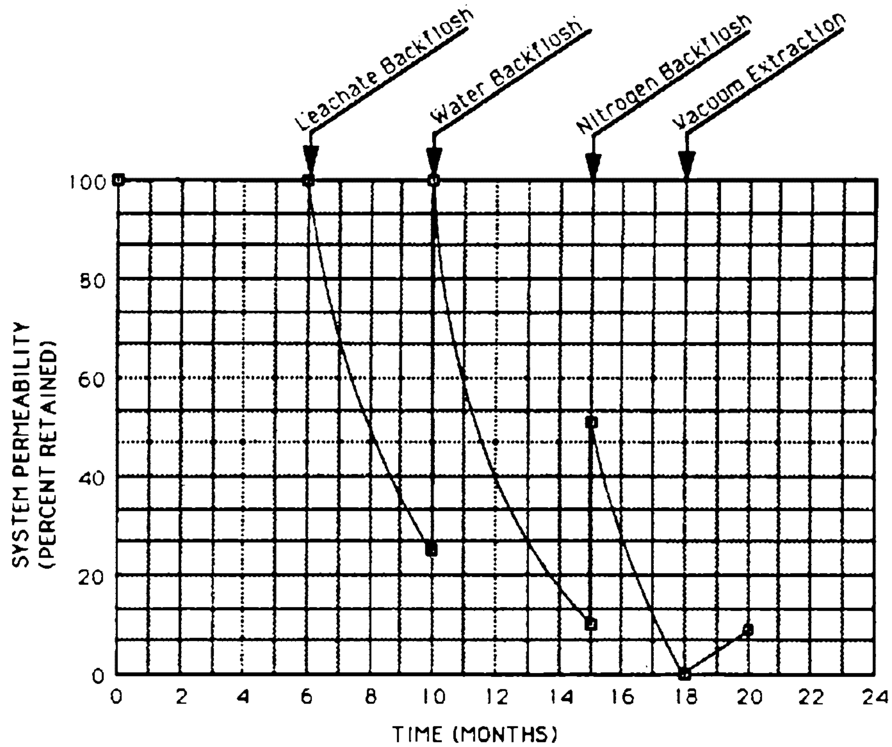


Figure 31 - System Permeability Retained and Various Remediation Attempts for Landfill NY-2 and Flow Test Column NW (N) 8 AN/W

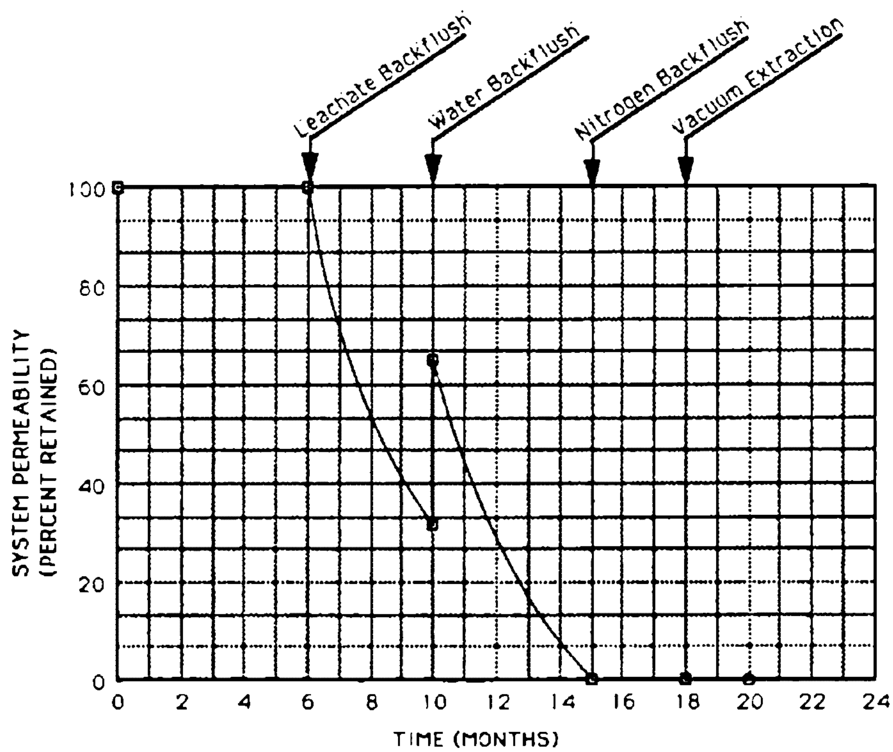


Figure 32 - System Permeability Retained and Various Remediation Attempts for Landfill NY-2 and Flow Test Column NW (N) 8 A/W

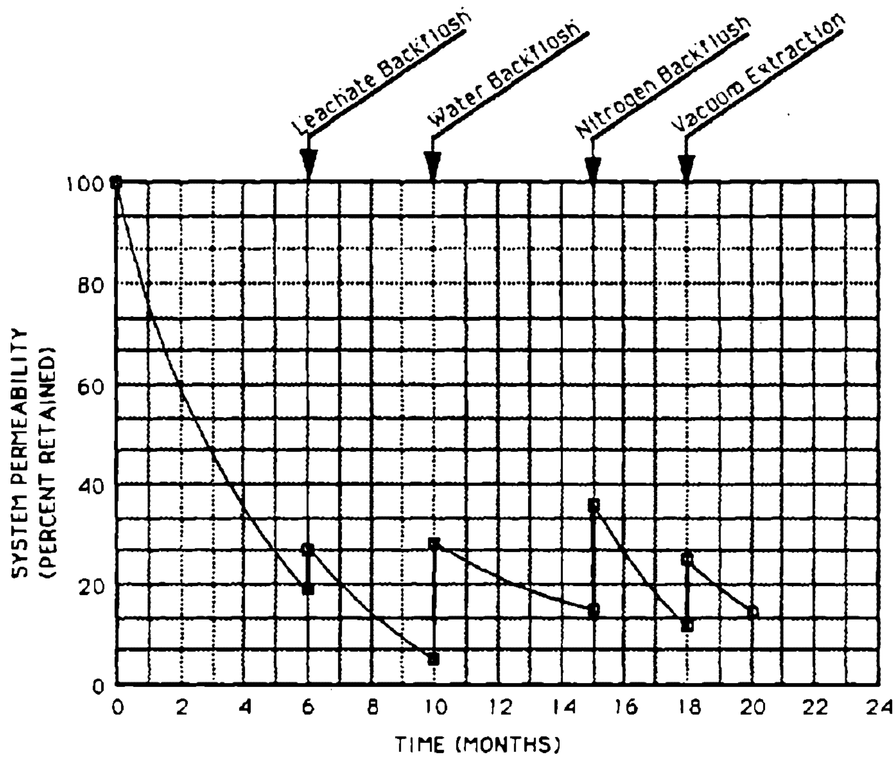


Figure 33 - System Permeability Retained and Various Remediation Attempts for Landfill DE-3 and Flow Test Column WM (NC) AN/S

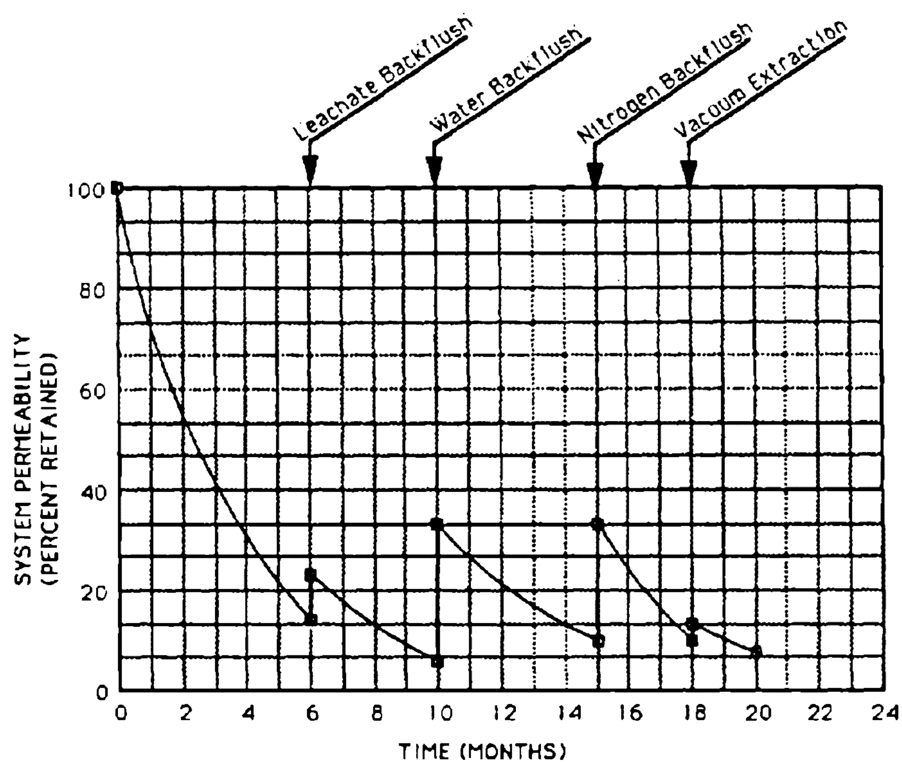


Figure 34 - System Permeability Retained and Various Remediation Attempts for Landfill DE-3 and Flow Test Column WM (NC) A/S

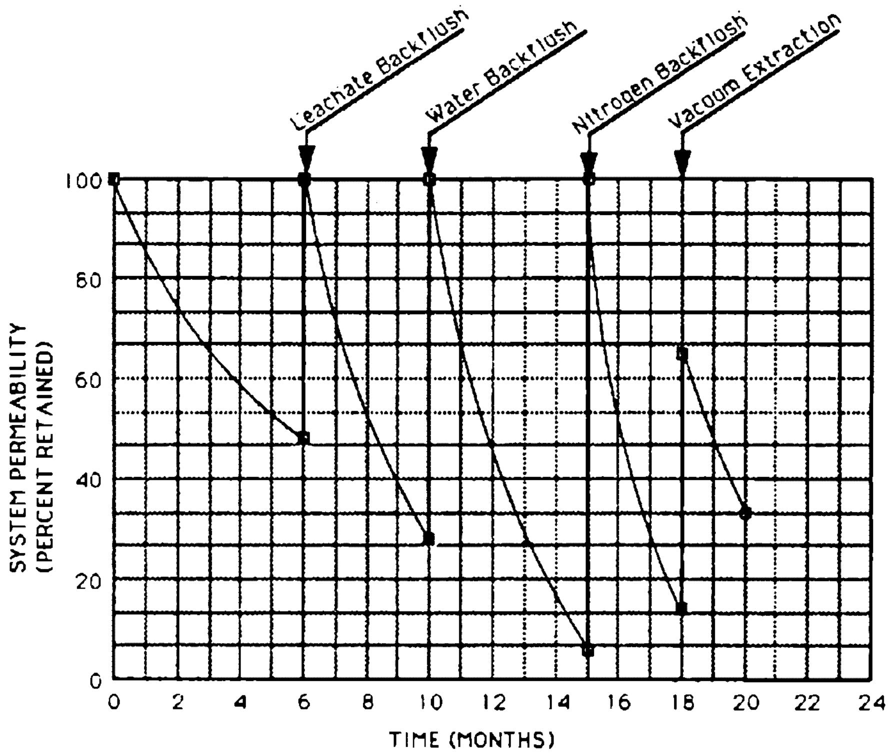


Figure 35 - System Permeability Retained and Various Remediation Attempts for Landfill DE-3 and Flow Test Column WM (NC) AN/W

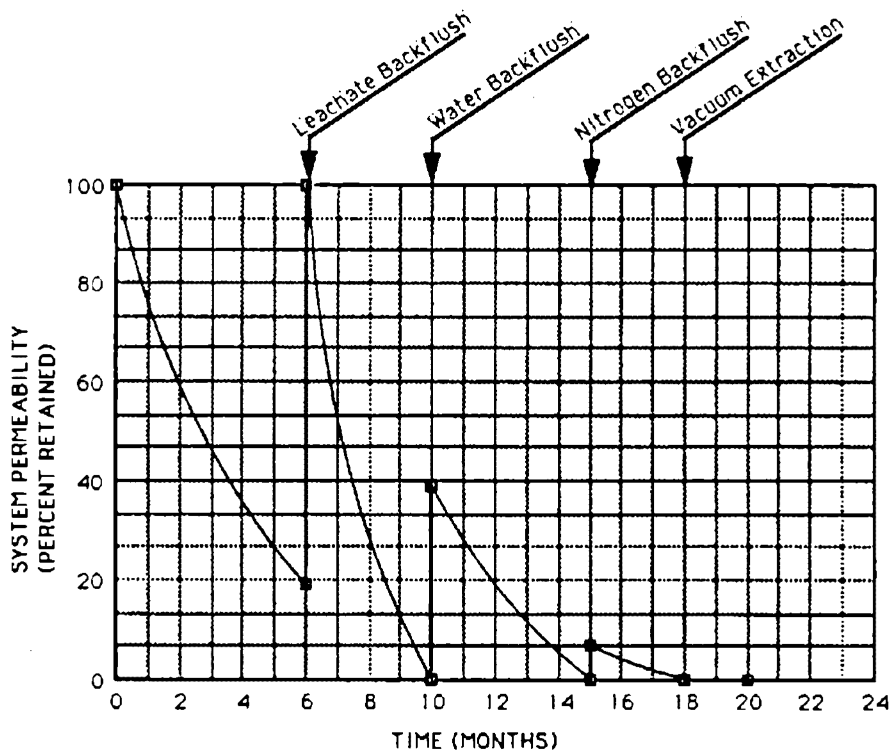


Figure 36 - System Permeability Retained and Various Remediation Attempts for Landfill DE-3 and Flow Test Column WM (NC) A/W

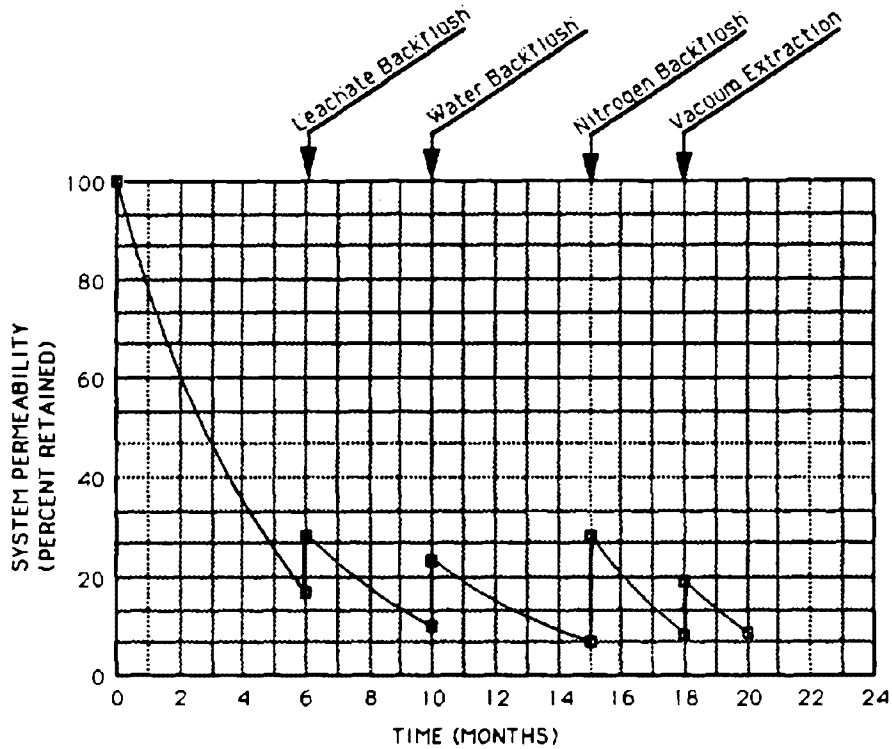


Figure 37 - System Permeability Retained and Various Remediation Attempts for Landfill DE-3 and Flow Test Column NW (HS) AN/S

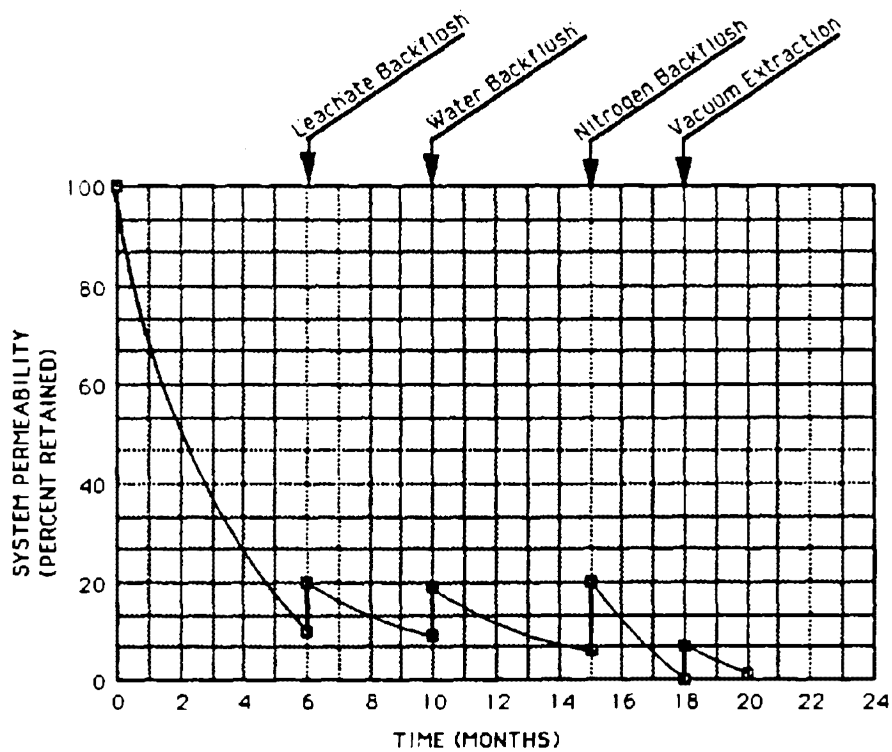


Figure 38 - System Permeability Retained and Various Remediation Attempts for Landfill DE-3 and Flow Test Column NW (HS) A/S

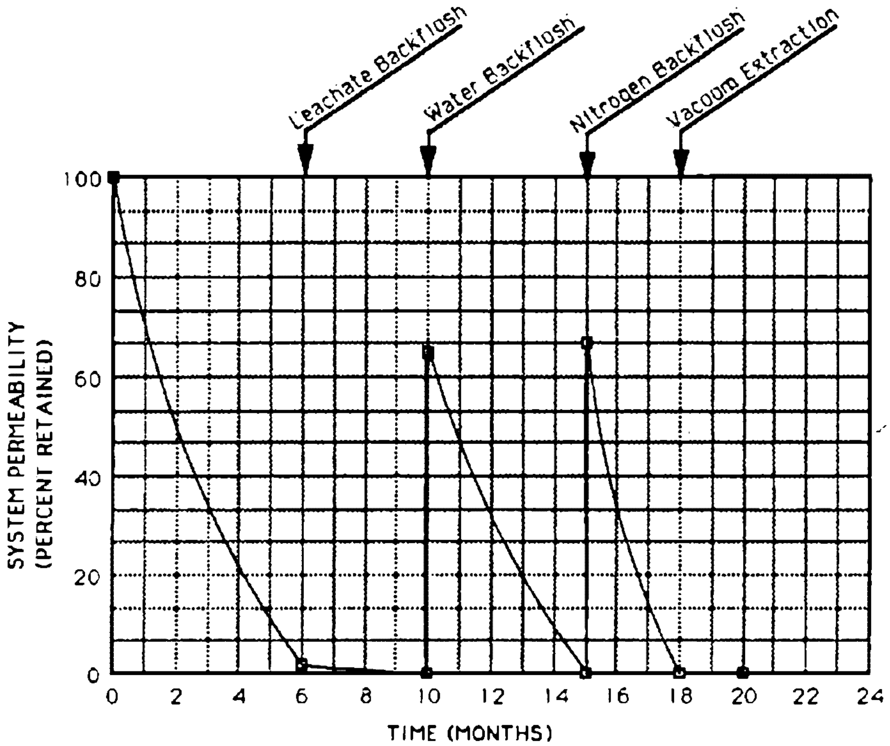


Figure 39 - System Permeability Retained and Various Remediation Attempts for Landfill De-3 and Flow Test Column NW (HS) AN/W

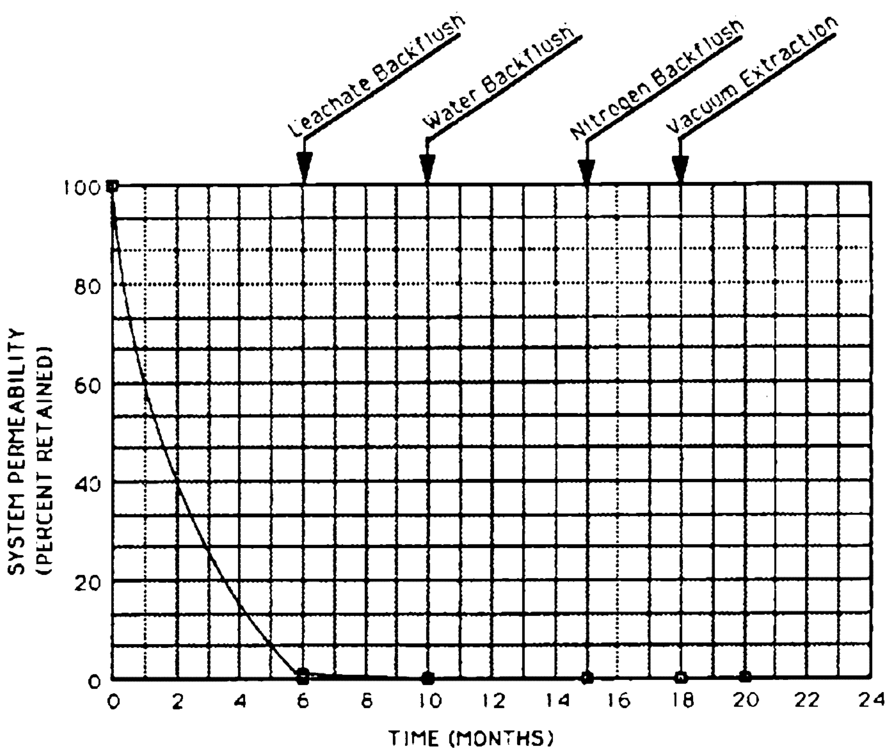


Figure 40 - System Permeability Retained and Various Remediation Attempts for Landfill DE-3 and Flow Test Column NW (HS) A/W

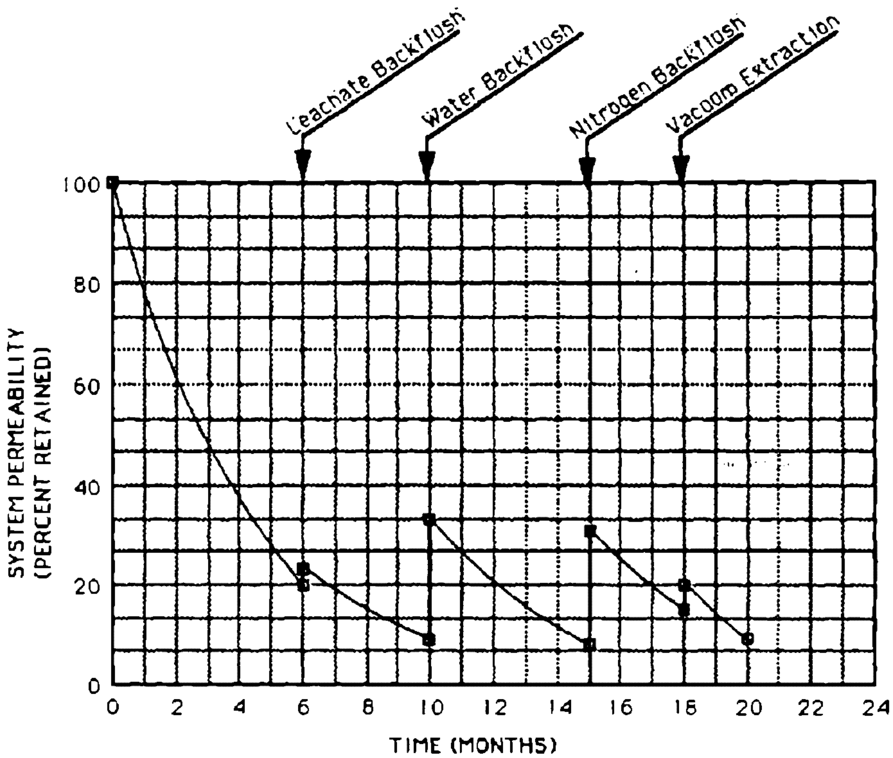


Figure 41 - System Permeability Retained and Various Remediation Attempts for Landfill DE-3 and Flow Test Column NW (16) AN/S

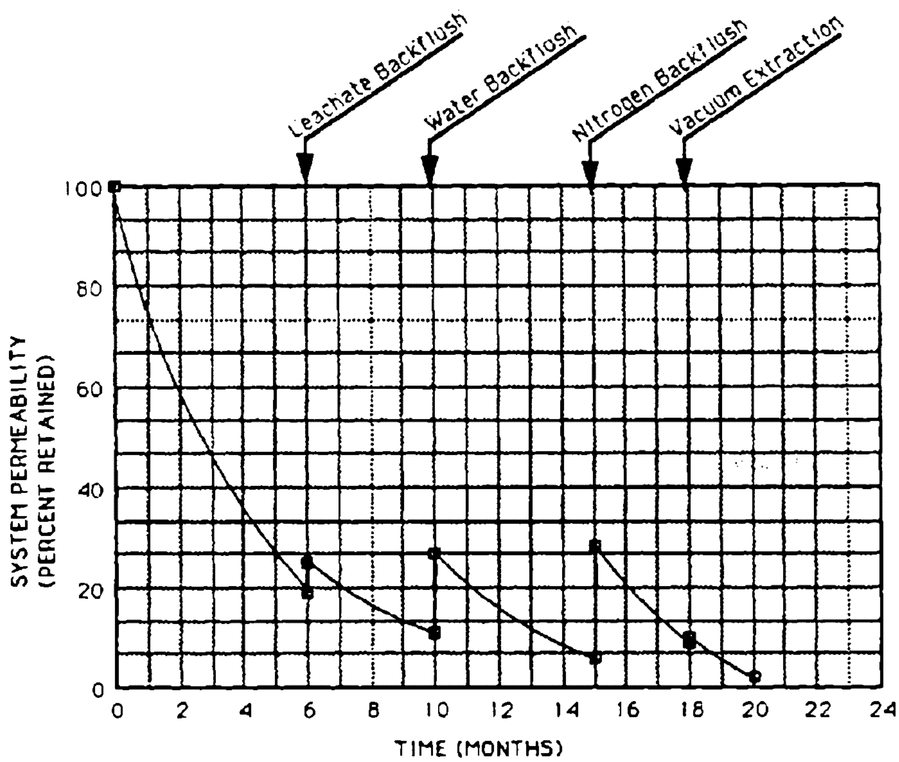


Figure 42 - System Permeability Retained and Various Remediation Attempts for Landfill DE-3 and Flow Test Column NW (16) A/S

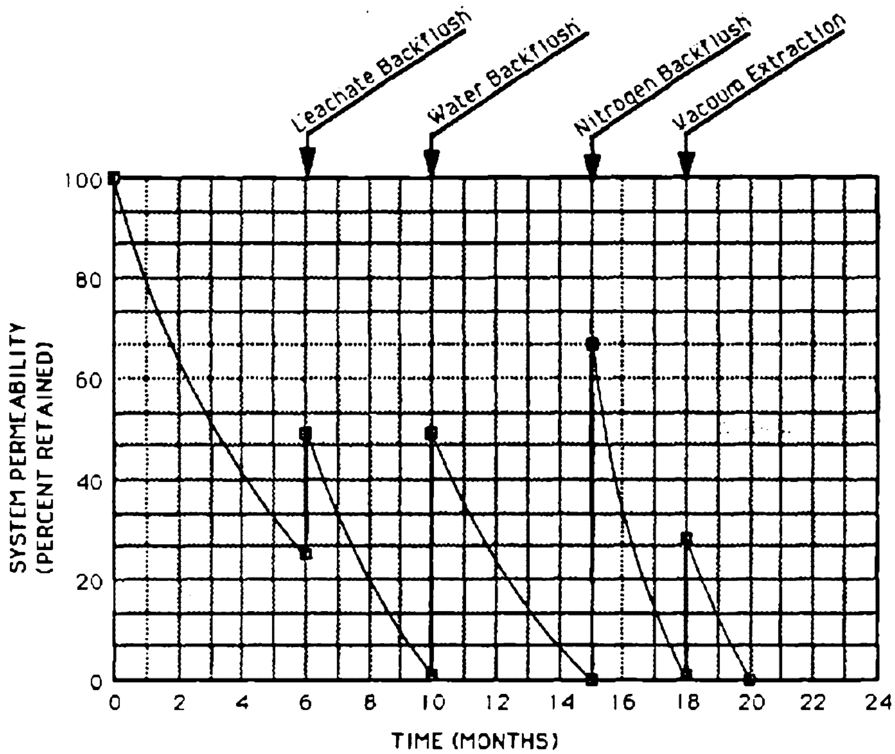


Figure 43 - System Permeability Retained and Various Remediation Attempts for Landfill DE-3 and Flow Test Column NW (16) AN/W

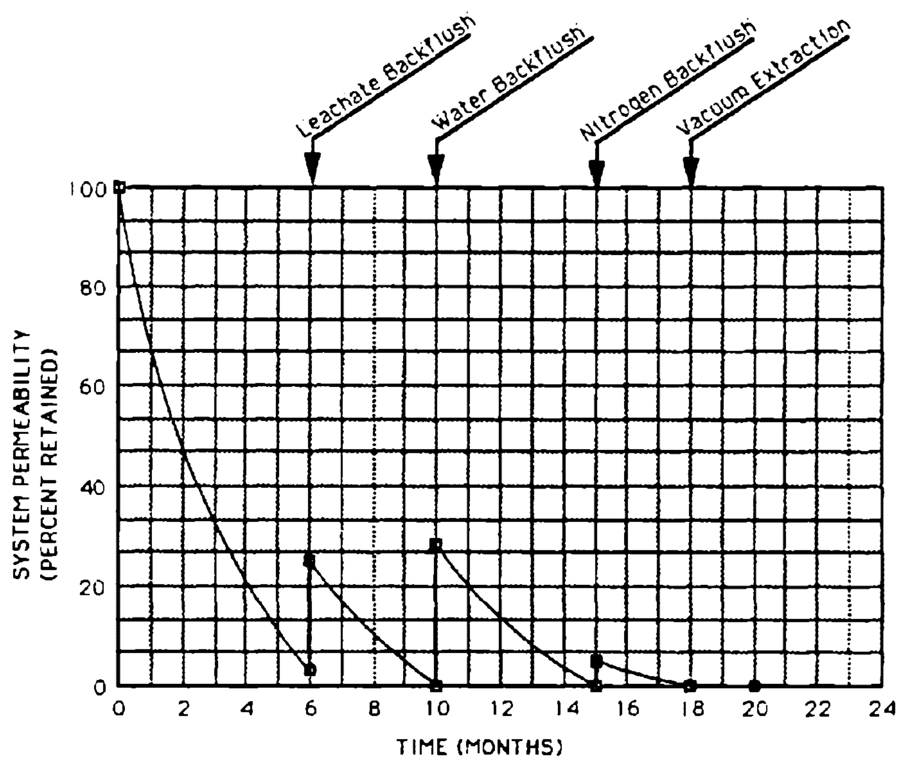


Figure 44 - System Permeability Retained and Various Remediation Attempts for Landfill DE-3 and Flow Test Column NW (16) A/W

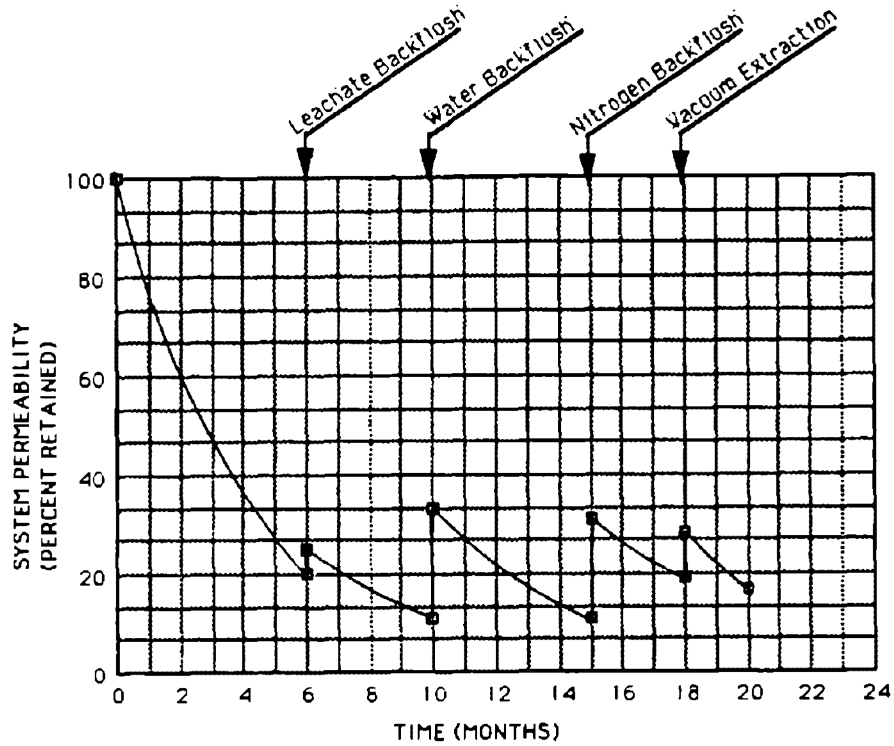


Figure 45 - System Permeability Retained and Various Remediation Attempts for Landfill DE-3 and Flow Test Column NW (8) AN/S

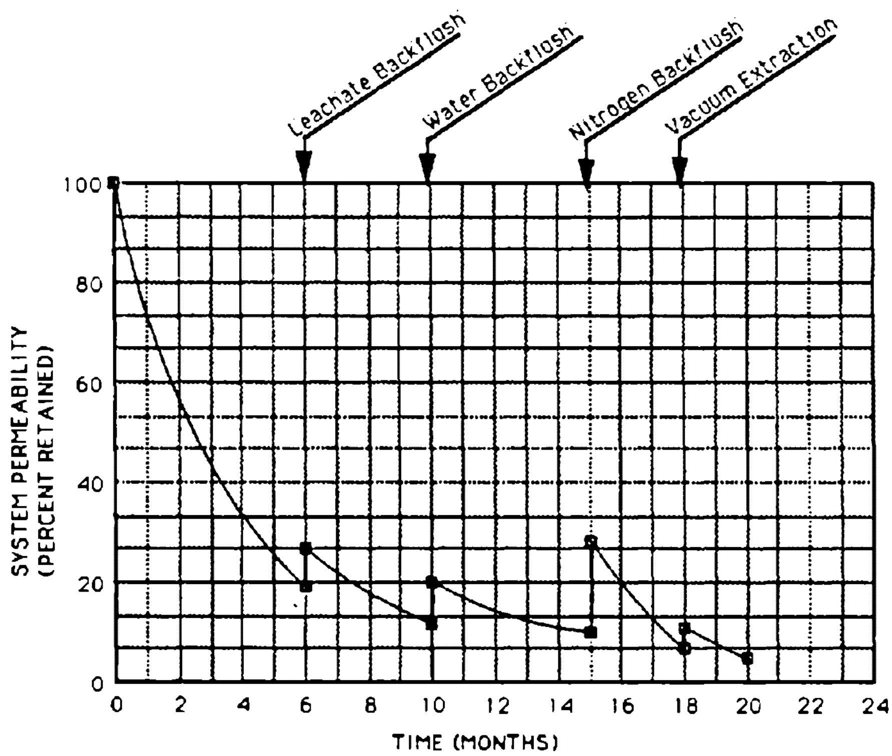


Figure 46 - System Permeability Retained and Various Remediation Attempts for Landfill DE-3 and Flow Test Column NW (8) A/S

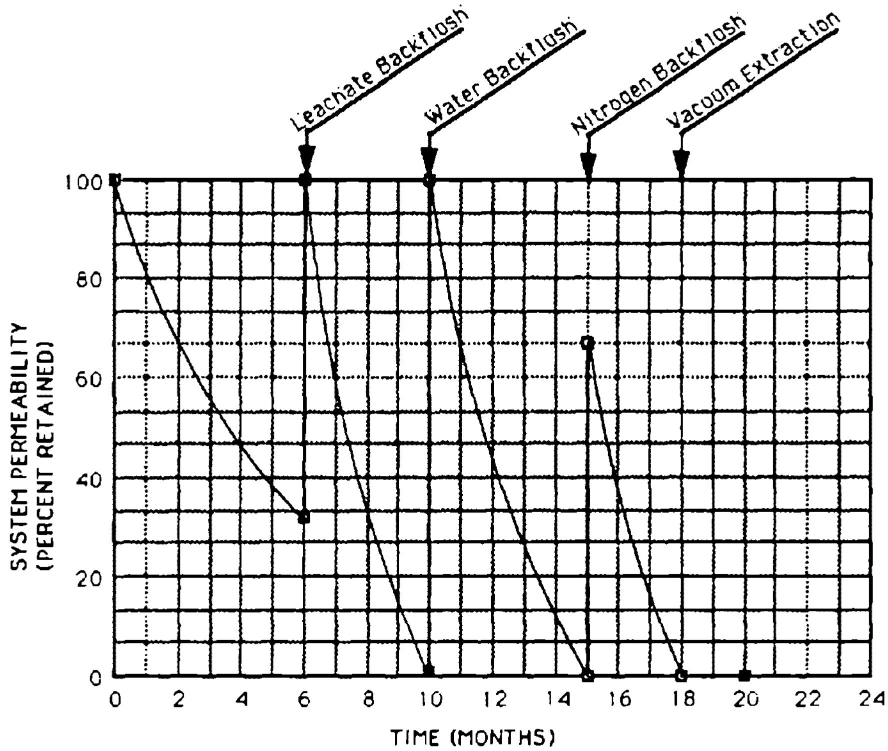


Figure 47 - System Permeability Retained and Various Remediation Attempts for Landfill DE-3 and Flow Test Column NW (8) AN/W

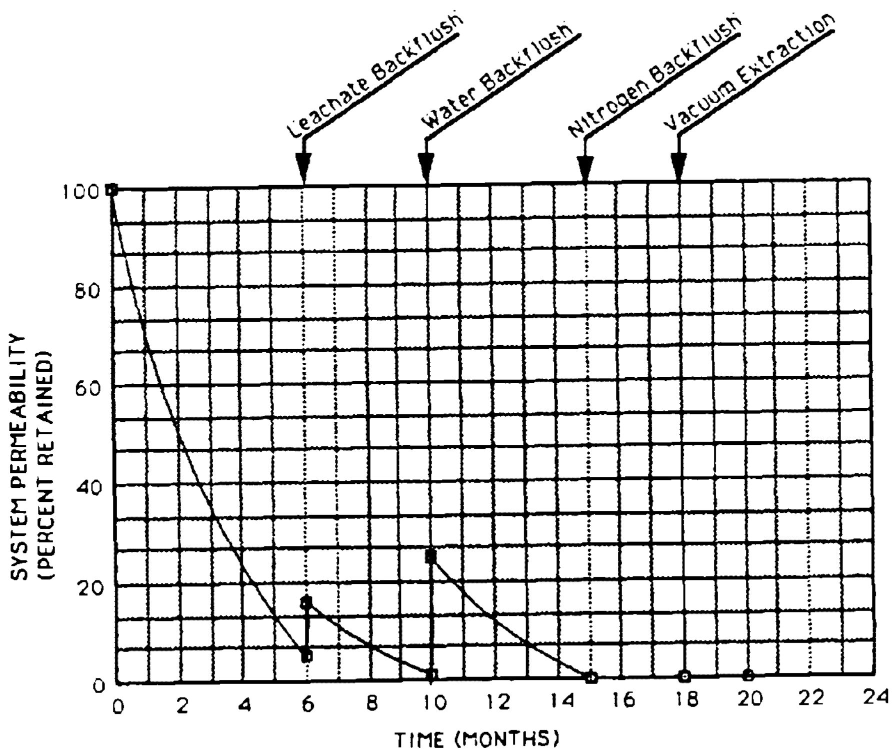


Figure 48 - System Permeability Retained and Various Remediation Attempts for Landfill DE-3 and Flow Test Column NW (8) A/W

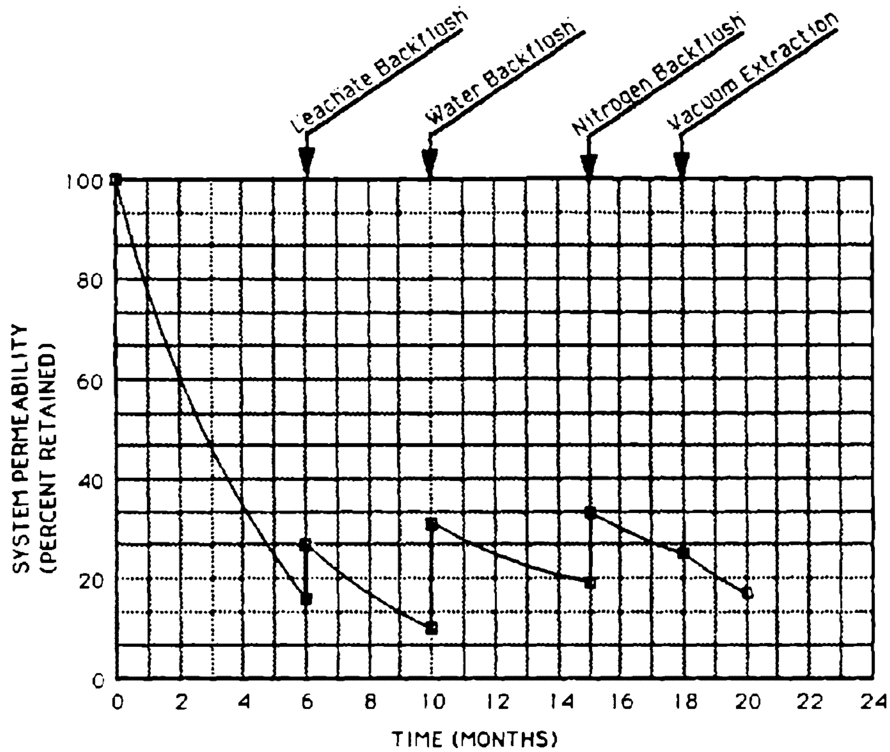


Figure 49 - System Permeability Retained and Various Remediation Attempts for Landfill NJ-4 and Flow Test Column WM (NC) AN/S

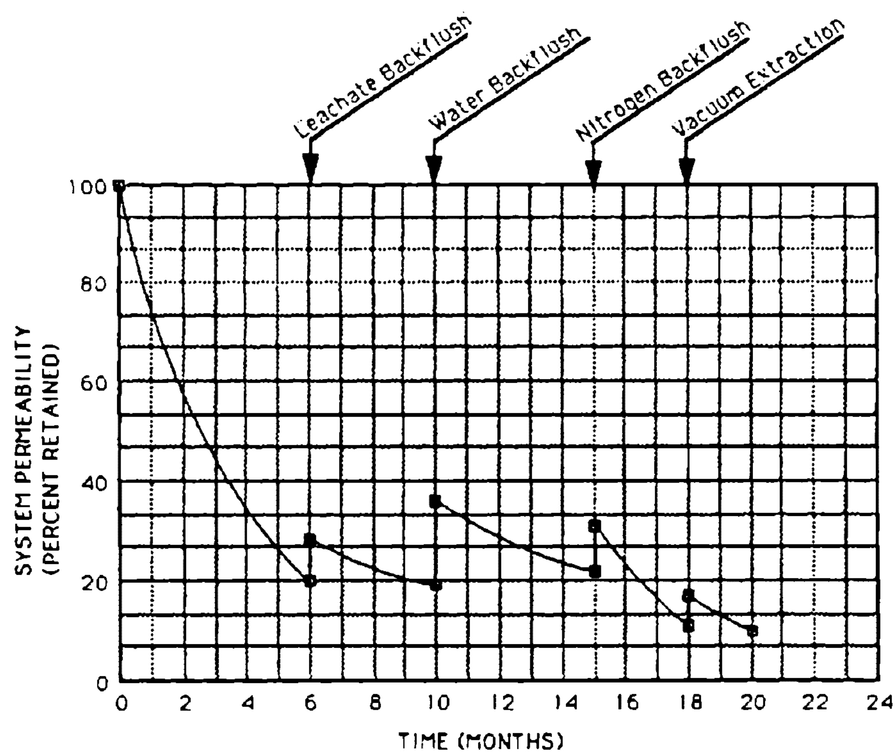


Figure 50 - System Permeability Retained and Various Remediation Attempts for Landfill NJ-4 and Flow Test Column WM (NC) A/S

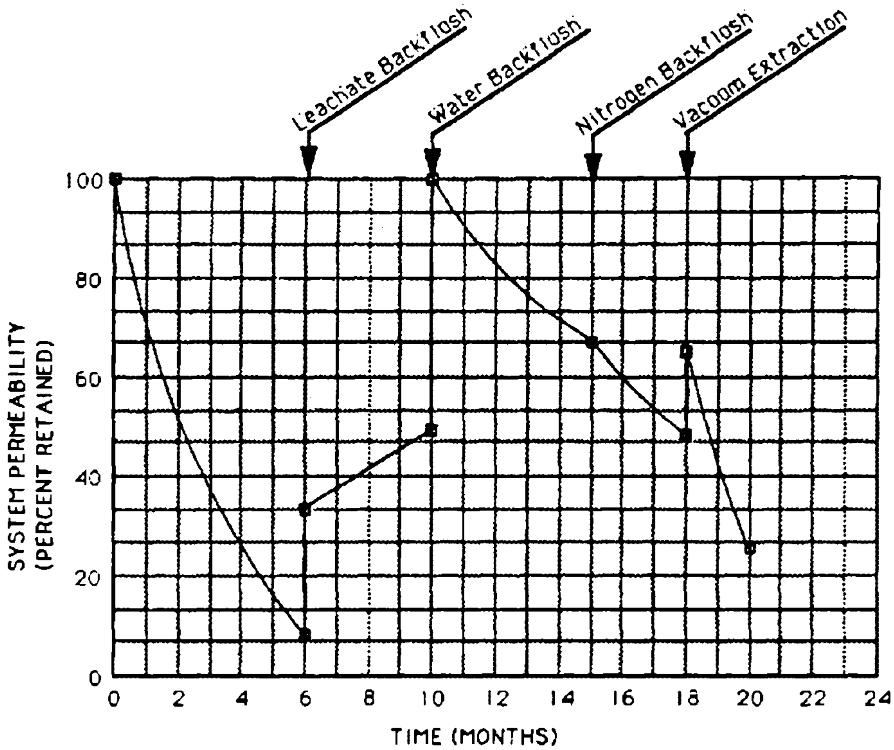


Figure 51 - System Permeability Retained and Various Remediation Attempts for Landfill NJ-4 and Flow Test Column WM (NC) AN/W

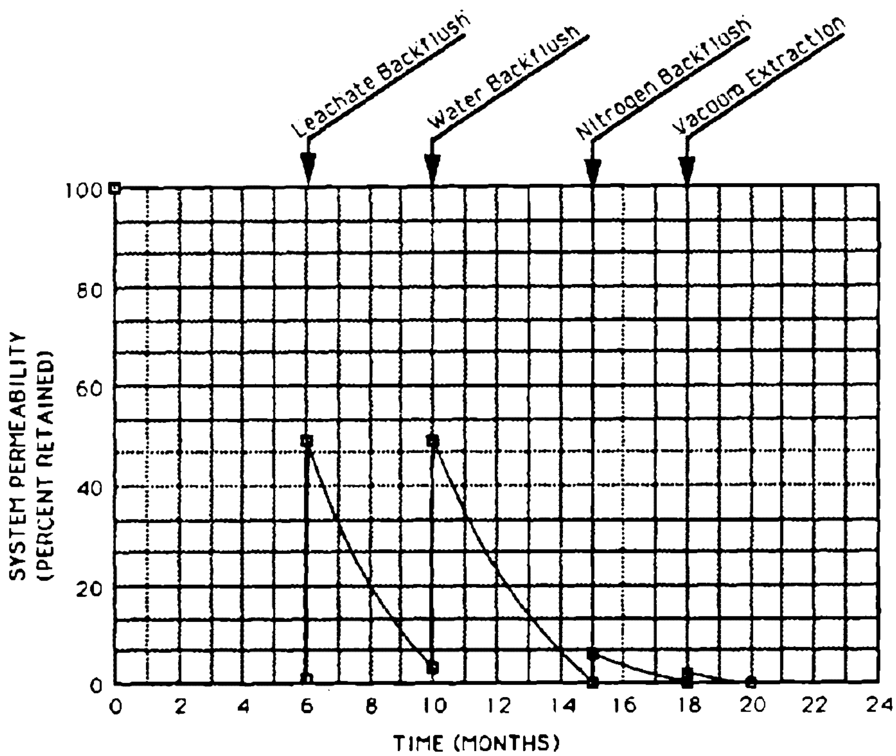


Figure 52 - System Permeability Retained and Various Remediation Attempts for Landfill NJ-4 and Flow Test Column WM (NC) A/W

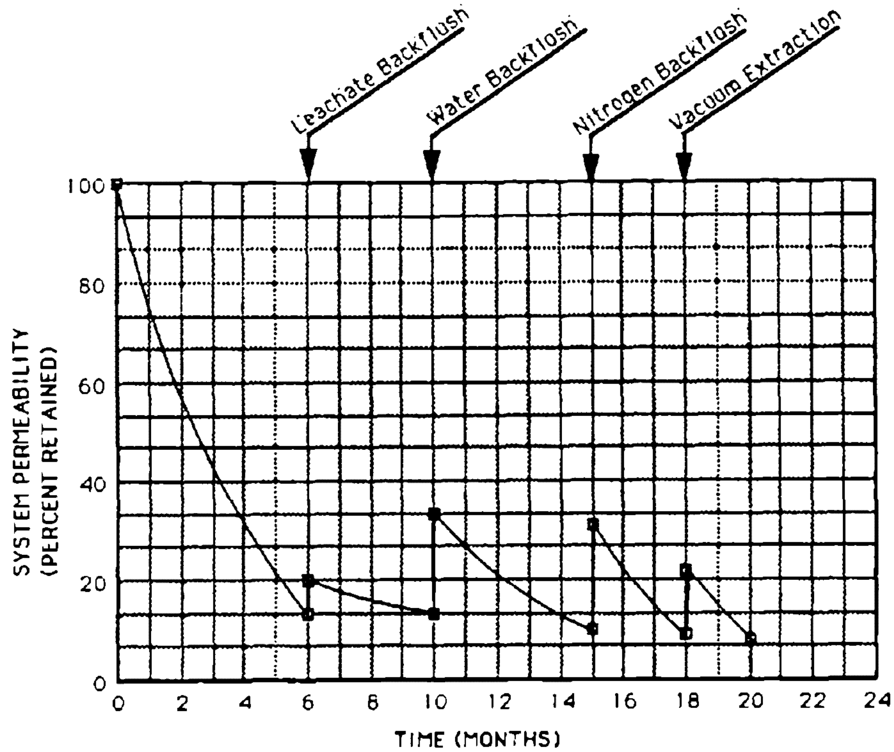


Figure 53 - System Permeability Retained and Various Remediation Attempts for Landfill NJ-4 and Flow Test Column NW (HS) AN/S

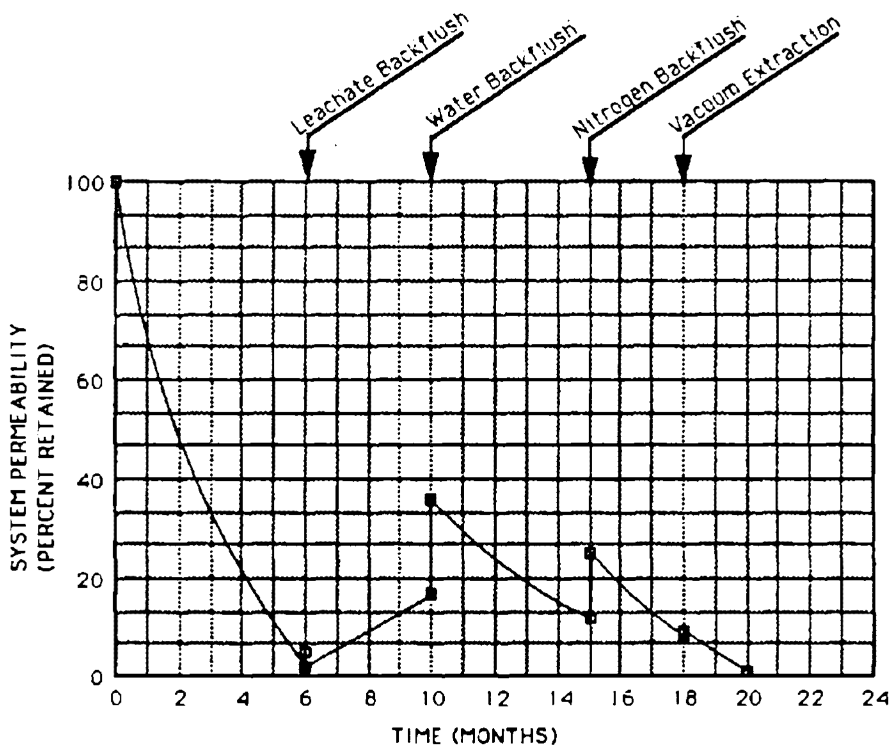


Figure 54 - System Permeability Retained and Various Remediation Attempts for Landfill NJ-4 and Flow Test Column NW (HS) A/S

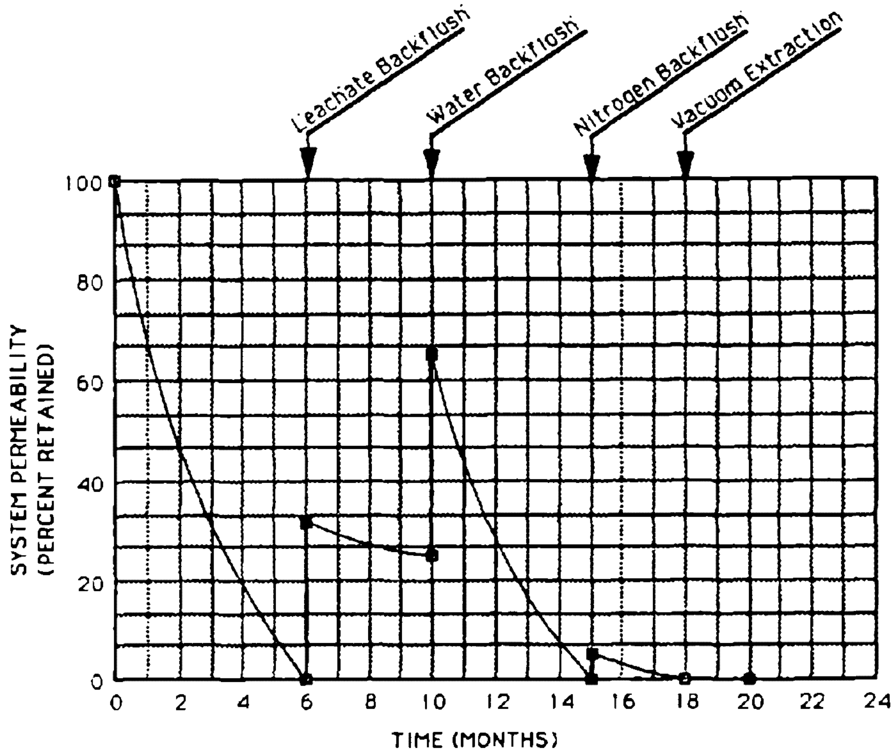


Figure 55 - System Permeability Retained and Various Remediation Attempts for Landfill NJ-4 and Flow Test Column NW (HS) AN/W

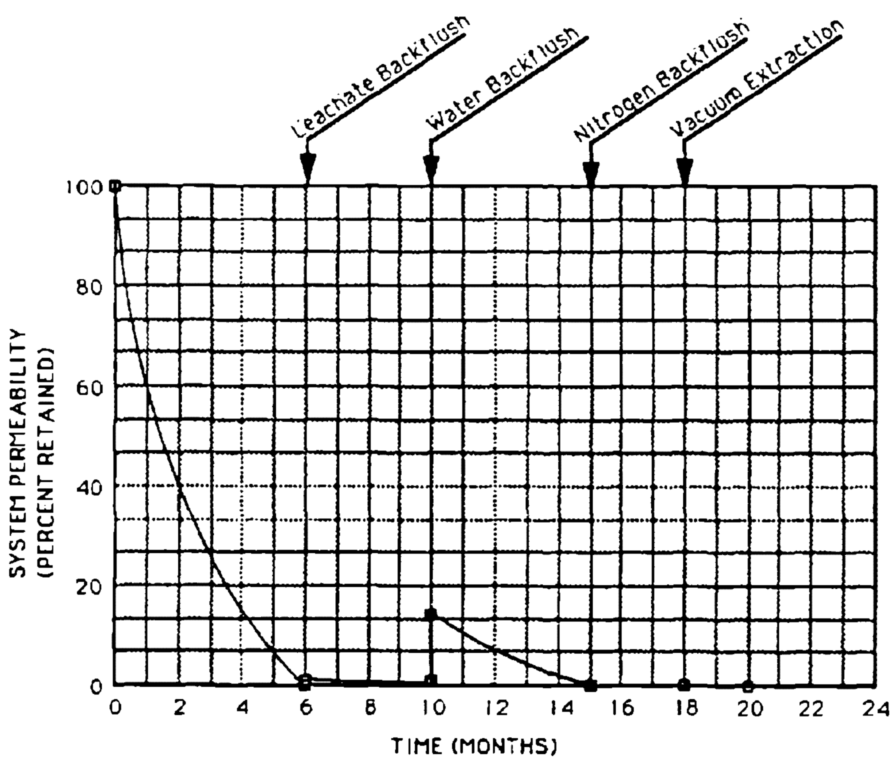


Figure 56 - System Permeability Retained and Various Remediation Attempts for Landfill NJ-4 and Flow Test Column NW (HS) A/W

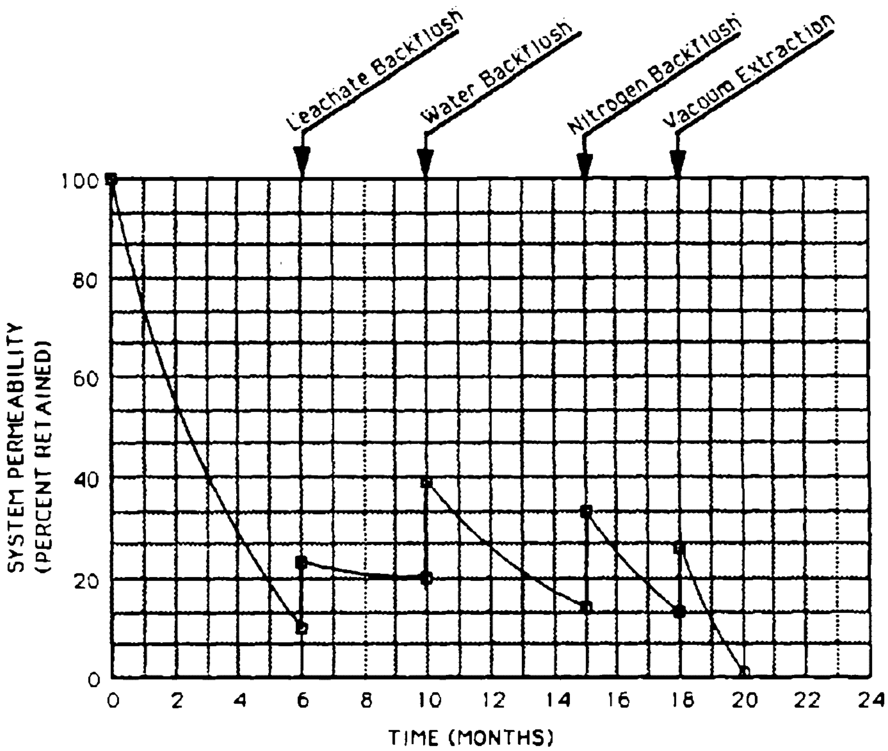


Figure 57 - System Permeability Retained and Various Remediation Attempts for Landfill NJ-4 and Flow Test Column NW (16) AN/S

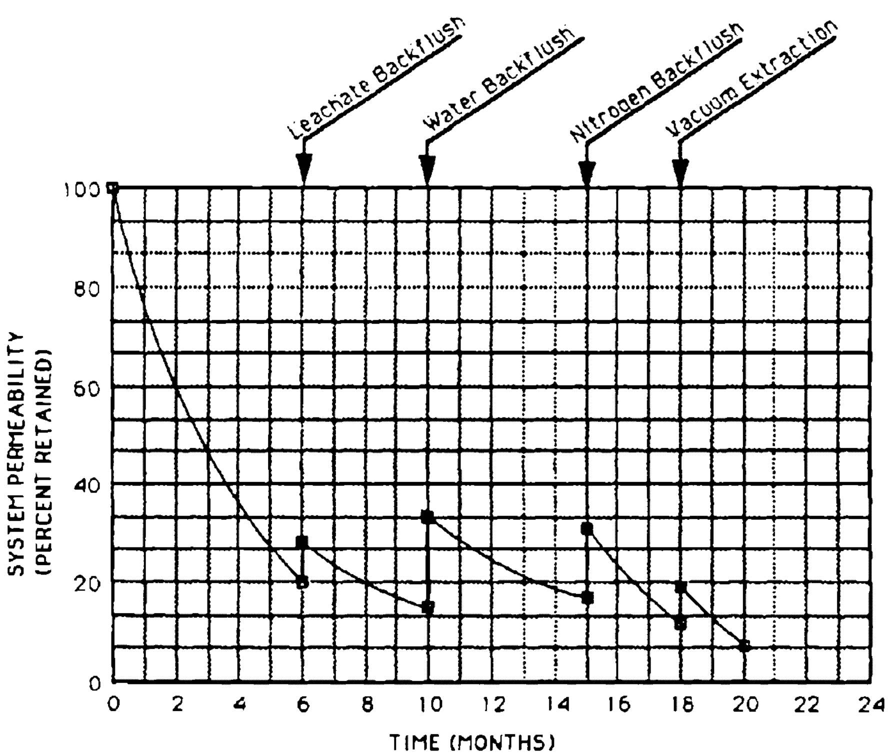


Figure 58 - System Permeability Retained and Various Remediation Attempts for Landfill NJ-4 and Flow Test Column NW (16) A/S

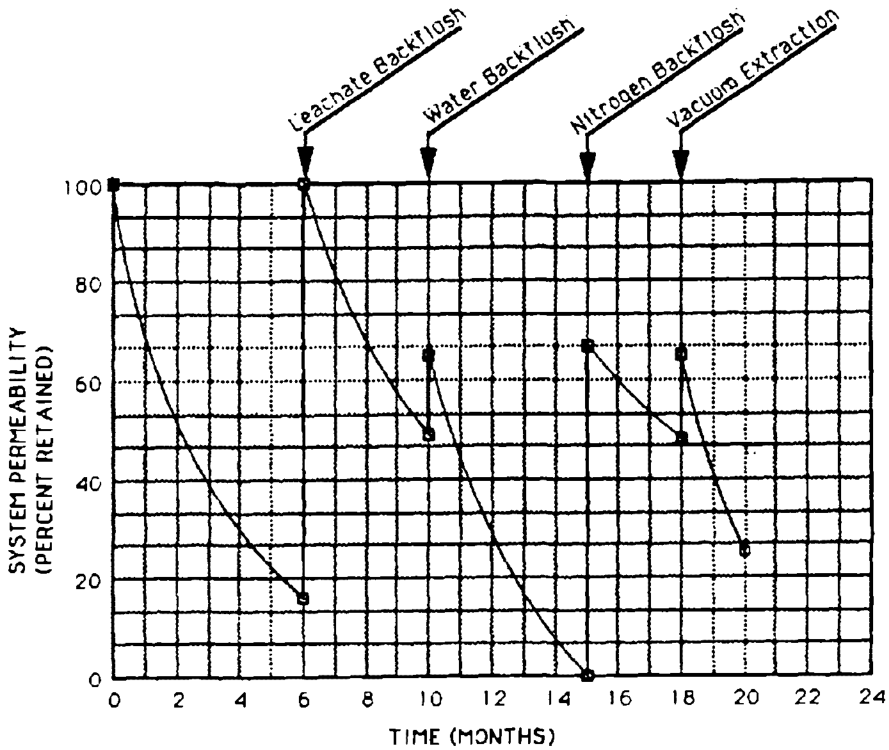


Figure 59 - System Permeability Retained and Various Remediation Attempts for Landfill NJ-4 and Flow Test Column NW (16) AN/W

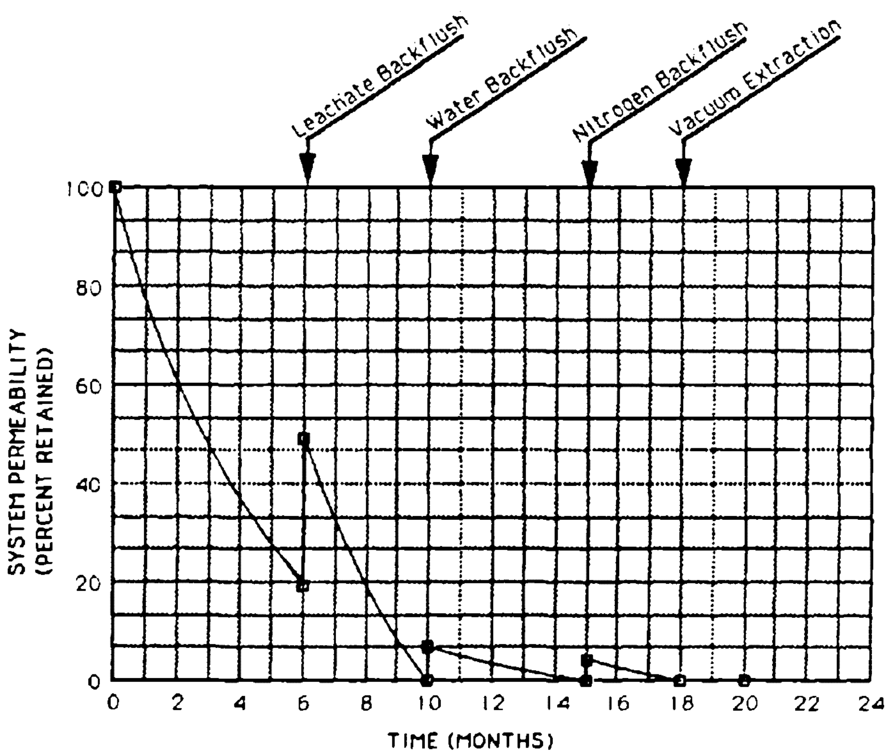


Figure 60 - System Permeability Retained and Various Remediation Attempts for Landfill NJ-4 and Flow Test Column NW (16) A/W

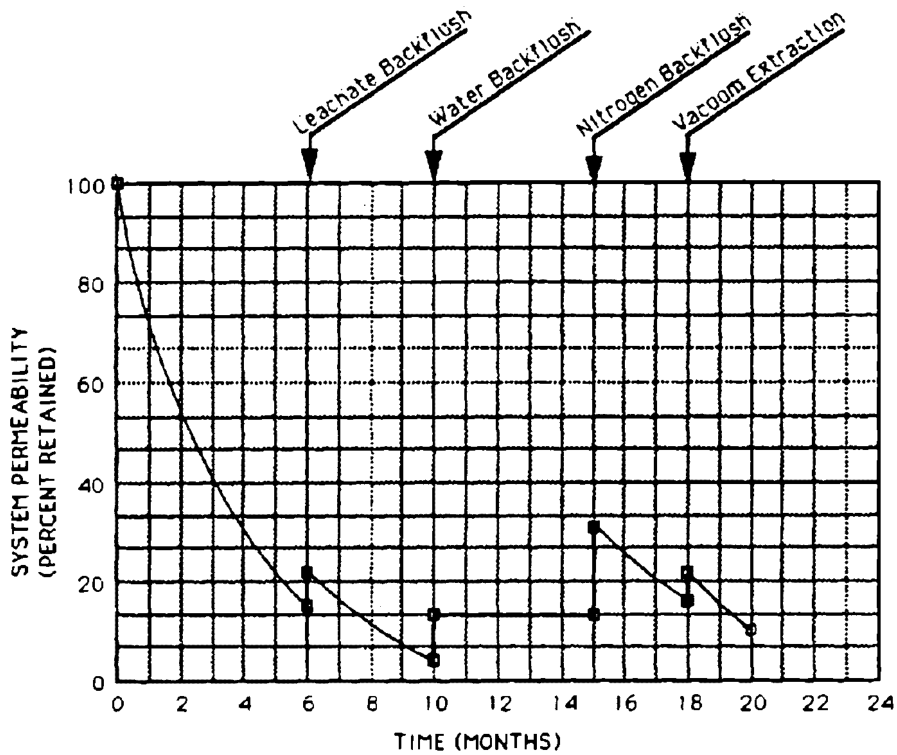


Figure 61 - System Permeability Retained and Various Remediation Attempts for Landfill NJ-4 and Flow Test Column NW (8) AN/S

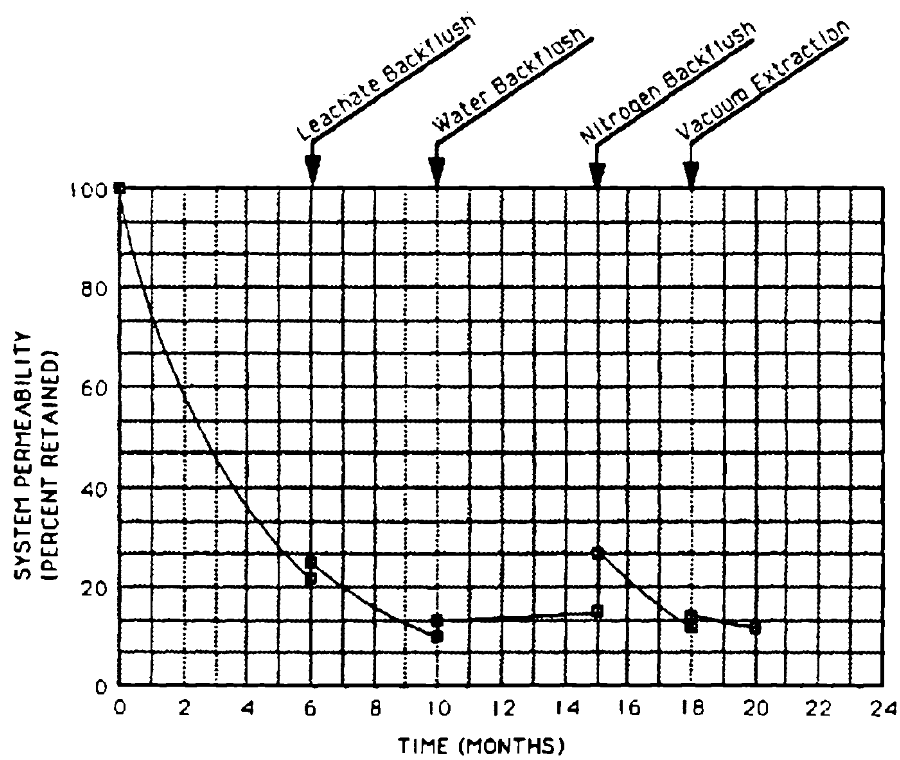


Figure 62 - System Permeability Retained and Various Remediation Attempts for Landfill NJ-4 and Flow Test Column NW (8) A/S

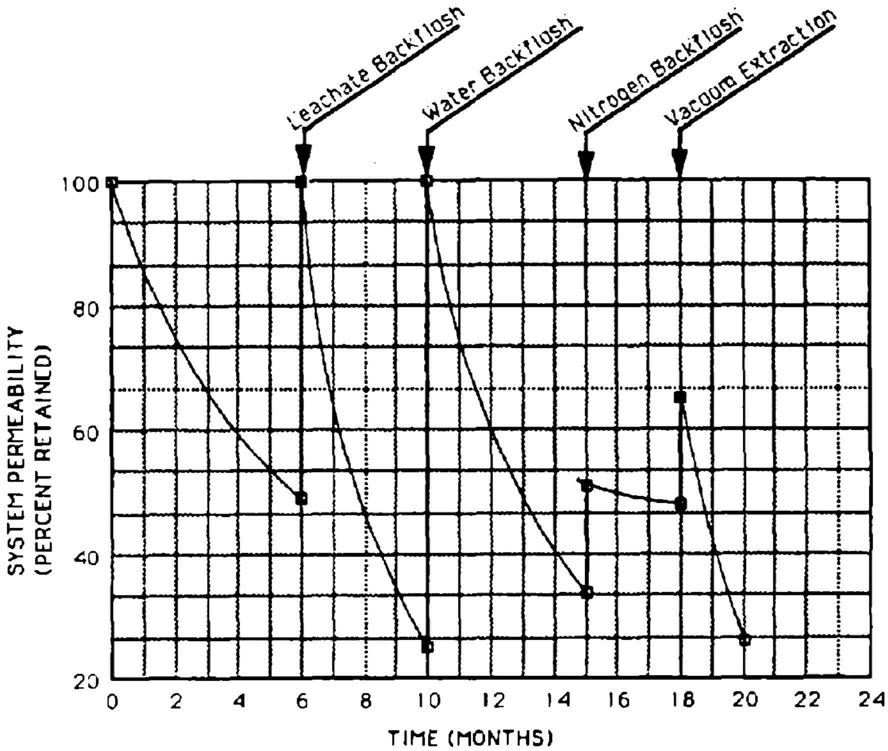


Figure 63 - System Permeability Retained and Various Remediation Attempts for Landfill NJ-4 and Flow Test Column NW (8) AN/W

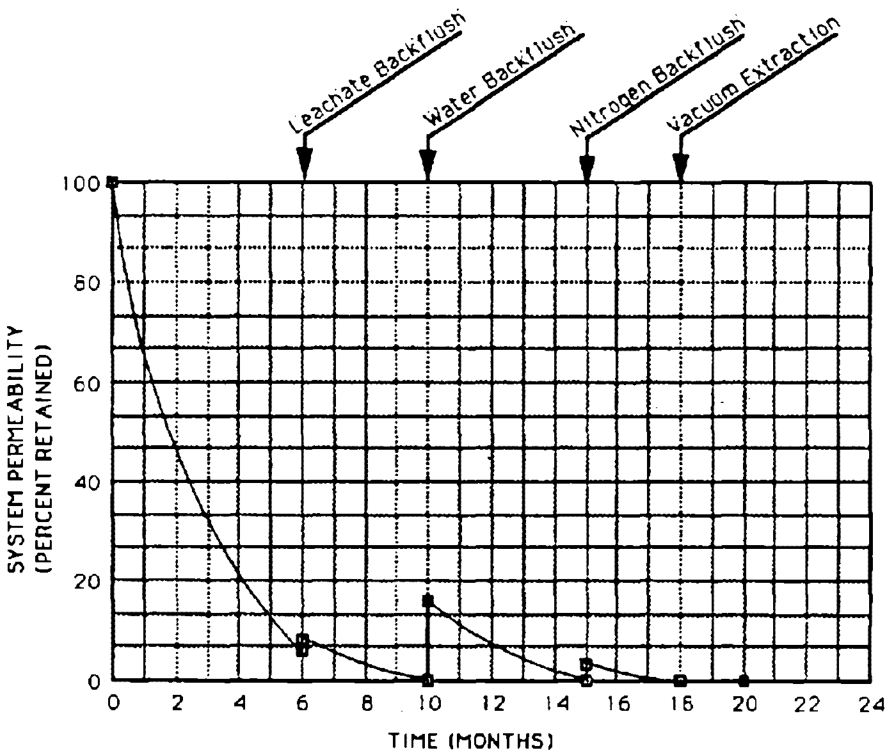


Figure 64 - System Permeability Retained and Various Remediation Attempts for Landfill NJ-4 and Flow Test Column NW (8) A/W

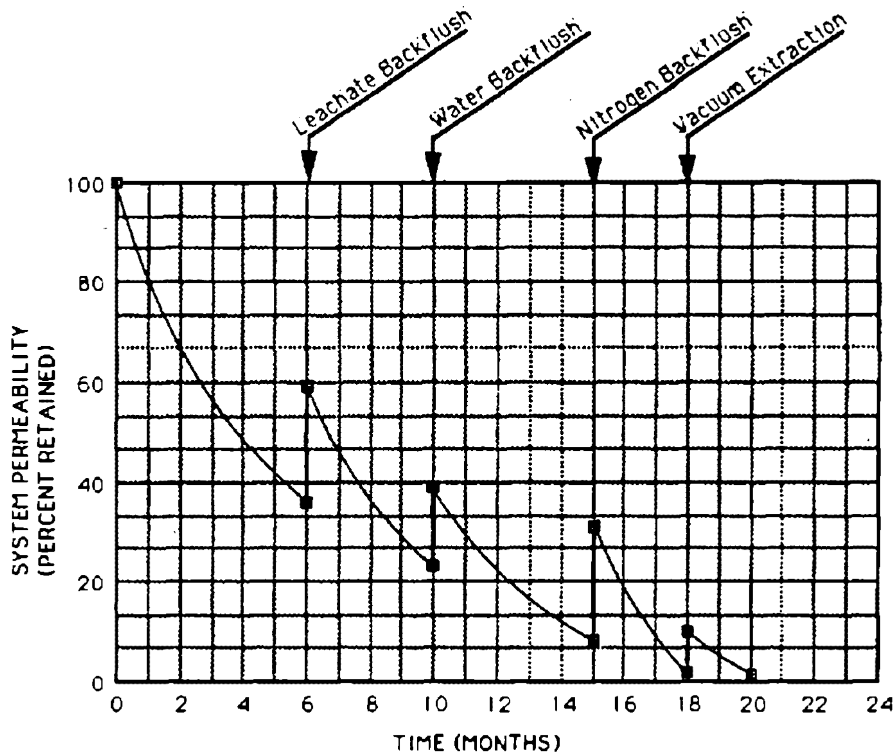


Figure 65 - System Permeability Retained and Various Remediation Attempts for Landfill MD-5 and Flow Test Column WM (NC) AN/S

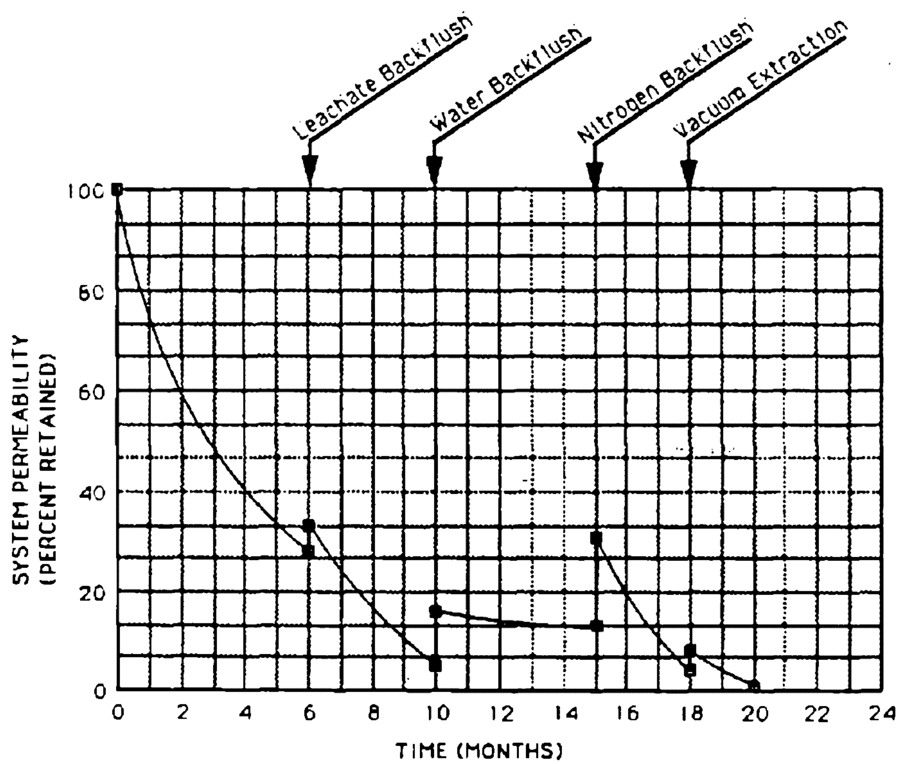


Figure 66 - System Permeability Retained and Various Remediation Attempts for Landfill MD-5 and Flow Test Column WM (NC) A/S

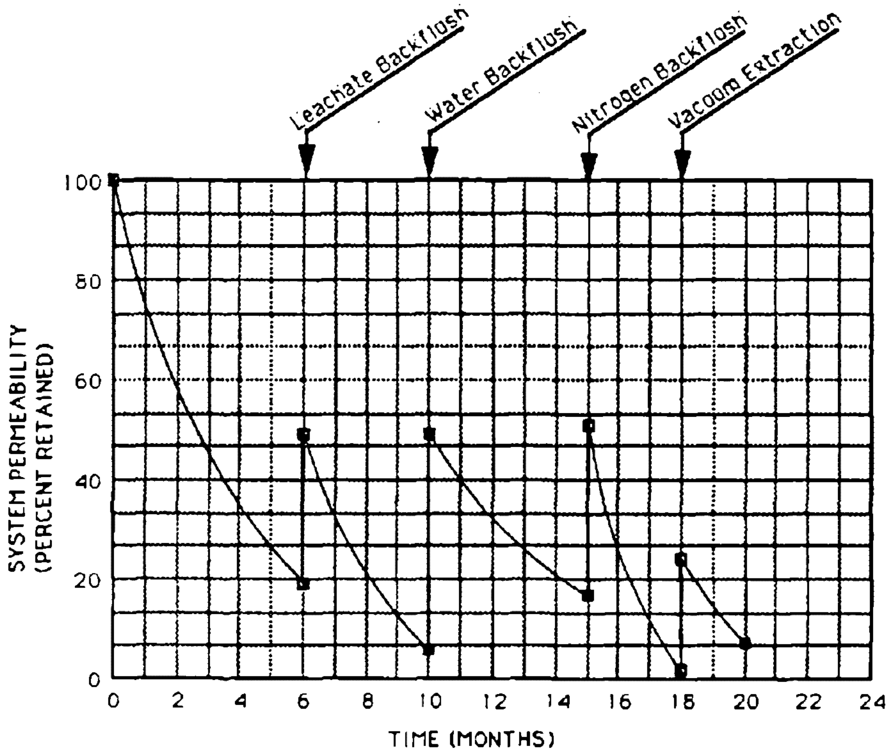


Figure 67 - System Permeability Retained and Various Remediation Attempts for Landfill MD-5 and Flow Test Column WM (NC) AN/W

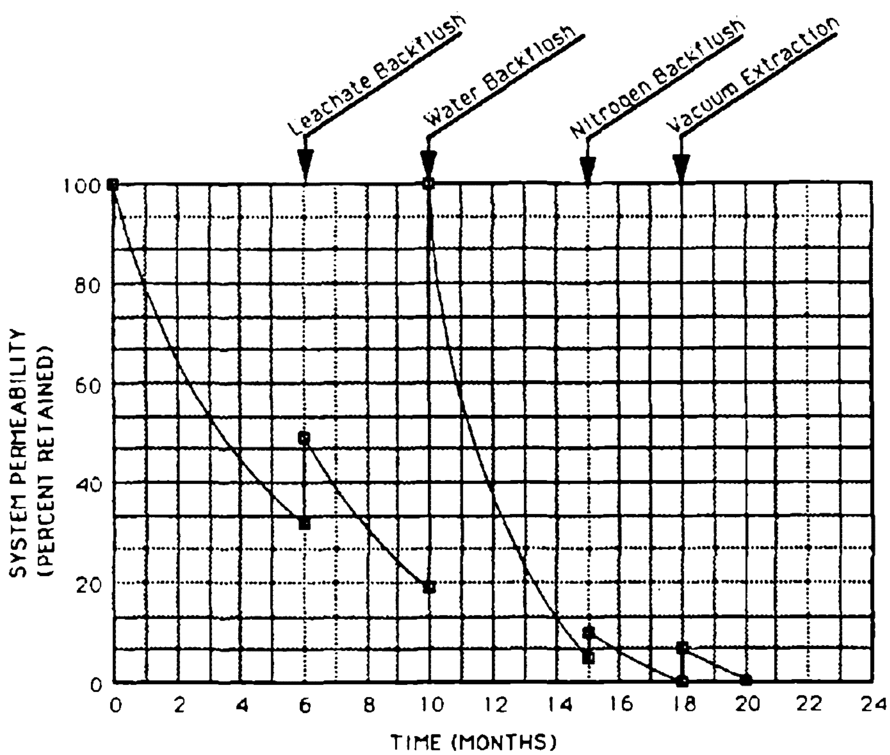


Figure 58 - System Permeability Retained and Various Remediation Attempts for Landfill MD-5 and Flow Test Column WM (NC) A/W

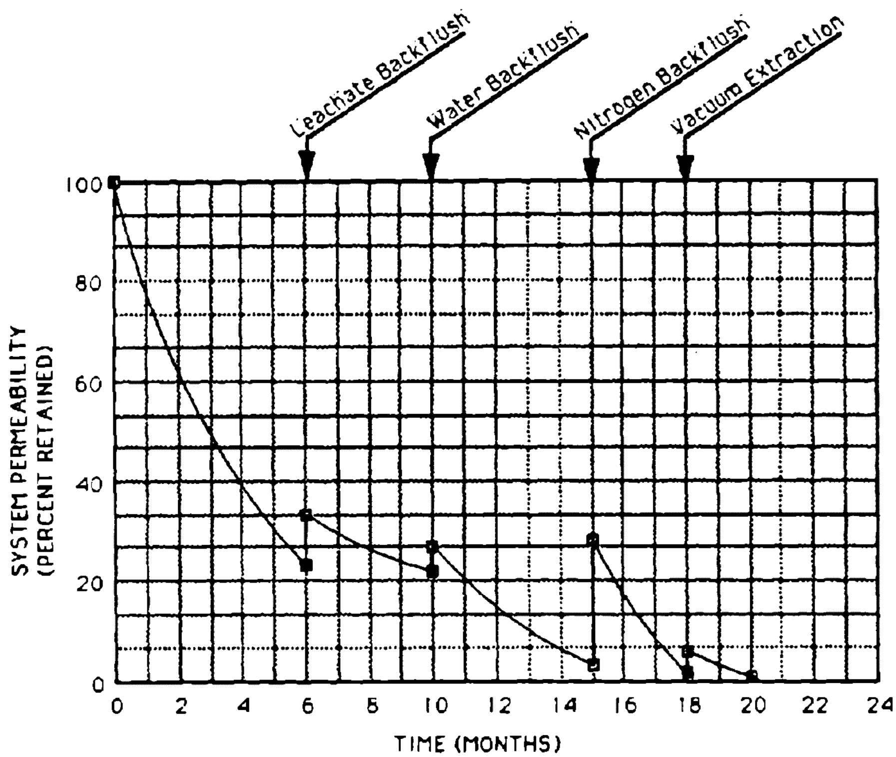


Figure 69 - System Permeability Retained and Various Remediation Attempts for Landfill MD-5 and Flow Test Column NW (HS) AN/S

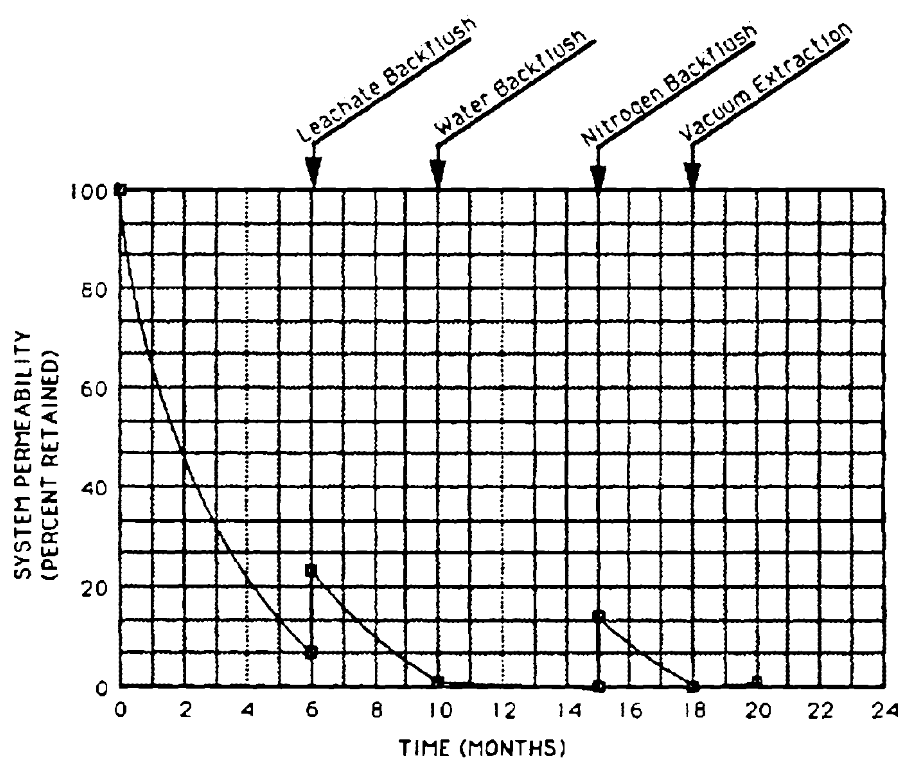


Figure 70 - System Permeability Retained and Various Remediation Attempts for Landfill MD-5 and Flow Test Column NW (HS) A/S

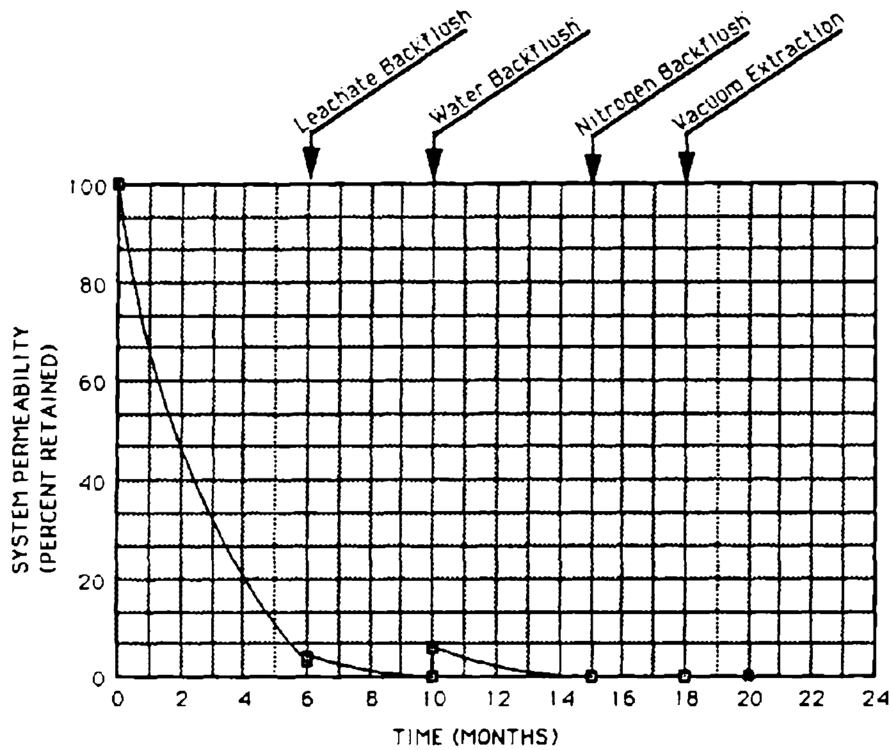


Figure 71 - System Permeability Retained and Various Remediation Attempts for Landfill MD-5 and Flow Test Column NW (HS) AN/W

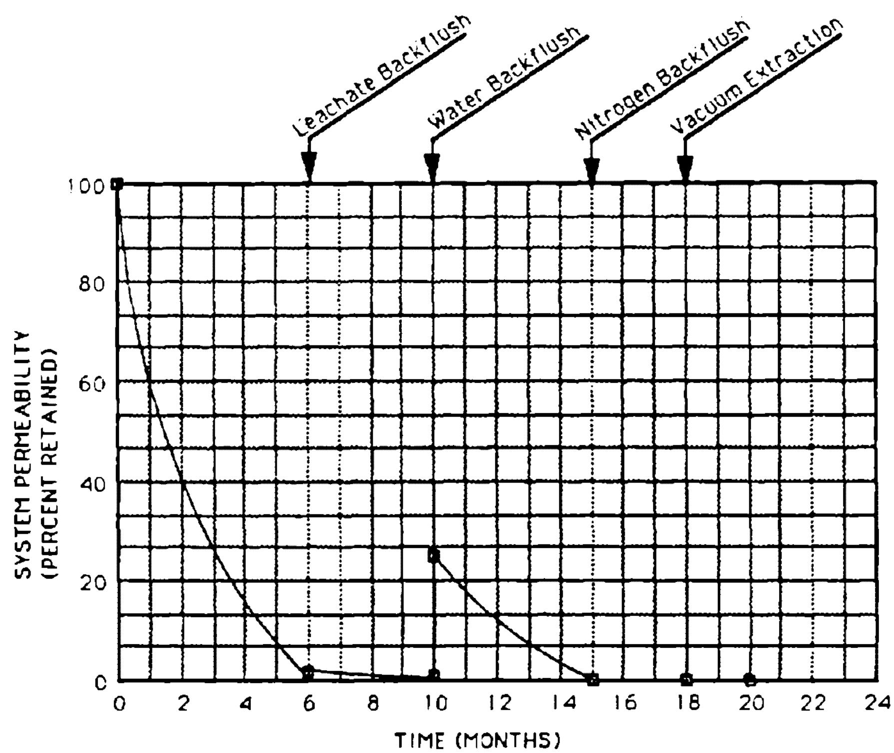


Figure 72 - System Permeability Retained and Various Remediation Attempts for Landfill MD-5 and Flow Test Column NW (HS) A/W

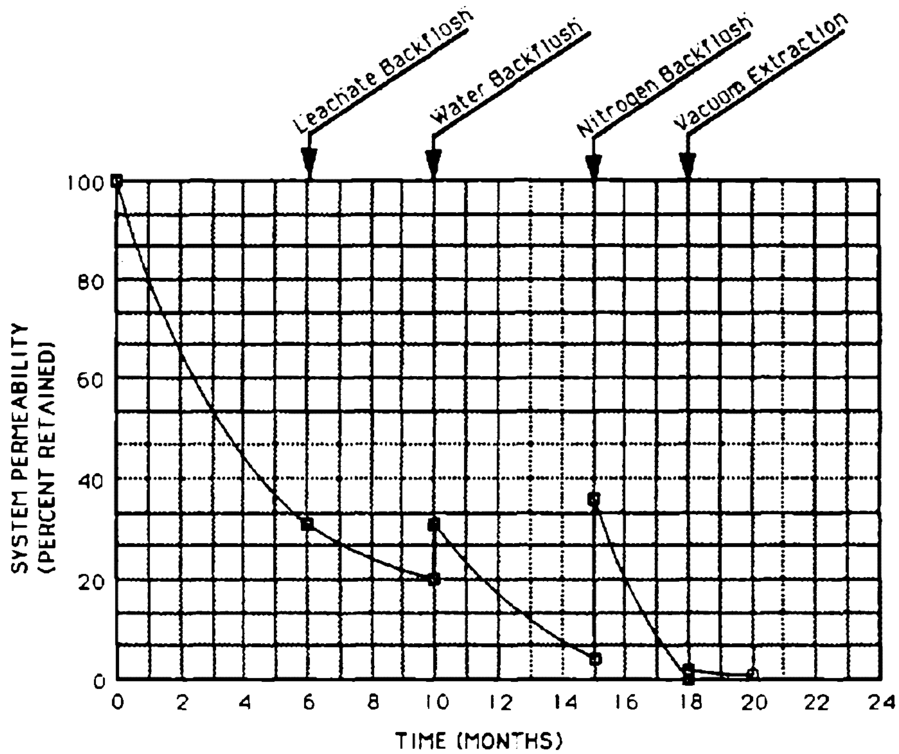


Figure 73 - System Permeability Retained and Various Remediation Attempts for Landfill MD-5 and Flow Test Column NW (16) AN/S

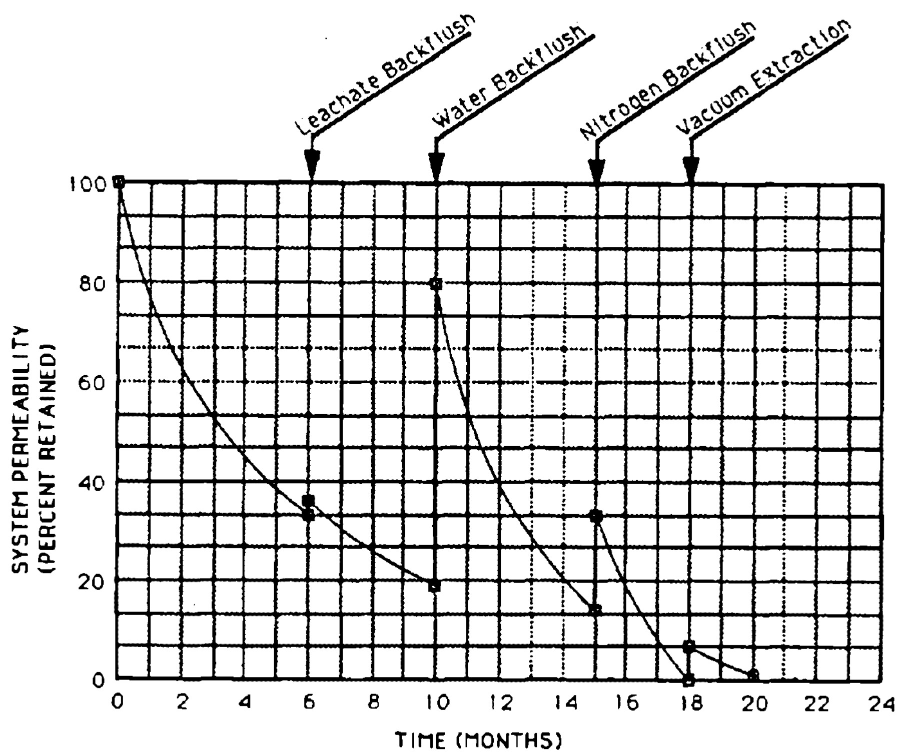


Figure 74 - System Permeability Retained and Various Remediation Attempts for Landfill MD-5 and Flow Test Column NW (16) A/S

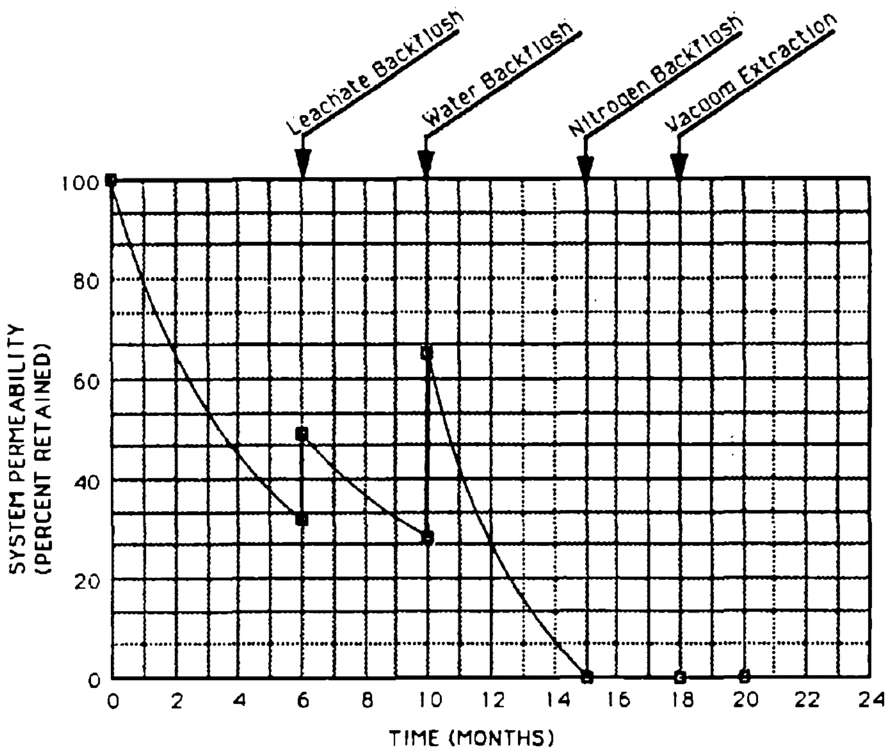


Figure 75 - System Permeability Retained and Various Remediation Attempts for Landfill MD-5 and Flow Test Column NW (16) AN/W

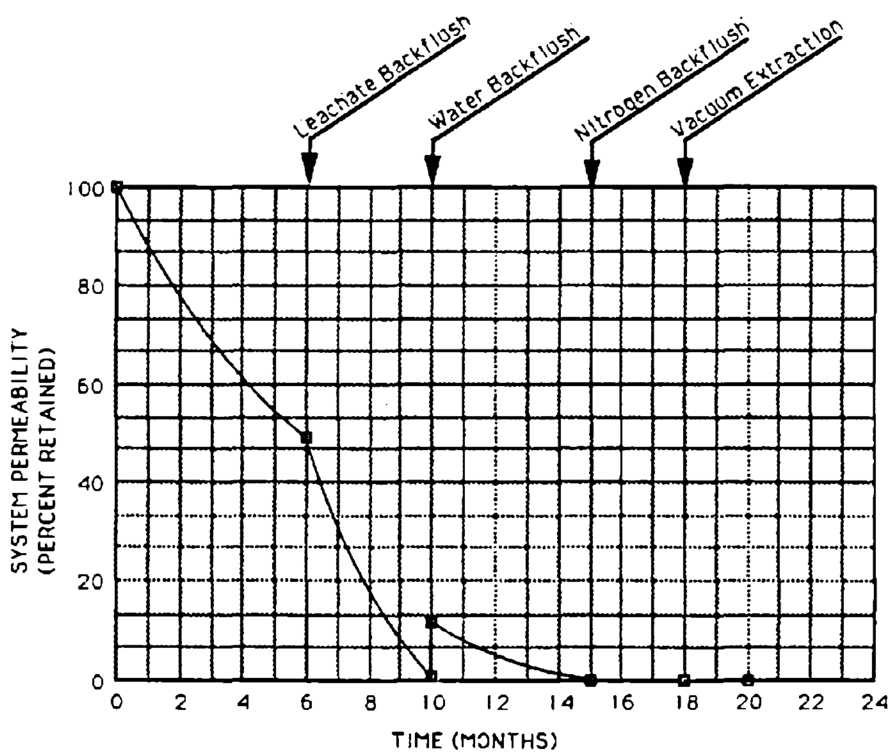


Figure 75 - System Permeability Retained and Various Remediation Attempts for Landfill MD-5 and Flow Test Column NW (16) A/W

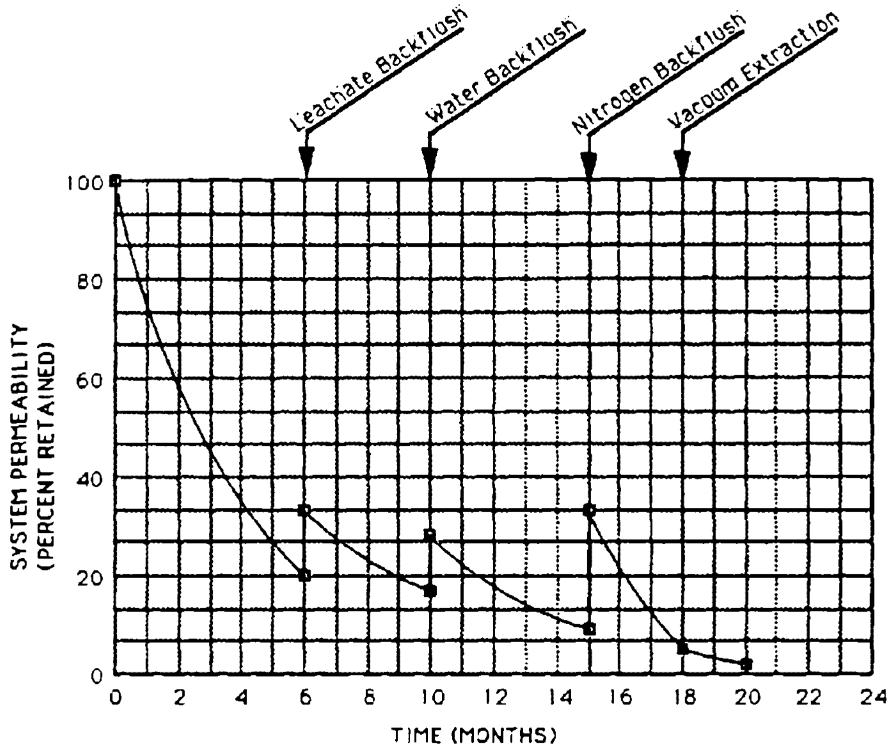


Figure 77 - System Permeability Retained and Various Remediation Attempts for Landfill MD-5 and Flow Test Column NW (8) AN/S

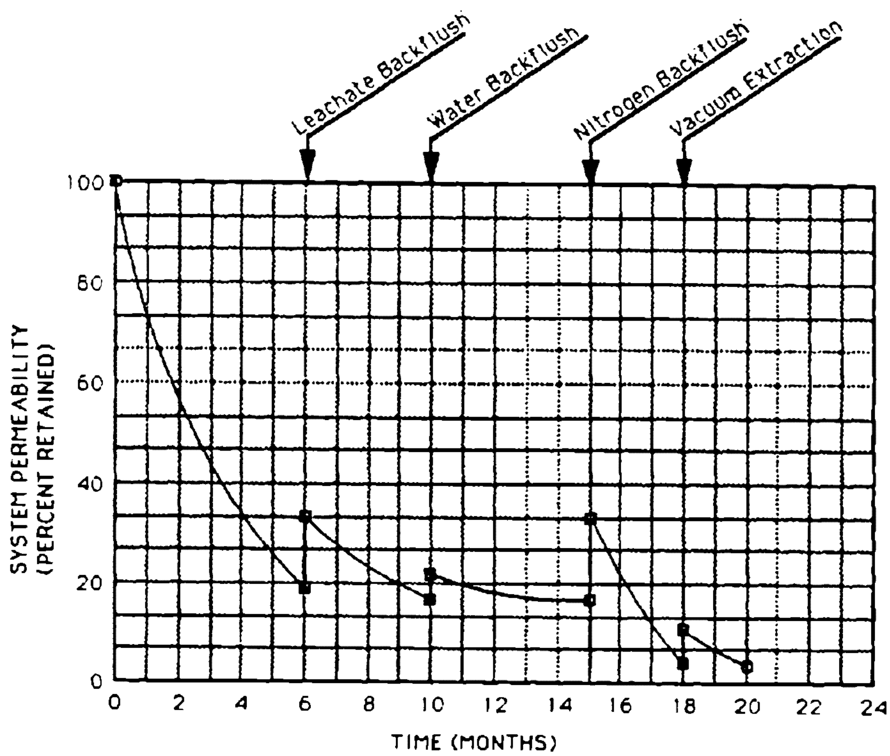


Figure 78 - System Permeability Retained and Various Remediation Attempts for Landfill MD-5 and Flow Test Column NW (8) A/S

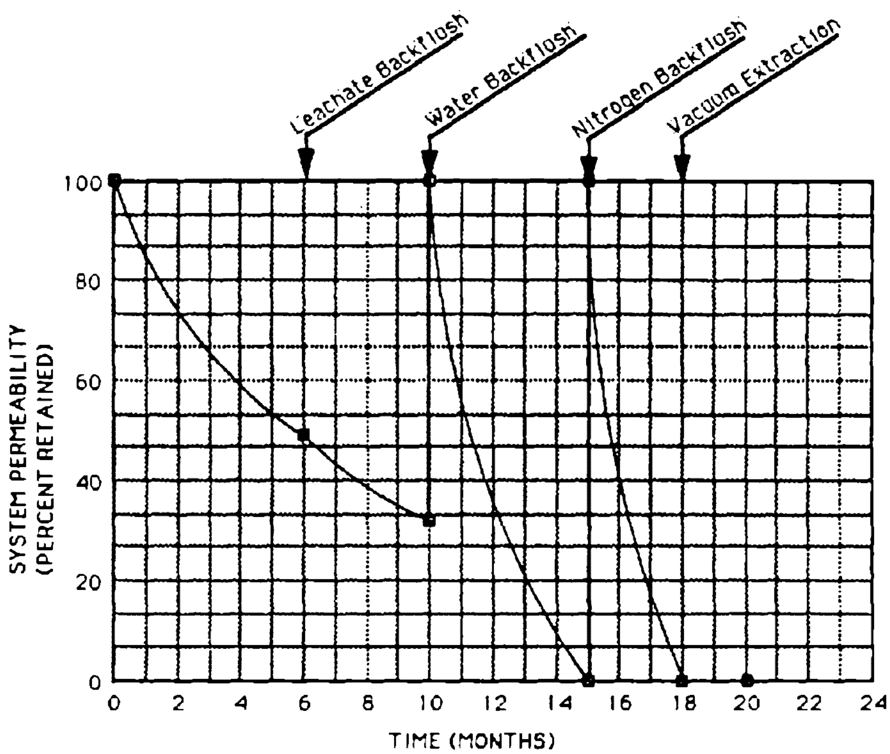


Figure 79 - System Permeability Retained and Various Remediation Attempts for Landfill MD-5 and Flow Test Column NW (8) AN/W

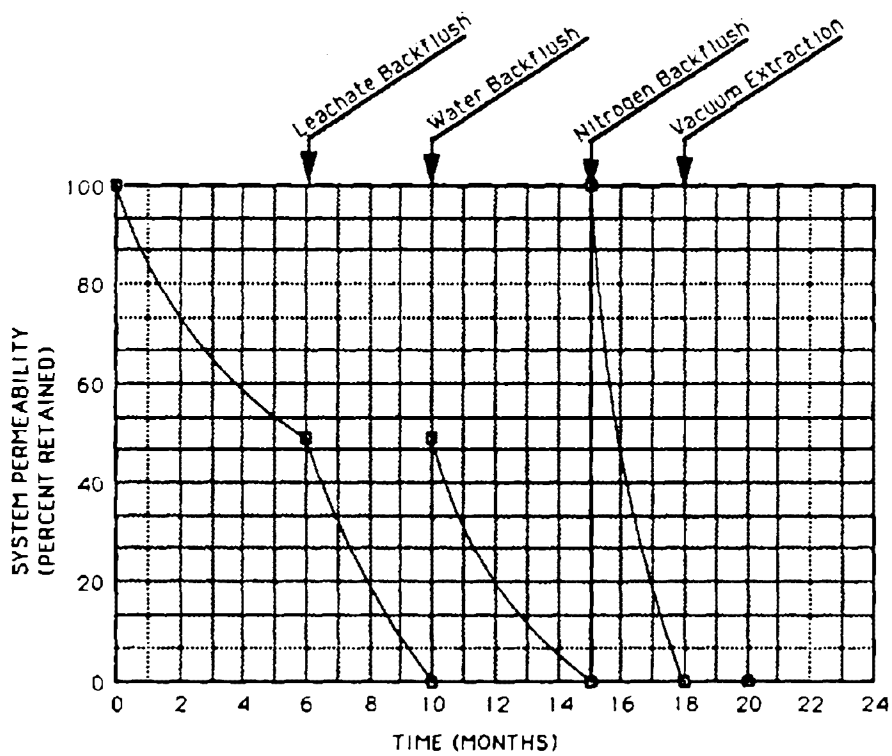


Figure 80 - System Permeability Retained and Various Remediation Attempts for Landfill MD-5 and Flow Test Column NW (8) A/W

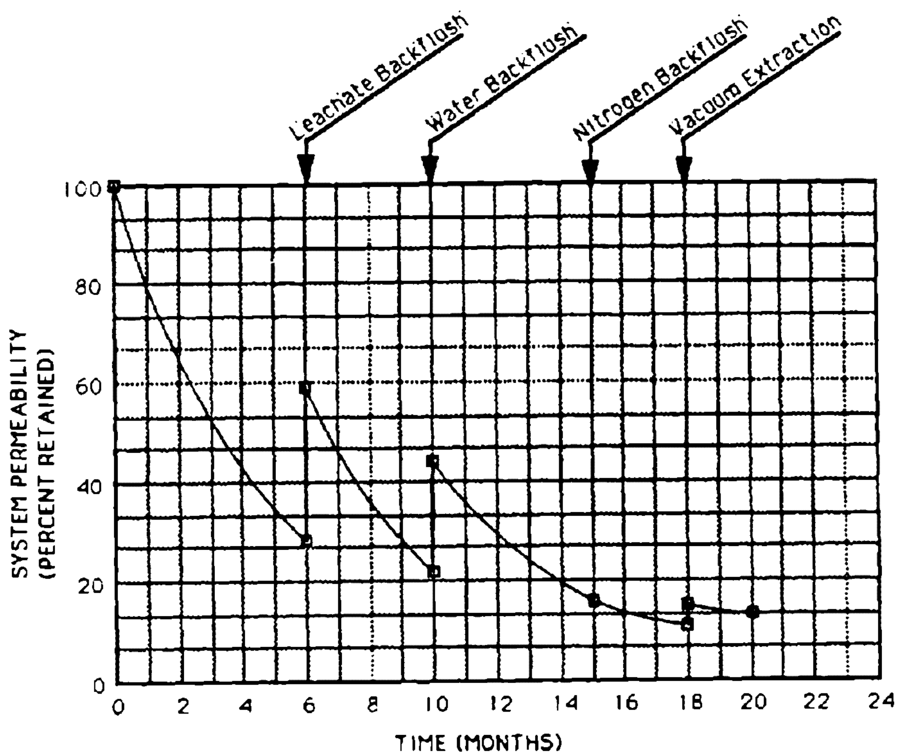


Figure 81 - System Permeability Retained and Various Remediation Attempts for Landfill PA-6 and Flow Test Column WM (NC) AN/S

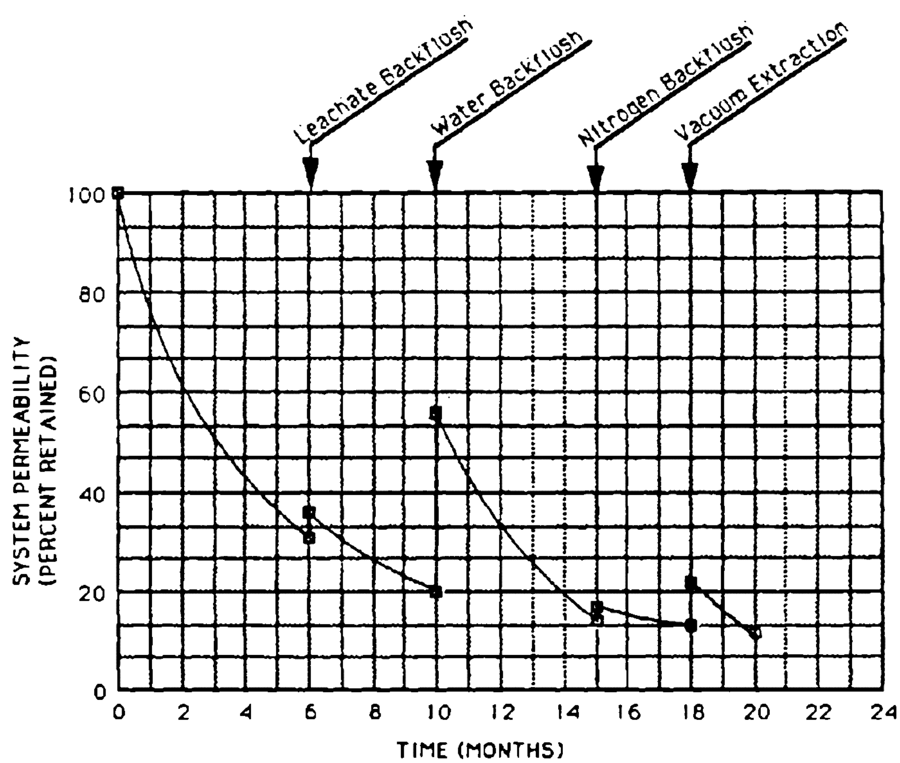


Figure 82 - System Permeability Retained and Various Remediation Attempts for Landfill PA-6 and Flow Test Column WM (NC) A/S

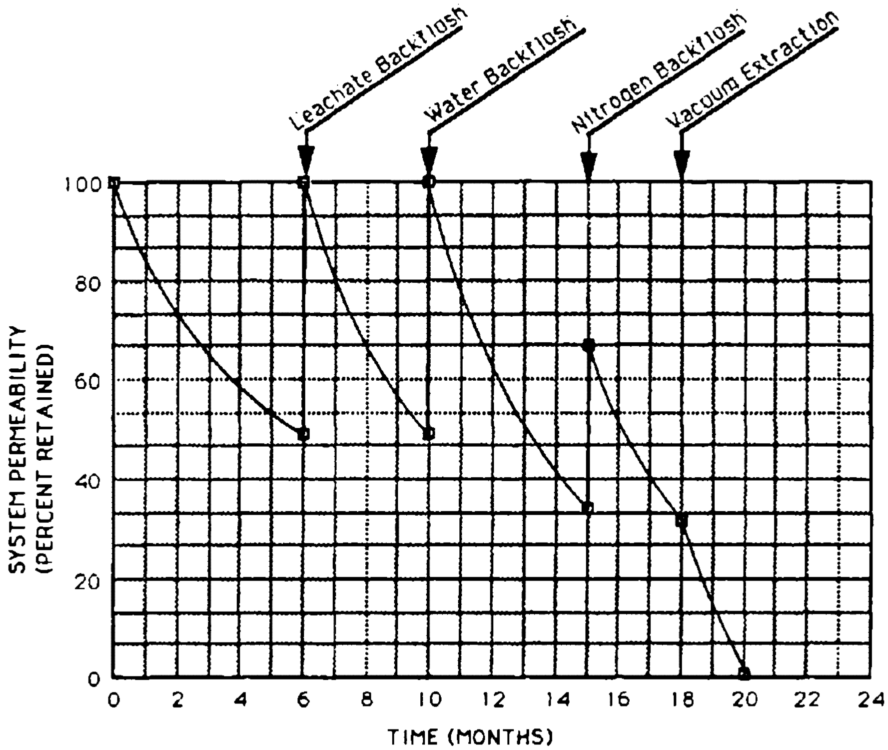


Figure 83 - System Permeability Retained and Various Remediation Attempts for Landfill PA-6 and Flow Test Column WM (NC) AN/W

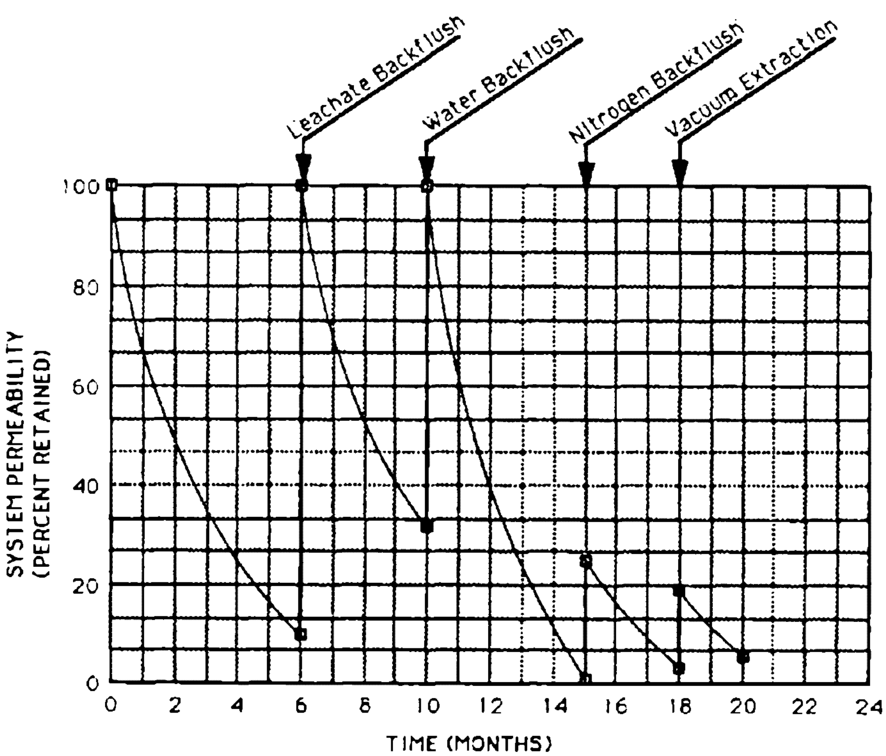


Figure 84 - System Permeability Retained and Various Remediation Attempts for Landfill PA-6 and Flow Test Column WM (NC) A/W

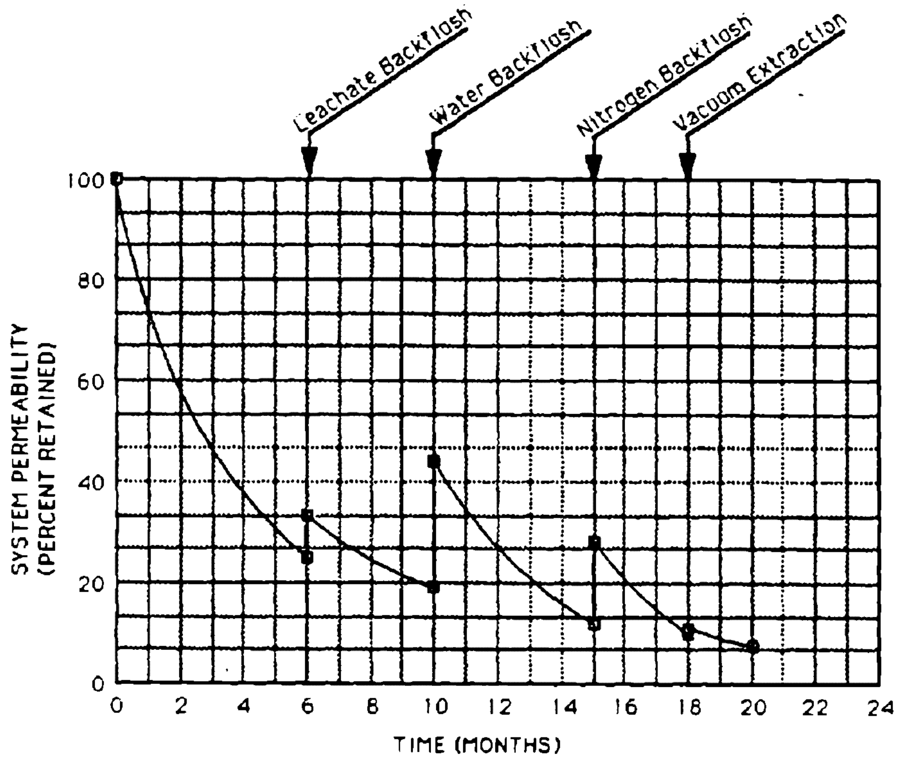


Figure 85 - System Permeability Retained and Various Remediation Attempts for Landfill PA-6 and Flow Test Column NW (HS) AN/S

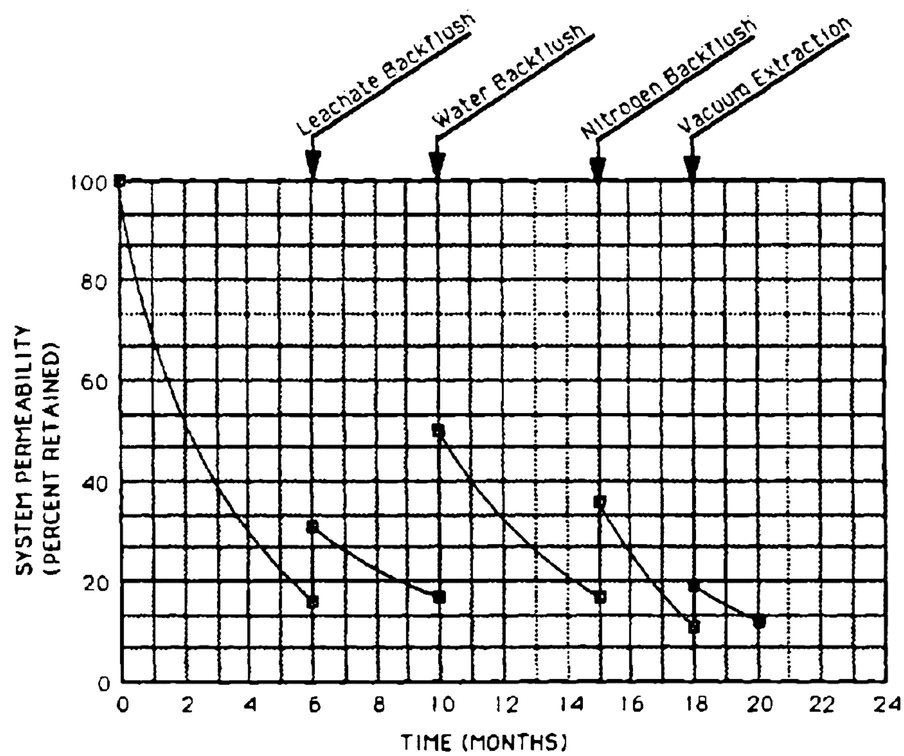


Figure 86 - System Permeability Retained and Various Remediation Attempts for Landfill PA-6 and Flow Test Column NW (HS) A/S

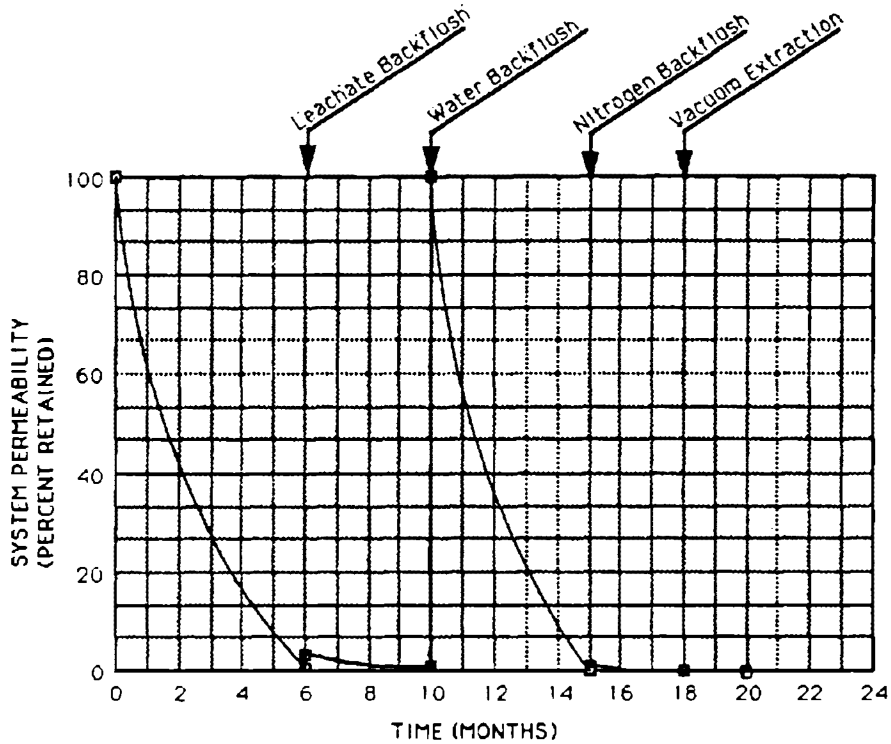


Figure 87 - System Permeability Retained and Various Remediation Attempts for Landfill PA-6 and Flow Test Column NW (HS) AN/W

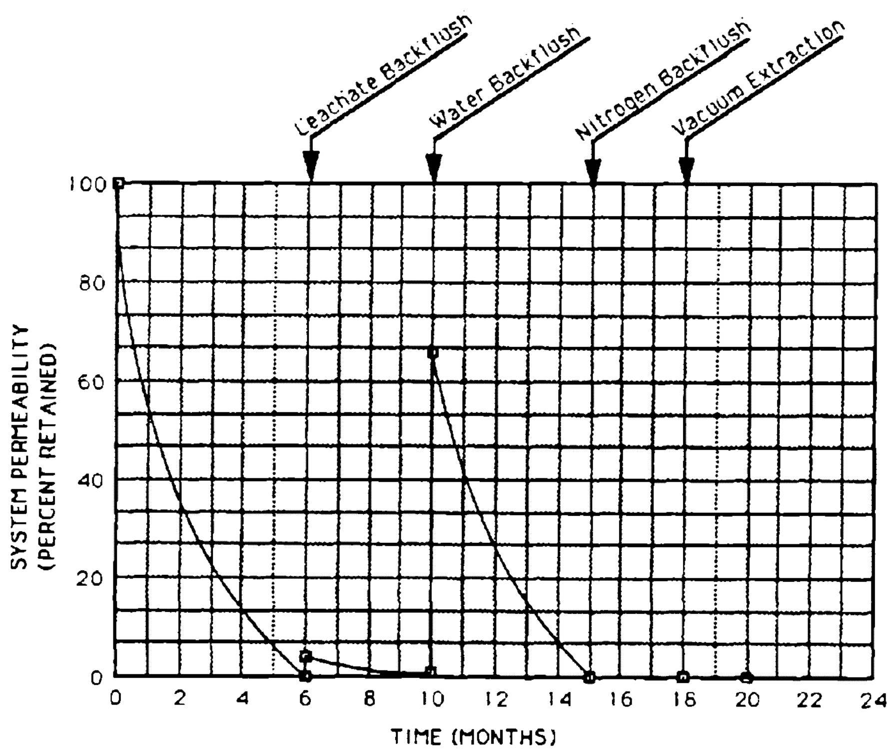


Figure 88 - System Permeability Retained and Various Remediation Attempts for Landfill PA-6 and Flow Test Column NW (HS) A/W

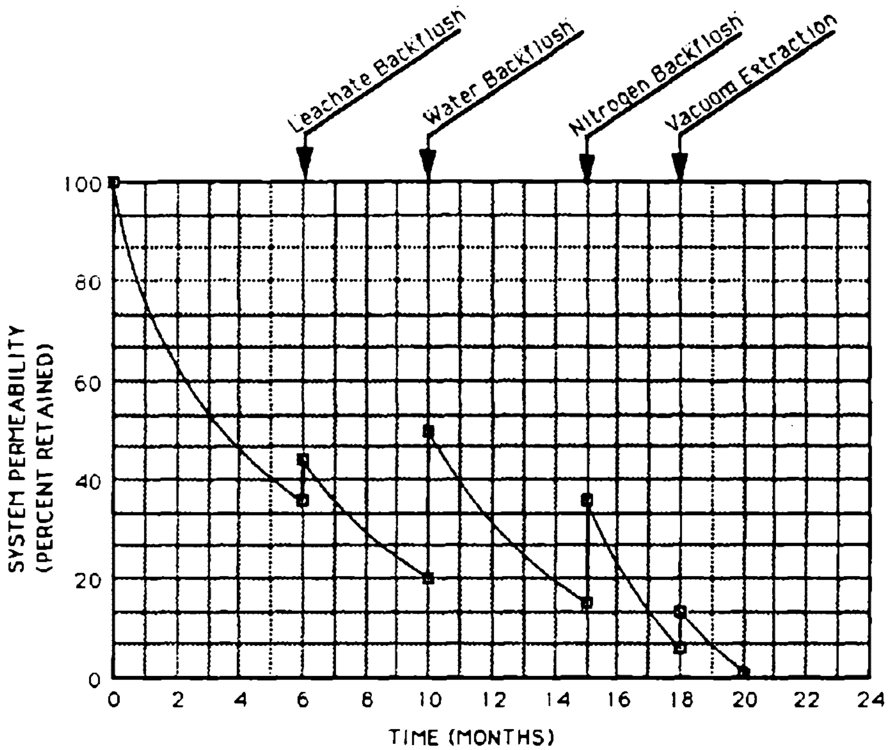


Figure 89 - System Permeability Retained and Various Remediation Attempts for Landfill PA-6 and Flow Test Column NW (16) AN/S

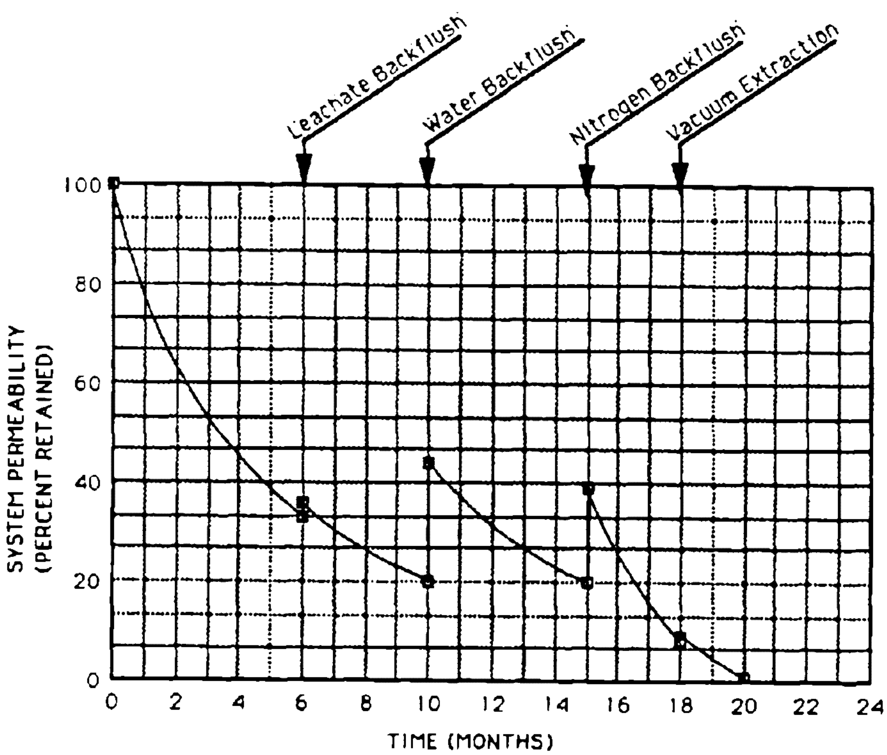


Figure 90 - System Permeability Retained and Various Remediation Attempts for Landfill PA-6 and Flow Test Column NW (16) A/S

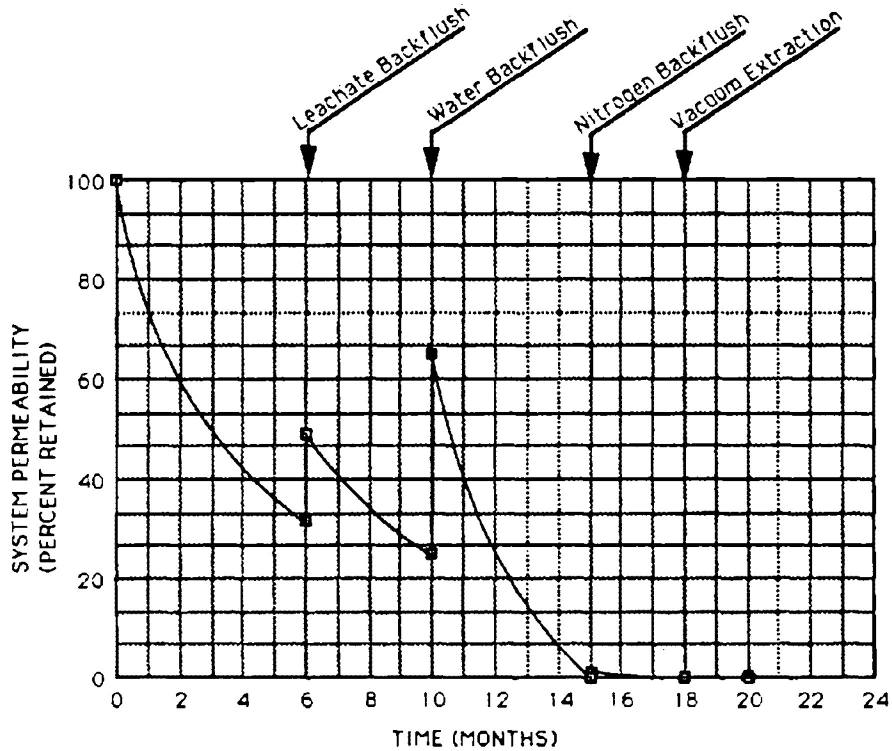


Figure 91 - System Permeability Retained and Various Remediation Attempts for Landfill PA-6 and Flow Test Column NW (16) AN/W

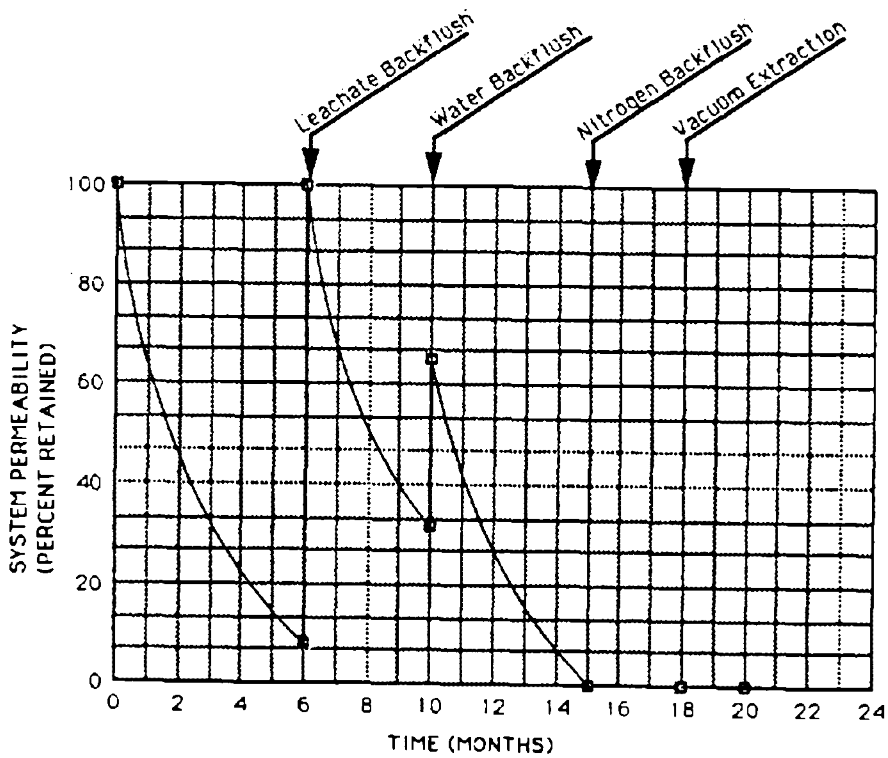


Figure 92 - System Permeability Retained and Various Remediation Attempts for Landfill PA-6 and Flow Test Column NW (16) A/W

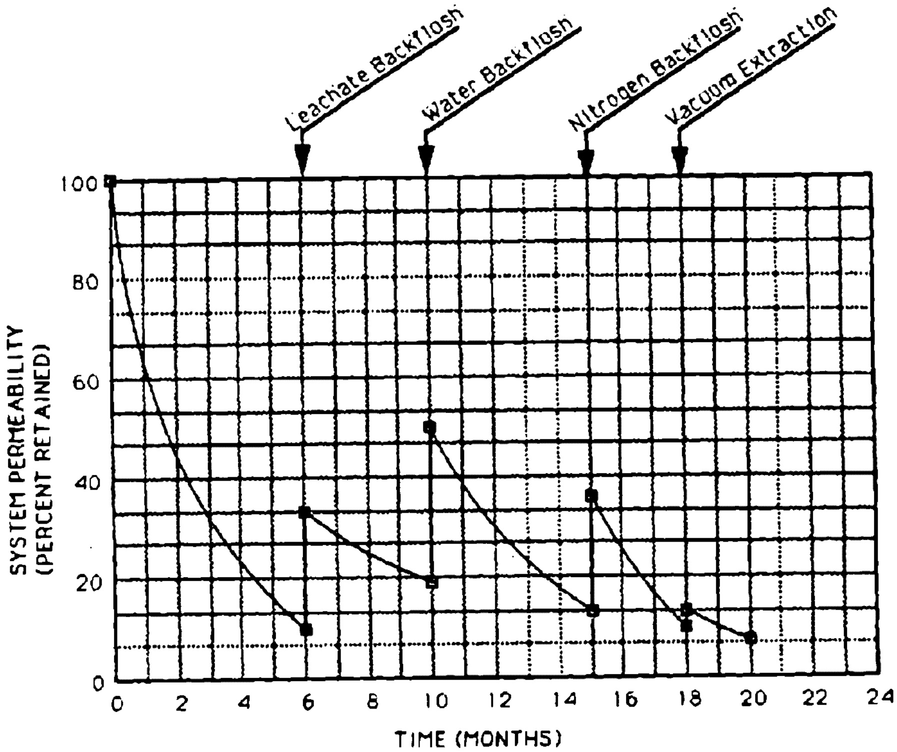


Figure 93 - System Permeability Retained and Various Remediation Attempts for Landfill PA-6 and Flow Test Column NW (8) AN/S

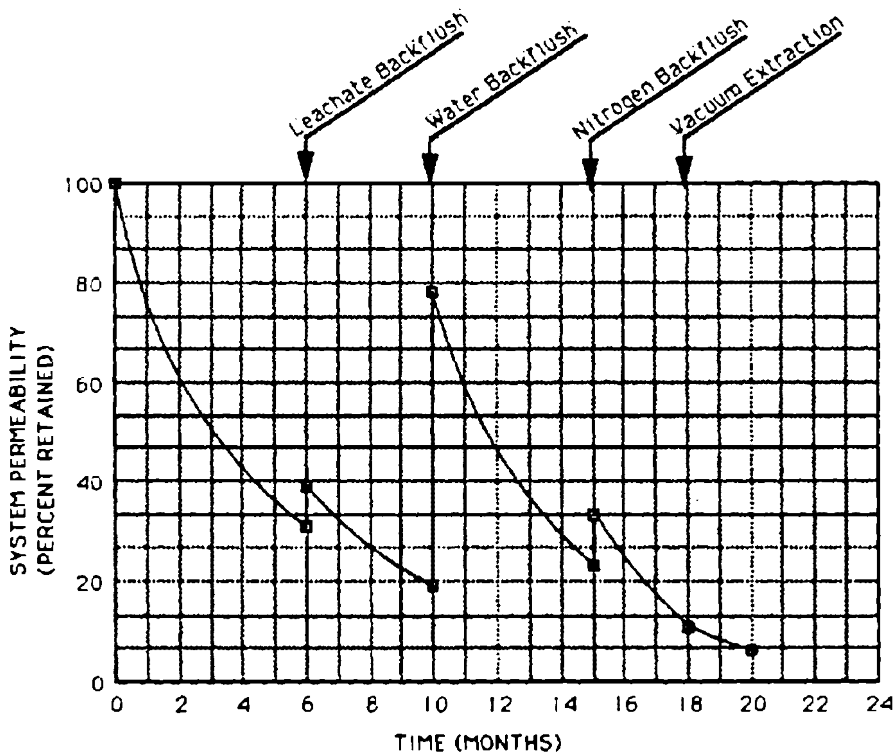


Figure 94 - System Permeability Retained and Various Remediation Attempts for Landfill PA-6 and Flow Test Column NW (8) A/S

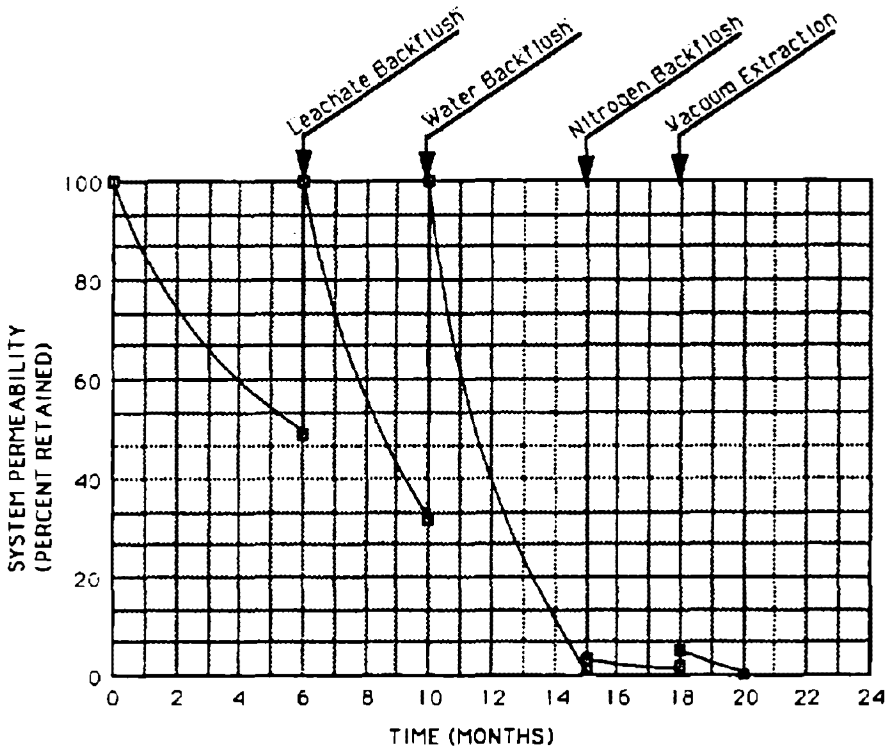


Figure 95 - System Permeability Retained and Various Remediation Attempts for Landfill PA-6 and Flow Test Column NW (8) AN/W

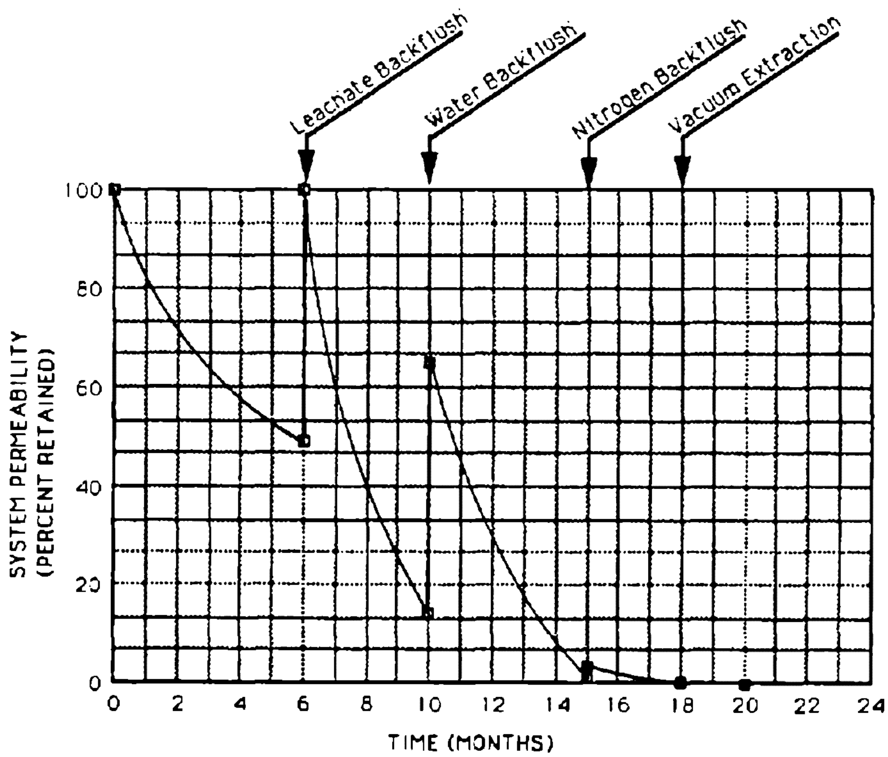


Figure 96 - System Permeability Retained and Various Remediation Attempts for Landfill PA-6 and Flow Test Column NW (8) A/W

Appendix "C"

**TEST DEVICE AND METHOD
TO ASSESS FILTER CLOGGING***

*This test method has been a Geosynthetic Research Institute Standard under the designation of GRI-GT2. As of March 1, 1991 it became an ASTM Standard under the designation of D1987-91. Hard copy should be available by May 1, 1991. At that time the GRI Standard will be eliminated from any further distribution.

Geotextiles Geomembranes Geogrids Geocomposites Geonets

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revised June 28, 1990

Standard Test Method for Biological Clogging of Geotextile or Soil/Geotextile Filters

1. Scope

1.1 This test method is used to determine the potential for, and relative degree of, biological growth which can accumulate on geotextile or geotextile/soil filters.

1.2 The method uses the measurement of flow rates over an extended period of time to determine the amount of clogging.

1.3 The method can be adapted for nonsaturated as well as saturated conditions.

1.4 The method can use constant head or falling head measurement techniques.

1.5 The method can also be used to give an indication as to the possibility of backflushing and/or biocide treatment for remediation purposes if biological clogging does occur.

1.6 The values in SI units are to be regarded as the standard. The values provided in inch-pound units are for information only.

1.7 This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 ASTM Standards

D123 Terminology Relating to Textiles
D1776 Conditioning Textiles for Testing
D4439 Terminology for Geotextiles
D4354 Practice for Sampling of Geotextile for Testing
D4491 Water Permeability of Geotextiles by Permittivity
G22 Determining Resistance of Plastics to Bacteria

3. Terminology

3.1 geotextile, n - a permeable geosynthetic comprised solely of textiles.

3.2 permeability, n - the rate of flow of a liquid under a differential pressure through a material.

Discussion - In geotextiles, permeability refers to hydraulic conductivity

3.3 permittivity, (ψ) (t^{-1}), n - of geotextiles, the volumetric flow rate of water per unit, in a cross sectional area head under laminar flow conditions.

3.4 aerobic, n - a condition in which a measurable volume of air is present in the incubation chamber or system.

Discussion - In geotextiles, this condition can potentially contribute to the growth of micro-organisms.

3.5 anaerobic, n - a condition in which no measurable volume of air is present in the incubation chamber or system.

Discussion - In geotextiles, this condition cannot contribute to the growth of micro-organisms.

3.6 back flushing, n - a process by which liquid is forced in the reverse direction to the flow direction.

Discussion - In other drainage application areas, this process is commonly used to free clogged drainage systems of materials that impede the intended direction of flow.

3.7 biocide, n - a chemical used to kill bacteria and other microorganisms.

4. Summary of Test Method

4.1 A geotextile filter specimen or geotextile/soil filter composite specimen is positioned in a flow column so that a designated liquid flows through it under either constant or falling head conditions.

4.1.1 The designated liquid might contain micro-organisms from which biological growth can occur.

4.2 Flow rate is measured over time, converted to either permittivity or permeability, and reported according.

4.2.1 Between readings, the test specimen can be allowed to be in either nonsaturated or saturated conditions.

4.2.2 Back flushing can be introduced from the direction opposite to the intended flow direction and evaluated accordingly.

4.2.3 Biocide can be introduced with the back flushing liquid, or introduced within the test specimen, and evaluated accordingly.

5. Significance and Use

5.1 This test method is performance oriented for determining if, and to what degree, different liquids create biological activity on geotextile filters thereby reducing their flow capability. The use of the method is primarily oriented toward landfill leachates but can be performed with any liquid coming from a particular site or synthesized from a predetermined mixture of biological microorganisms.

5.2 The test can be used to compare the flow capability of different types of geotextiles or soil/geotextile combinations.

5.3 This test will usually take considerable time, e.g., up to 1,000 hours, for the biological activity to initiate, grow, and reach an equilibrium condition. The curves resulting from the test are intended to indicate the in situ behavior of a geotextile or soil/geotextile filter.

5.4 The test specimen can be incubated under non-saturated drained conditions between readings, or kept saturated at all times. The first case allows for air penetration into the flow column and thus aerobic conditions. The second case can result in the absence of air, thus it may simulate anaerobic conditions.

5.5 The flow rate can be determined using either a constant head test procedure or on the basis of a falling head test procedure. In either case the flow column containing the geotextile or soil/geotextile is the same, only the head control devices change.

Note 1 — It has been found that once biological clogging initiates, constant head tests often pass inadequate quantities of liquid to accurately measure. It thus becomes necessary to use falling head tests which can be measured on the basis of time of movement of a relatively small quantity of liquid between two designated points on a clear plastic standpipe.

5.6 If the establishment of an unacceptably high degree of clogging is seen in the flow rate curves, the device allows for backflushing with water or with water containing a biocide.

5.7 The resulting flow rate curves are intended for use in the design of full scale geotextile or soil/geotextile filtration systems and possible remediation schemes in the case of landfill leachate collection and removal systems.

6. Apparatus

6.1 *The flow column and specimen mount* consists of a 100 mm (4.0 in.) inside diameter containment ring for placement of the geotextile specimen along with upper and lower flow tubes to allow for uniform flow trajectories (see Figure 1). The flow tubes are each sealed with end caps which have entry and exit tubing connections (see Figure 1). The upper tube can be made sufficiently long so as to provide for a soil column to be placed above the geotextile. When this type of combined soil/geotextile cross section is used, however, it is difficult to distinguish which material is clogging i.e., the soil or the geotextile. It does however simulate many existing filtration systems. In such cases, a separate test setup with the geotextile by itself will be required as a control test and the difference in behavior between the two tests will give an indication as to the contribution of soil clogging to the flow reduction.

6.2 *Hydraulic head control devices* are required at both the inlet and outlet ends of the flow column. Figure 2 shows the complete setup based on constant hydraulic head monitoring where concentric plastic cylinders are used with the inner cylinders being at the elevation from which head is measured. The elevation difference between the inner cylinder at the inlet end and the inner cylinder at the outlet end is the total head across the geotextile test specimen (or soil/geotextile test specimen in the case of a combined test column). Note that the elevation of the outlet must be above the elevation of the geotextile.

6.3 *A hydraulic head standpipe* above the flow column is required for falling hydraulic head monitoring. Figure 3 shows this type of test configuration in which a clear plastic standpipe is placed above the flow column. Liquid movement is monitored for the time of flight between two marks on the standpipe. Note that the elevation of the outlet must be above the elevation of the geotextile.

6.4 *The overall test system* dimensions are sufficiently small so that either of the above mentioned units can be used at a field site if desirable. They can either be kept stationary in the laboratory or in the field, or they can be transported from the laboratory to the field site when required.

6.5 *The permeating liquid* is generally site specific and often comprises landfill leachate. Other liquids for which biological clogging is of concern can also be evaluated. The liquid can be synthesized on an as-required basis.

Note 2 — A synthesized liquid which has been used in determining the resistance of plastics to bacteria is Pseudomonas aeruginosa ATCC 13388 (available from American Type Culture Collection, 12301 Parklawn Drive, Rockville, MD 20852) or MYCO B 1468 (available from Mycological Services, P. O. Box 126, Amherst, MA 01002). Specific details must be agreed upon by the parties involved.

7. Sampling

7.1 *Lot Sample* — Divide the product into lots and take the lot sample as directed in Practice D4354.

7.2 *Laboratory Sample* — For the laboratory sample, take a swatch extending the full width of the geotextile of sufficient length along the selvage from each sample roll so that the requirements of the following section can be met. Take a sample that will exclude material from the outer wrap and inner wrap around the core unless the sample is taken at the production site, then inner and outer wrap material may be used.

7.3 *Test Specimens* — From the laboratory sample select the number of specimens as per the number of flow columns to be evaluated. Space the specimens along a diagonal on the unit of the laboratory sample. Take no specimens nearer the selvage or edge of the laboratory sample than 10% of the width of the laboratory sample. The minimum specimen diameter should be 100 mm (4.0 in.) so that full fixity can be achieved around the inside of the flow column.

8. Conditioning

8.1 There is no conditioning of the geotextile test specimen, per se, since this test method is a hydraulic one and the conditions of the permeating fluid will be the controlling factor.

8.2 The relative humidity should be 100% except during times of air drying between non-saturated test readings. For saturated conditions the relative humidity should always be 100%.

8.3 The temperature of the test over its entire duration is important. It is desirable to track temperature continuously. If not possible, frequent readings at regular intervals are required.

9. Procedure "A" - Constant Head Test

9.1 Select and properly prepare the geotextile test specimen. Trim the specimen to the exact and full diameter of the inside of the flow column.

9.2 Fix the geotextile test specimen to the inside of the containment ring. If a water insoluable glue is used be sure that any excess does not extend into the flow area of the geotextile.

9.3 Caulk the upper surface of the geotextile to the inside of the containment ring using a silicon based caulk and allow it to completely cure. The caulk must be carefully placed so as not to restrict flow through the geotextile.

9.4 Insert the upper and lower tubes into the containment ring and create a seal. If polyvinyl chloride (PVC) tubing and fittings are being used, first a cleaner and then a solvent wipe is used to make the bond.

9.5 If a screen or gravel of approximately 50 mm (2 in.) size is necessary to support the geotextile it must be placed with the device in an inverted position.

9.6 Place the lower end cap on the device and make its seal.

9.7 If soil is to be placed over the geotextile, place it at this time. Place the soil at its targeted moisture content and density taking care not to dislodge or damage the geotextile beneath.

9.8 Place the upper end cap on the device and make a permanently seal.

9.9 Connect flexible plastic tubing from the flow column's top and bottom to the head control devices. At this point the system should appear as shown in the photograph of Figure 2.

9.10 Adjust the total head lost to 50 mm (2.0 in.) and initiate flow via the introduction of the permeating fluid to the system. When using leachate, proper safety and health precautions must be maintained depending upon the nature of the leachate itself.

> Note 3 — It is suggested to use 50 mm (2 in.) total head difference since this is the prescribed value used in the permittivity test of ASTM D4491. Other values of head or hydraulic gradient, as mutually decided upon by the parties involved, could also be used.

9.11 Convert the liquid collected from the discharge tube to flow rate (liters/min or gal./min.) and repeat the measurement three times. Report the average of this value.

9.12 Increase the total head lost if desired. Heads of 100 mm (4.0 in.), 200 mm (8.0 in.), and 300 mm (12.0 in.) might be considered. These relatively high values of total head may be required if the geotextile begins to clog.

9.13 After readings are completed, disconnect the head control devices. If non-saturated (aerobic) conditions are desired, the bottom end cap outlet is allowed to vent to the atmosphere. If saturated conditions are desired, the flexible plastic tubing from the bottom end cap must remain in position and be brought higher than the elevation of the geotextile or soil within the test column. This will maintain saturated conditions between readings.

9.14 Use fresh liquid for each set of measurements since changes, either biological or particulate in nature, may influence the test results.

10. Procedure "B" - Falling Head Test

10.1 Select and properly prepare the geotextile test specimen. Trim the specimen to the exact and full diameter of the inside of the flow column.

10.2 Fix the geotextile test specimen to the inside of the containment ring. If a water insoluable glue is used be sure that an excess amount does not extend into the flow area of the geotextile.

10.3 Caulk the upper surface of the geotextile to the inside of the containment ring using a silicon based caulk and allow it to completely cure. The caulk must be carefully placed so as not to restrict flow through the geotextile.

10.4 Insert the upper and lower tubes into the containment ring and create a permanent seal. If polyvinyl chloride (PVC) tubing and fittings are being used, first a cleaner and then a solvent wipe is used to make the bond.

10.5 If a screen or a gravel of approximately 50 cm (2 in.) size is necessary to support the geotextile it must be placed with the device in an inverted position.

10.6 Place the lower end cap on the device and make its seal.

10.7 If soil is to be placed over the geotextile, place it at this time. The soil should be placed at its targeted moisture content and density taking care not to dislodge or damage the geotextile beneath.

10.8 Place the upper end cap on the device and make a seal.

10.9 Attach a clear, rigid plastic standpipe to the upper end cap. The standpipe should have clearly visible markings at regular intervals to monitor the movement of liquid. At this point the system should appear as shown in the photograph of Figure 3.

10.10 Fill the standpipe to a level above its upper mark.

10.11 Allow for flow through the system until the liquid level reaches the upper mark and then start a stopwatch.

10.12 Allow flow to continue unimpeded until the liquid level reaches the lower standpipe mark and immediately stop the stopwatch so as to record the elapsed time.

10.13 Repeat this measurement procedure three times. The average of this value is to be reported.

10.14 After readings are completed, disconnect the head control devices. If nonsaturated conditions are desired, the bottom end cap outlet is allowed to vent to the atmosphere. If saturated conditions are desired, the flexible plastic tubing from the bottom end cap must remain in position and be brought higher than the elevation of the geotextile or soil within the test column. This will maintain saturated conditions between readings.

10.15 Use fresh liquid for each set of measurements since changes, either biological or particulate in nature, may influence the test results.

11. Calculations for Procedure "A" - Constant Head Test

11.1 *Flow Rate per Unit Area* is calculated on the basis of the average flow rate measured during conducting of the test. This value is then divided by the cross sectional area of the geotextile for the flow rate per unit area, or "flux". The units are liters/min-cm^2 or gal/min-ft^2.

11.2 Permittivity can be calculated using Darcy's formula for a constant head flow test.

$$q = k\,i\,A$$

$$\frac{q}{A} = k\,i$$

$$= k\frac{\Delta h}{t}$$

$$\frac{q}{A(\Delta h)} = \frac{k}{t}$$

$$\text{and } \frac{k}{t} = \psi = \frac{q}{A(\Delta h)}$$

where

q	= flow rate (L^3/T)
A	= cross sectional area (L^2)
k	= coefficient of permeability (L/T)
t	= geotextile thickness (L)
i	= hydraulic gradient (L/L)
Δh	= change in total head (L)
ψ	= permittivity (T^{-1})

11.3 Plotting of the results is very descriptive of the process as it is ongoing. Figure 4 presents a number of possible trends in the resulting behavior.

12. Calculation for Procedure "B" - Falling Head Test

12.1 Permittivity is calculated when using the geotextile by itself with no soil. It is based on Darcy's formula which is integrated over the head lost during the arbitrary time interval Δt and results in the following equation.

$$\frac{k}{t} = \psi = 2.3\,\frac{a}{A\,\Delta T}\,\log_{10}\frac{h_o}{h_f}$$

k = coefficient of permeability (L/T)
t = thickness (L)
ψ = permittivity (T^{-1})
a = area of liquid supply standpipe (L^2)
A = area of test specimen (L^2)
ΔT = time change between h_0 and h_f (T)
h_0 = head at beginning of test (L)
h_f = head at end of test (L)

12.2 The permeability coefficient is calculated when using soil and geotextile together. It uses the exact formulation as above in the following form.

$$k = 2.3 \frac{a t}{A \Delta T} \log_{10} \frac{h_o}{h_f}$$

12.3 Plotting of the results is very descriptive of the process as it is ongoing. Figure 4 presents a number of possible trends in the resulting behavior.

13. Report

13.1 State that the specimens were treated as directed in this Test Method or state what modifications were made.

13.2 Report on the following information:
- 13.2.1 The method of holding the test specimen in the containment ring.
- 13.2.2 The use or nonuse of soil above the geotextile.
- 13.2.3 The type, style and description of the geotextile test specimen
- 13.2.4 The type of permeating liquid.
- 13.2.5 Whether nonsaturated or saturated test conditions.

13.3 Report on trends in the results:
- 13.3.1 The behavior of the curves (see Figure 4 for possible trends).
- 13.3.2 The reasons for terminating the tests.
- 13.3.3 The temperature of the liquid used in the tests.
- 13.3.4 Possible remediation schemes if clogging occurred.

13.4 Identify the microorganisms which caused the clogging if it occurred (optional).

14. Precision and Bias

14.1 *Precision* — The precision of the procedure in this test method for measuring the biological clogging of geotextiles is being established.

14.2 *Bias* — The procedure in this test method for measuring the biological clogging of geotextiles has no bias because the value of that property can be defined only in terms of a test method.

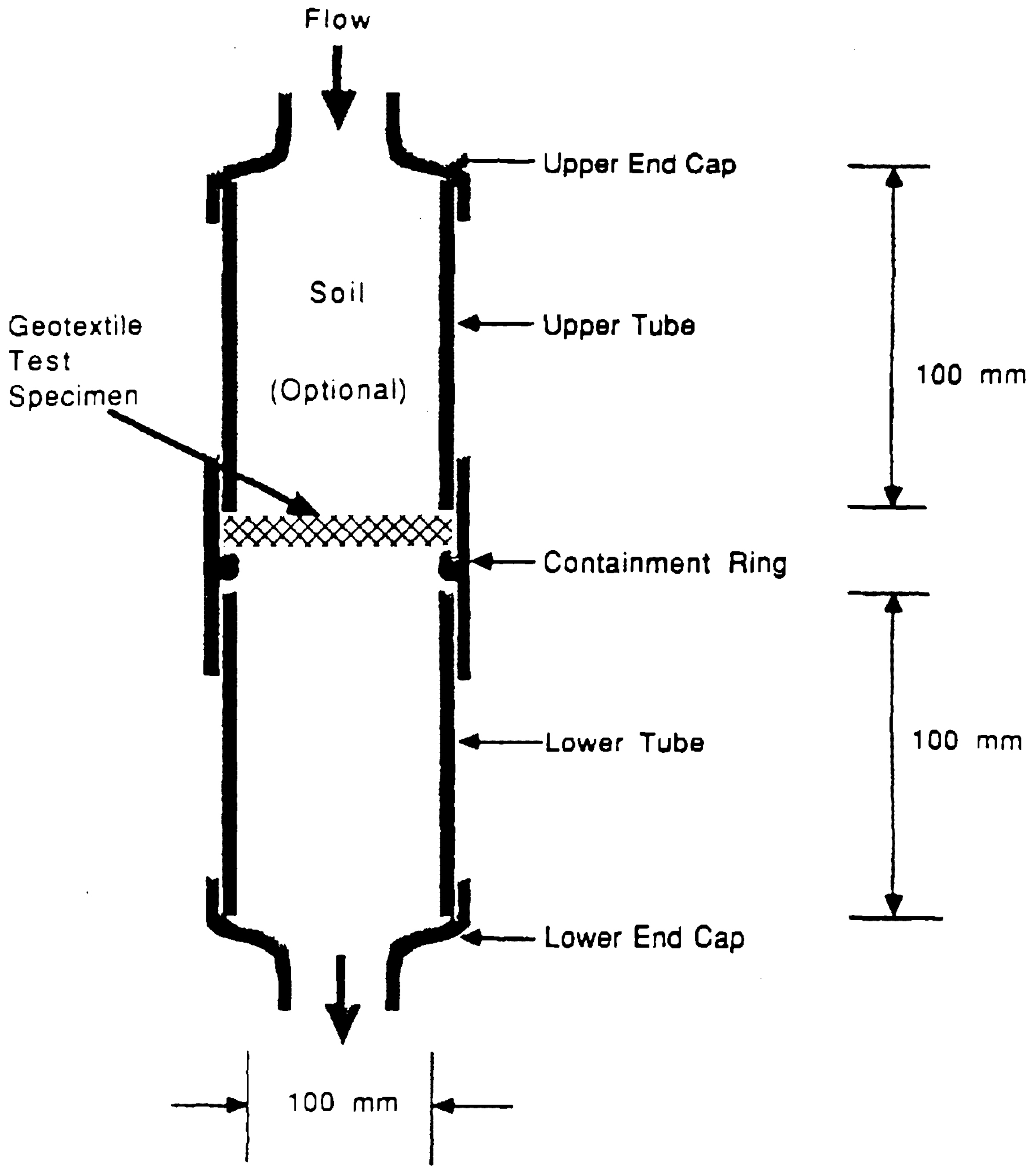

Figure 1 - Flow Column to Contain Geotextile Test Specimen

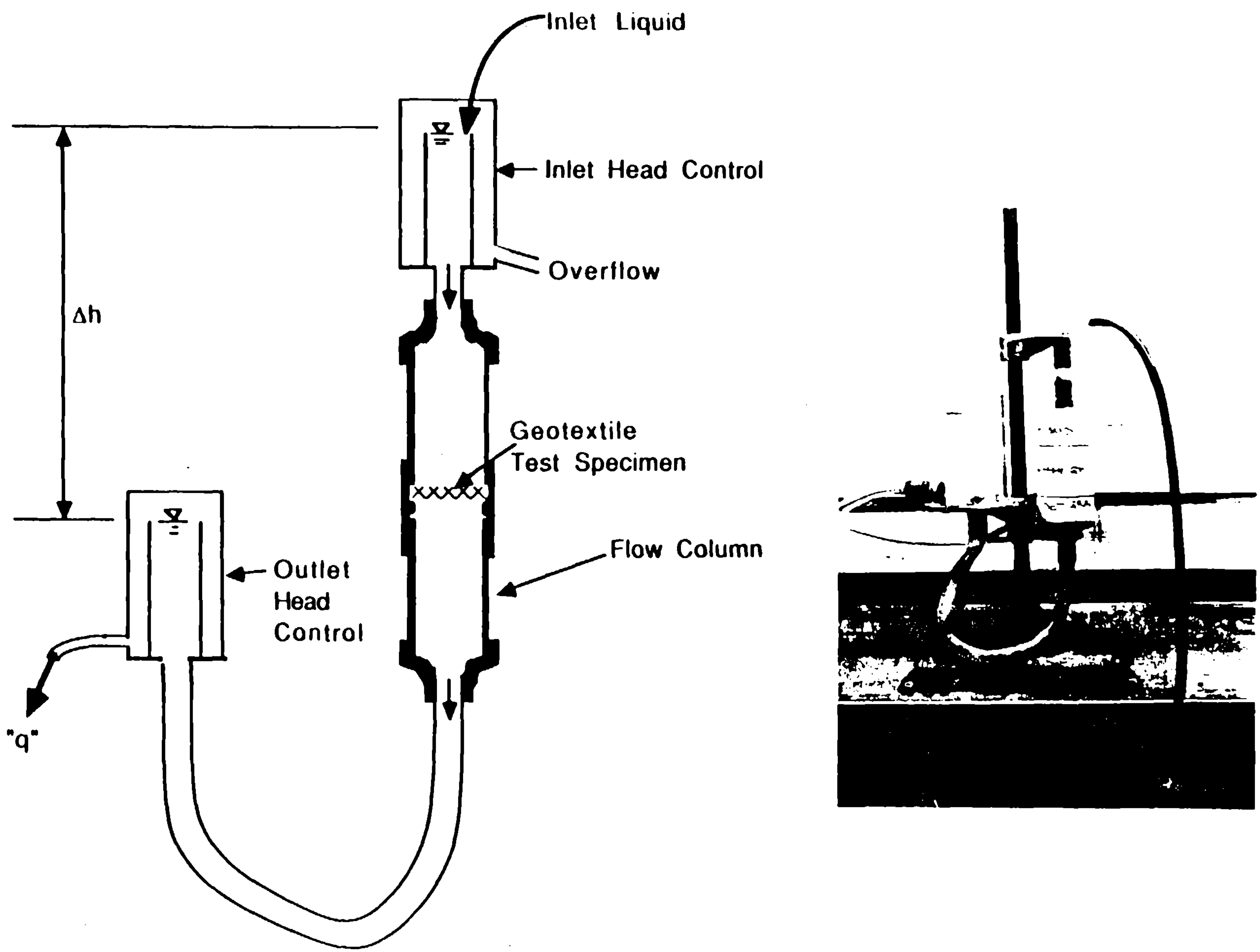

Figure 2 - Flow Column with Inlet and Outlet Hydraulic Head Control Devices For Constant Head Test

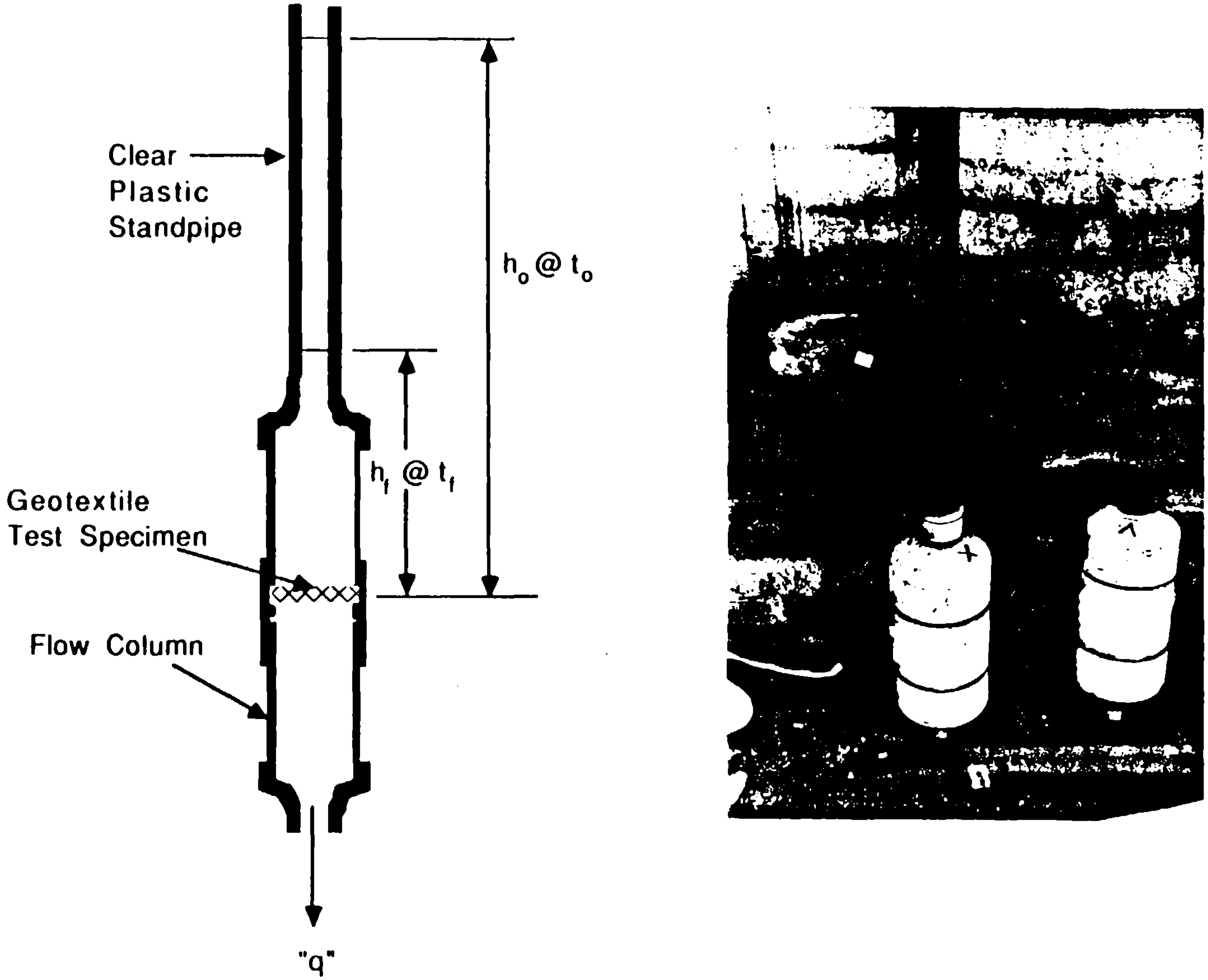

Figure 3 - Flow Column with Standpipe For Variable (Falling) Head Test

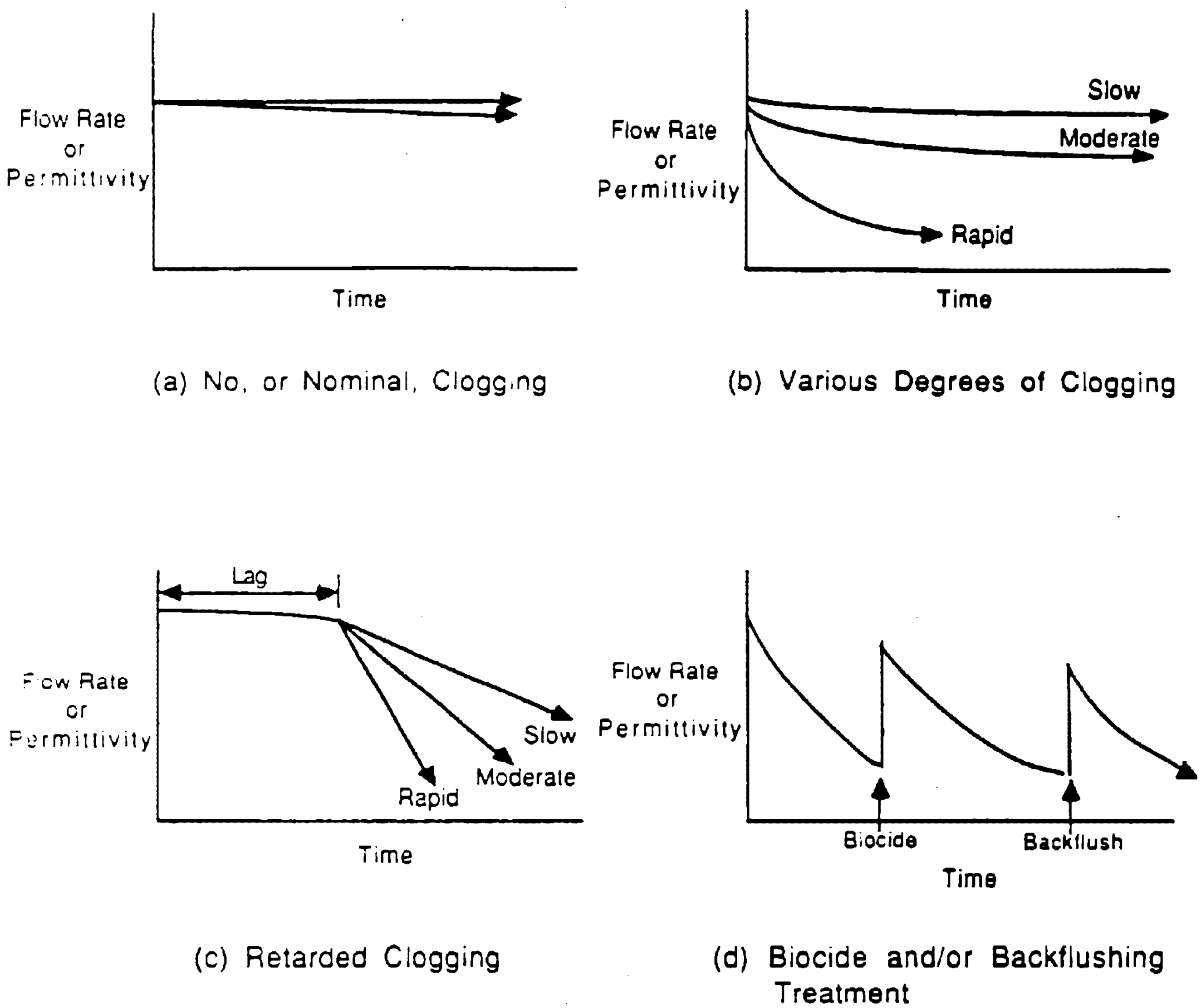

Figure 4 - Possible Long-Term Flow Behavior of Geotextile Filters Subjected to Liquids Containing Biological Microorganisms