Journal of the Korean Nuclear Society
Volume 32, Number 3, pp.274~282, June 2000

Water Balance Evaluation of Final Closure Cover for Near-Surface Radioactive Wastes Disposal Facility

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(Received December 30, 1999)

Abstract

The simulation of water balance was conducted for suggested four alternative multi-layer cover design of near-surface radioactive waste disposal facility under domestic climate condition. The analysis was also conducted for the most favorable one out of four alternative cover design under conservative scenarios. Until 100 years after closure of disposal vault, the infiltration flux for the most favorable cover design was negligible even under doubling of the ambient precipitation condition. When the degradation of asphalt and geomembrane after 100 years of closure was considered, the infiltration flux significantly increased almost to the design criteria of cover system in l' Aube disposal facility. And it was found that the hydraulic conductivity of bentonite/sand as a bottom barrier should be no greater than 1×10^{-7}cm/sec recommended by U.S. EPA.

Key Words : radioactive waste disposal facility, water balance, multi-layer cover design

1. Introduction

The primary objective of a final disposal cover system for near-surface radioactive waste disposal facility is to minimize the potential of deep infiltration of precipitation into the disposal vault, thus limiting the amount of water potentially contacting the waste. It is generally accepted that multi-layer cover system may have advantage over single-layer cover by allowing subsurface drainage to occur in more than one layer[1-3]. In this study, four kinds of conceptual multi-layer cover system were suggested. The numerical simulation was conducted to validate the performance of each cover system under domestic climate condition observed at a hypothetical site. As a result, the most favorable cover design was determined and water balance for this design was simulated for conservative scenarios as well as normal scenarios. The conservative scenarios included the doubling of the ambient precipitation and design storm condition. The degradation of artificial barriers and increase of hydraulic conductivity of bentonite/sand barrier were also considered in conservative scenario. The infiltration flux into a disposal vault was estimated to define the upper boundary conditions for the detailed modelling of groundwater flow and radionuclide transport. Water balance analyses were conducted using the Hydrologic Evaluation of Landfill Performance(HELP) code[4] which is recommended for humid sites characterized by high annual rainfall and short-duration high-density precipitation events.

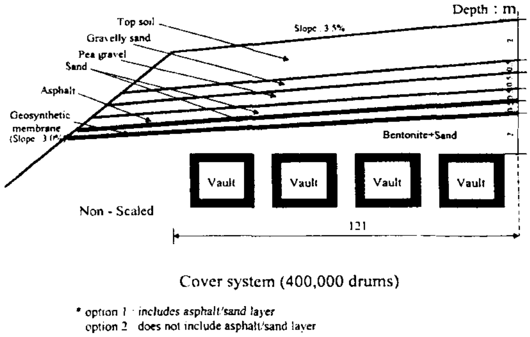

Fig. 1. Concept of Final Disposal Cover for Near-surface Radioactive Waste Vaults

2. Conceptual Model of Final Disposal Cover

A candidate cover system design for repository closure was suggested in the conceptual design stage of the domestic low- and intermediate-level radioactive waste disposal facility. The cover system, as illustrated in Fig.1, consists of multiple layers of materials, each serving a particular purpose. A detailed description of each layer starting with the uppermost layer and proceeding downward follows:

- Layer 1 is a 2 m thick topsoil surface layer. The functions of this layer are to support the growth of vegetation and thereby promote evapotranspiration, to prevent soil erosion, and to temporarily intercept and store moisture for later removal by evapotranspiration.
- Layer 2 is a 0.5 m thick gravelly sand layer designed to function as layer 1, except that this layer acts as a filter layer to prevent migration of topsoil into underlying gravel (layer 3).
- Layer 3 is a 0.5 m thick protective layer made of pea gravel. Its function is to protect underlying layers from degradation through repeated freeze/thaw cycles, repeated excessive wetting/drying, and plant roots or animal intrusion.
- Layer 4 and 6 are a 0.5 m thick sand drainage layers designed to facilitate lateral drainage and prevent head build-up over the underlying asphalt and geosynthetic membrane (layer 5 and 7).
- Layer 5 and 7 are a 0.1 m thick asphalt and geosynthetic membrane layers, respectively. These layers act as artificial barriers to minimize infiltration into the underlying materials. High-density polyethylene(HPDE) was assumed as geomembranes in this study. .
- Layer 8 is a 2 m thick composite barrier consisted of 20%-bentonite and 80%-sand which make a role to limit the infiltration flux to very small values for the performance requirements.

3. Modeling for Water Balance Evaluation

3.1. Theoretical Background of HELP Code

HELP is a quasi two-dimensional, deterministic water balance code that maintains a continuous water balance between surface runoff, evapotranspiration, vertical drainage, and lateral drainage. It was developed to evaluate the hydrologic performance of proposed cover designs, and is appropriate to calculate the

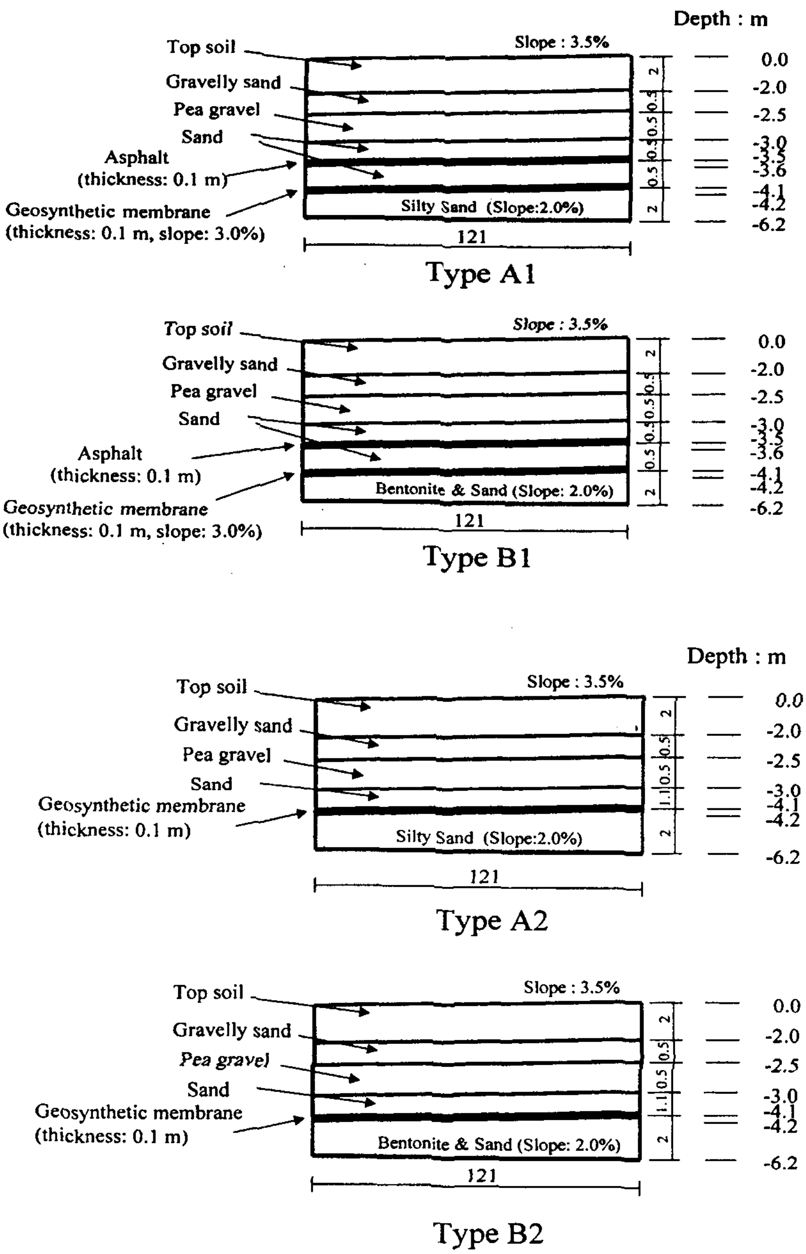

Fig. 2. Cover Profiles for the HELP Simulations

seepage into the disposal vault and natural recharge to the aquifer. HELP uses a mass balance approach to partition flow into water balance components. The code assumes that only gravitational forces act on pore water. Solution algorithms of HELP code are based on the concept of fixed water extraction limits. Storage limits are assigned to each soil layer. Surface runoff is calculated from empirical runoff curves which are a function of soil type, vegetation, slope

Table 1. Hydraulic Parameters for Each Soil Layer[1,6]

Parameter layer	Porosity (cm^3/cm^3)	Field Capacity (cm^3/cm^3)	Wilting Point (cm^3/cm^3)	Hydraulic Conductivity (cm/s)
Top soil (Silty sand)	0.47	0.1894	0.1123	1.0×10^{-4}
Gravelly sand	0.32	0.0203	0.02	0.01
Pea gravel	0.26	0.03002	0.03	1.0
Sand	0.37	0.0559	0.0452	0.03
Asphalt	0.022	0.021	0.020	1.0×10^{-7}
Bentonite(20%)/Sand mixture	0.26	0.138	0.1055	1.0×10^{-7}
Geosynthetic membrane	2^{a}	2^{b}	$1.0\times10^{-4\,c}$	1.0×10^{-11}

* a. Pinhole density (#/ha) b. Installation defect (#/ha) c. Geotextile transmissivity (cm^2/s)

and precipitation rate. Potential evapotranspiration is calculated from precipitation, solar radiation, temperature, and relative humidity. Potential evapotranspiration is separated into potential evaporation and transpiration by the leaf area index. Transpiration is extracted from a root sink function, which is not limited by the soils' hydraulic conductivity. Lateral drainage is determined by Darcy' s law when saturated conditions exist over a barrier material. Unit hydraulic gradient in the direction of drainage is assumed in HELP.

3.2. HELP Simulation Models for Each Alternative

Four alternative cover profiles for the HELP simulations were developed as shown in Fig. 2. Water balance simulations for each cover profile were conducted for three precipitation scenarios: (a) ambient precipitation, (b) doubling of the ambient precipitation, and (c) design storm condition. The ambient precipitation scenario corresponding to daily precipitation data collected at the Youngkwang was simulated for 100 years by the weather generator module of HELP. The doubling of the ambient precipitation condition was realized by doubling the precipitation that was recorded each day rather than by doubling the number of days during which precipitation occurred. This scenario was used to evaluate the effects of climate changes which would result in dramatically more precipitation. The design storm scenario was simulated to determine the maximum runoff which might occur during the barriers' life-span. In order to find the most appropriate cover, annual water balance analysis was performed for 100 years after closure of disposal facility under ambient precipitation condition. Then, the long-term performance of the selected cover was simulated by considering the degradation of artificial barrier materials after 100 years under the above three precipitation conditions. Additionally, the HELP code was used to evaluate the percolation of water through the undisturbed portions of the site.

3.3. Input Parameters

The HELP model requires three general types of input data: soil hydraulic properties, cover design specifications, and climatological records. The

Table 2. General Climate of Hypothetical Site[7]

Month	Average Temperature (℃)	Average Humidity (%)	Monthly Precipitation (mm)	Maximum Precipitation in 24hrs (mm)	Maximum Snows in 24hrs (cm)	Maximum Wind Speed (m/sec)	Average Wind Speed (m/sec)
1	0.2	69.9	46.0	33.3	19.6	18.1	4.4
2	1.4	77.4	41.8	24.8	27.5	18.1	4.3
3	5.5	71.0	48.7	32.6	4.8	16.7	3.9
4	12.1	70.6	71.4	65.4	-	18.9	3.8
5	16.6	73.8	82.7	95.2	-	18.6	4.2
6	22.8	79.8	121.9	126.1	-	18.3	3.1
7	26.8	84.7	253.6	139.8	-	14.7	3.7
8	25.6	80.2	184.1	110.9	-	19.5	3.5
9	23.4	76.2	138.9	76.0	-	19.5	3.3
10	15.9	70.9	57.5	69.4	-	20.0	3.6
11	9.4	68.3	55.9	43.7	4.5	19.5	4.3
12	3.3	69.8	47.4	33.6	30.4	19.7	4.3
Annual	13.6	74.4	1149.9	139.8	30.4	20.0	3.8

hydraulic properties for each soil layer are listed in Table 1. Field capacity and wilting point were calculated from the van Genuchten water retention relationship[5](Eq.1) evaluated at 0.3 bar and 15 bar, respectively, using the parameters from Table1[1,6].

$$\theta = \theta_r + (\theta_s - \theta_r)\ [1+(\alpha h)^n]^{-m} \qquad (1)$$

where h: suction head, θ: volumetric moisture content, θ_r: residual moisture content, θ_s: porosity, m, n: curve fitting parameters(m = 1-1/n), and α: inverse air-entry potential.

The following empirical equations, which were developed using data from natural soils with a wide range of sand and clay content[1], were used to calculate the field capacity and wilting point for the bentonite/sand mixture :

$$\text{Field Capacity} = 0.1535-(0.0018)(\%\ \text{Sand}) + (0.0039)(\%\ \text{Clay}) + (0.1943)(\text{Total Porosity}) \qquad (2)$$

$$\text{Wilting Point} = 0.0370-(0.0004)(\%\ \text{Sand}) + (0.0044)(\%\ \text{Clay}) + (0.0482)(\text{Total Porosity}) \qquad (3)$$

The meteorologic data in Table 2[7] were obtained for a hypothetical site meteorology station.

4. Simulation of Water Balance for Disposal Cover Design

4.1. Simulation of Water Balance for 4 Alternative Cover Design

Table 3 summarized the average annual water balance for 4 alternative cover designs and a natural soil layer over 100-year period after closure of radioactive waste disposal vault. The weather data were generated based on the climate data listed in Table 2. In this study, each layer of cover designs was assumed to keep its initial hydraulic properties during the simulation period. Since, the climate condition, evaporation depth, plant condition and the hydraulic properties of top layer for all cover designs were same, the precipitation, runoff and evapotranspiration resulted in same value. The percolation through the bottom layer depends on the location and

Table 3. Average Annual Water Balance for 4 Alternative Cover Designs

Case	Precipitation (mm)	Runoff (mm)	Evapo-transpiration (mm)	Lateral Drainage (mm)	Percolation or leakage (mm)	Remarks
N1	1143.11	8.40 (0.73 %)	787.93 (68.93 %)	-	340.39 (29.78 %)	Natural soil layer
A1	1143.11	19.10 (1.67 %)	788.23 (68.96 %)	332.36 (29.07 %)	2.64 (0.23 %)	
A2	1143.11	19.10 (1.67 %)	788.23 (68.96 %)	319.22 (27.93 %)	14.92 (1.31 %)	
B1	1143.11	19.10 (1.67 %)	788.23 (68.96%)	334.98 (29.30%)	0.020 (0.0017%)	
B2	1143.11	19.10 (1.67 %)	788.23 (68.96%)	334.21 (29.24 %)	0.098 (0.0085 %)	

(OO %) : Ratio of each value over precipitation

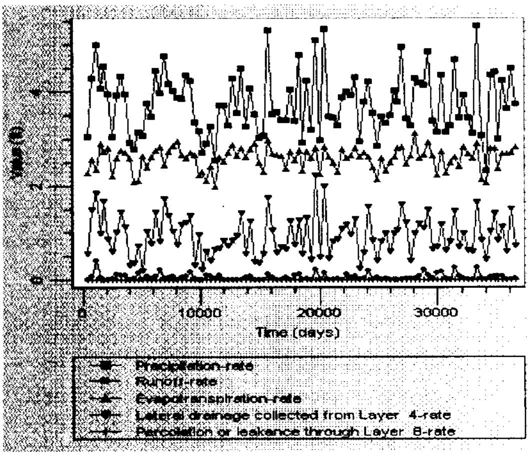

Fig. 3. Daily Water Balance for the B1 Design Over 100-year Period

number of drainage layers and the hydraulic properties of barrier layer. As the B1 designs has two drainage layers and two barrier layers, the percolation for the B1 design showed the smallest value compared with other models. On the contrary, the A2 design has just one drainage layer and larger value of the hydraulic conductivity of the bottom layer than the B1 design. For the B1 cover design, only about 0.0017 % of total precipitation was infiltrated into the disposal vault. Therefore the B1 design could be considered as almost impermeable under normal climate condition.

Fig.3 shows daily water balance for the B1 design over 100-year period. The precipitation was almost equal to the sum of evapotranspiration and subsurface lateral drainage.

The infiltration rate for natural soil cover was nearly 30 % of precipitation, which could affect the performance of waste disposal facility. This illustrates that the cover system is essential to control the infiltration of precipitation into disposal vault.

4.2. Simulation of Water Balance of a Cover System Under Conservative Conditions

As explained earlier, the B1 design showed the smallest infiltration rate among four alternative cover designs. In this study, the simulation was conducted for the B1 design under conservative conditions. The precipitation scenarios were

Table 4. Average Annual Water Balance for the B1 Design for Various Conditions

Case	Precipitation(mm)	Runoff (mm)	Evapotranspiration (mm)	Lateral Drainage (mm)	Percolation or leakage (mm)	Remarks
B1-N	1147.05	19.10 (1.67 %)	788.23 (68.96%)	334.98 (29.30%)	0.020 (0.0017%)	0 - 100 years Ambient
B1-M	1147.05	22.895 (2.0 %)	788.12 (68.71 %)	335.24 (29.23 %)	0.020 (0.0017%)	0 - 100 years Design storm condition
B1-D	2286.34	234.38 (10.25%)	873.14 (38.19 %)	1178.22 (51.53 %)	0.0315 (0.0030%)	0 - 100 years Doubling of the Ambient precipitation
B2-N	1143.11	19.10 (1.67 %)	788.23 (68.96 %)	301.57 (26.38 %)	32.42 (2.84 %)	100-200 years Ambient precipitation & Degradation
B2-M	1143.11	22.895 (2.0 %)	788.12 (68.71 %)	301.83 (26.31 %)	32.42 (2.84 %)	100-200 years Design storm condition & Degradation
B2-D	2286.34	234.38 (10.25 %)	873.14 (38.19 %)	1142.0 (49.95 %)	34.83 (1.52 %)	100-200 years Doubling of the ambient precipitation & egradation

(OO %) : Ratio of each value over precipitation

(a)ambient, (b)doubling of the ambient and (c)design storm conditions respectively. The design storm conditions was built by applying maximum precipitation value on the day following the largest simulated precipitation event when soil moisture content was at a maximum. This value was determined as 394.7 mm/day, adopted from the design criteria of Youngkwang nuclear power plant. Long-term processes that will significantly affect flow are the degradation of the artificial barrier layers such as asphalt and geomembrane. In this study, asphalt and geomembrane were assumed to be degraded after 100 years of closure. The degradation was realized by changing the hydraulic properties of artificial layer to those of sand listed in Table 1. However the layer of bentonite/sand was assumed to keep its initial properties even after 100 years of closure.

As listed in Table 4, the surface run-off and the subsurface lateral drainage highly increased under doubling of the ambient condition over 100-year period. Since the parameters which control evapotranspiration were independent of the precipitation conditions after full saturation of soils, the evapotranspiration was not nearly changed for the different precipitation scenarios. The increase of percolation was not significant under doubling of the ambient condition. Taking the design criteria of cover system for radioactive waste disposal facility in l' Aube, France[8], it was concluded that the percolation under doubling of the ambient condition was far below the design criteria of cover system within 100 years of closure.

Table 4 also illustrate the water balance for 100 to 200 years. As explained earlier, due to the degradation of asphalt and geomembrane after 100 years of closure, the function of asphalt and geomembrane layer was converted from barrier to drainage in the simulation. The results showed that the percolation estimates through the bottom layer under all precipitation scenarios increased by

Table 5. Average Annual Water Balance for B1 Model with Increase of Hydraulic Conductivity of Bottom Barrier

Model	Precipitati on(mm)	Runoff (mm)	Evapo-transpiration (mm)	Lateral Drainage (mm)	Percolation or leakage (mm)	Remarks
BB1-N	1143.11	19.10 (1.67 %)	788.23 (68.96%)	334.91 (29.29 %)	0.095 (0.0083%)	0 - 100 year Ambient precipitation
BB1-D	2286.43	234.38 (10.25%)	873.14 (38.19 %)	1178.09 (51.54 %)	0.159 (0.0070%)	0 - 100 year Doubling of the ambient precipitation
BB2-N	1143.11	19.10 (1.67 %)	788.23 (68.96%)	125.06 (10.94%)	208.99 (18.28%)	100 - 200 year Ambient precipitation & Degradation
BB2-D	2286.34	234.38 (10.25%)	873.14 (38.19 %)	846.18 (37.01%)	330.65 (14.46%)	100 - 200 year Doubling of the ambient precipitation & Degradation

(OO %) : Ratio of each value over precipitation

more than 1000 times compared to those over 100-year period. But the percolation estimates were still below the design criteria of cover system in l' Aube for 200-year period even when the degradation of artificial barriers was considered. It is, therefore, concluded that the performance of the B1 cover system would not be deteriorated under the conservative scenarios considered in this study.

To obtain more conservative results, the conductivity of bottom layer, mixture of bentonite and sand, was then increased by ten times for the B1 model. Also the degradation of asphalt and geomembrane was considered after 100 years of closure.

Table 5 summarized the simulation results of water balance under ambient and doubling of the ambient conditions. Compared to the results listed in Table 4 under the same precipitation conditions, the percolation through the cover system would be increased. Even though the conductivity of bentonite-sand layer was increased by 10 times, the percolation was below the design criteria of cover system in l' Aube waste disposal facility. This is because the other artificial barriers would maintain their initial hydraulic properties until 100 years of closure.

When the degradation of artificial layers was considered after 100 year of closure, the percolation significantly increased approaching almost that for natural soil layer under doubling of the ambient conditions. Therefore, it is concluded that the conductivity of bottom barrier should be at least more than 1×10^{-7}cm/sec, which is recommended by U.S. EPA[9].

5. Conclusions

1. The infiltration rate for natural soil layer amounted nearly 30 % of precipitation, which could affect the performance of waste disposal facility. This illustrates that the cover system is essential to control the infiltration of precipitation into the disposal vault.
2. The B1 cover design which has two drainage layers and two artificial barriers in addition to a bentonite and sand mixture, would be the most favorable to resist the infiltration of precipitation into disposal vault. The infiltration into disposal vault was just about 0.0017% of

precipitation. Therefore the B1 design could be considered as almost impermeable for 100 years of closure under normal climate condition.

3. For 100 year simulation, the infiltration estimates were far below the design criteria of cover system in l' Aube radioactive waste disposal facility even under doubling of the ambient and design storm conditions.
4. Under the assumption of the degradation of asphalt and geomembrane, the percolation estimates through the bottom layer for all precipitation scenarios significantly increased. However, the percolation estimates was slightly below the design criteria of cover system in l' Aube for 200-year period considered in this study even when the degradation of artificial barriers was considered. It is, therefore, concluded that the performance of the B1 cover system would not be deteriorated under the conservative scenarios.
5. In case, the hydraulic conductivity of the bentonite/sand barrier increased to 1×10^{-6} cm/sec after 100 years of closure, the percolation through the bottom layer approached the value for natural soil layer. Therefore, it is concluded that the conductivity of bottom barrier should be at least more than 1×10^{-7}cm/sec, which is recommended by U.S. EPA.

References

1. P. D. Meyer, M.L. Rockhold, W.E. Nichols & G.W. Gee., " Hydrologic Evaluation Methodology for Estimating Water Movement Through the Unsaturated Zone at Commercial Low-Level Radioactive Waste Disposal Sites," NUREG/CR-6346 (1996).
2. J.D. smyth, E. Bresler, G.W. Gee & C.T. Kincard., "Development of an Infiltration Evaluation Methodology for Low-Level Waste Shallow land Burial Sites," NUREG/CR-5523 (1990).
3. P.D. Meyer & T.J. Nicholson, "Application of an Infiltration Evaluation Methodology to a Hypothetical Low-Level Waste Disposal Facility", NUREG/CR-6114 Vol.1 (1993).
4. P. R. Schroeder, N. M. Aziz, C. M. Lloyd, and P. A. Zappi, "The Hydrologic Evaluation of Landfill Performance (HELP) Model : User' s Guide for Version 3," EPA/600/R-94/168a, U.S. Environmental Protection Agency Office of Research and Development, Washington, DC. (1994).
5. M.Th. van Genuchten, "A closed-form equation for predicting the hydraulic conductivity of unsaturated soils," Soil Sci. Soc. Am. J., 44:892-898 (1980).
6. P.Martian, "Calibration of HELP Version2.0 and performance Assessment of Three Infiltration Barrier Designs for Hanford Site Remediation," EGG-EES-11455 (1994).
7. Korea Electric Power Corporation, "Final Safety Analysis Report," Youngkwang Nuclear Power Plant, Units 3&4. Vol.1 (1995).
8. L.P. Cousin, " Shallow-Land Disposal Technology," NETEC workshop in Shallow Land Disposal Technology, Taejon, Korea (1997).
9. U.S. EPA, "Technical guidance Document. Final Covers on Harzardous Waste Landfills and Surface Impoundments," EPA/530-SW-89-047. Washington, D.C. (1989).