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Control of Water Infiltration Into Near Surface LLW Disposal Units

TASK

Progress Report on Field Experiments at a Humid Region Site, Beltsville, Maryland

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ABSTRACT

This study's objective is to assess means for controlling water infiltration through waste disposal unit covers in humid regions. Experimental work is being performed in large-scale lysimeters (75 ft × 45 ft × 10 ft) at Beltsville, Maryland. Results of the assessment are applicable to disposal of low-level radioactive waste (LLW), uranium mill tailings, hazardous waste, and sanitary landfills.

Three kinds of waste disposal unit covers or barriers to water infiltration are being investigated: (1) resistive layer barrier, (2) conductive layer barrier, and (3) bioengineering management. The resistive layer barrier consists of compacted earthen material (e.g., clay). The conductive layer barrier consists of a conductive layer in conjunction with a capillary break. As long as unsaturated flow conditions are maintained, the conductive layer will wick water around the capillary break. Below-grade layered covers such as (1) and (2) will fail if there is appreciable subsidence of the cover, and remedial action for this kind of failure will be difficult. A surface cover, called bioengineering management, is meant to overcome this problem. The bioengineering management surface barrier is easily repairable if damaged by subsidence; therefore, it could be the system of choice under active subsidence conditions. The bioengineering management procedure also has been shown to be effective in dewatering saturated trenches and could be used for remedial action efforts. After cessation of subsidence, that procedure could be replaced by a resistive layer barrier or, perhaps even better, by a resistive layer barrier/conductive layer barrier system. The latter system would then give long-term effective protection against water entry into waste without institutional care.

As mentioned in the preceding paragraph, a bioengineering management cover might well be the cover of choice during the active subsidence phase of a waste disposal unit. Some maintenance is required during that period. Final closure, using geological materials, could follow cessation of subsidence. No further significant maintenance would then be required. If the geological material used is merely a clay barrier to water infiltration, the cover will be "sensitive" to imperfect construction or degradation by penetrating roots. The roots will die and decay, causing markedly increased permeability of the clay with the passage of time. A system using a conductive layer under the clay layer as a water-scavenging system will, in comparison, be "robust." Roots will still degrade the clay layer but will not degrade the scavenging layer. A root hole through the conductive layer will be analogous to a hole through a wick. It will do no significant damage. The combination of a resistive layer with a conductive (scavenging) layer underneath is thus less dependent on perfect construction techniques and will be resistant to damage by root invasion. In the absence of subsidence such a system will function effectively for millennia.

Another very useful application of the resistive layer barrier/conductive layer barrier system would be to protect an earth-mounded concrete bunker disposal unit. In that case, the barrier system would shield the concrete from exposure to flowing water. The resulting stagnant alkaline film of water would tend to protect the concrete from degradation over a long time period. Similarly, a resistive layer barrier/conductive layer barrier system could be used to protect high-level waste. If high-level waste were disposed of in fractured rock, this system could be used to divert possible fracture flow water around the waste.

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INTRODUCTION

Infiltration of water into waste is the foremost problem associated with near-surface disposal of low-level radioactive waste (LLW). Up to this time, disposal unit covers have generally been constructed from soil materials. In humid areas, these soil or clay covers have generally proved less than satisfactory; often, the cover itself has served as the principal pathway for water entry into the waste (1). Water infiltrating to buried wastes, contacting the wastes, then exiting the area can reasonably be expected to be the most important of radionuclide transport agents. Some radionuclides, such as tritium (present as tritium oxide), and those present in anionic form, will essentially move with the flow of water; others, present as multivalent cations, will move much more slowly, but all will move to a greater or lesser degree. Clearly then, it is advantageous to reduce water infiltration to buried waste to as low a level as reasonably achievable. It is the purpose of our work to examine and demonstrate various approaches for achieving that goal.

Three kinds of waste disposal unit covers or barriers are being investigated in this work: (1) resistive layer barrier, (2) conductive layer barrier, and (3) bioengineering management. The resistive layer barrier is the well-known compacted clay layer and depends on compaction of permeable porous materials to obtain low flow rates. A simplified model is shown in Figure 1. Flow through porous media is described by Darcy's law (2). Investigations on flow through such layers have gone on for over 100 years, so further progress in this area can be expected to be slow.

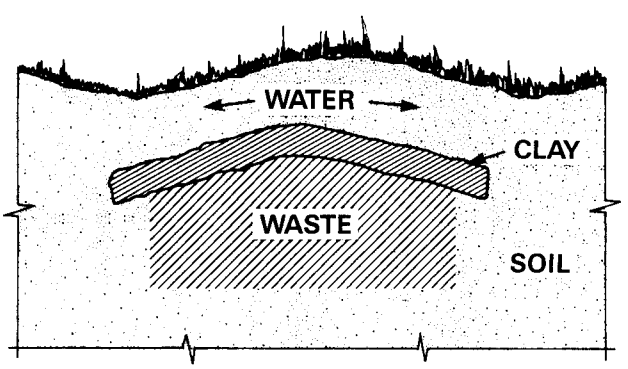


Fig. 1. Resistive layer barrier.

The conductive layer barrier (1) is a special case of the capillary barrier (3). Use is made of the capillary barrier phenomenon not only to increase the moisture content above an interface, but to divert water away from and around the waste. During such diversion, water is at all times at negative capillary potential or under tension. A simplified model is shown in Figure 2.

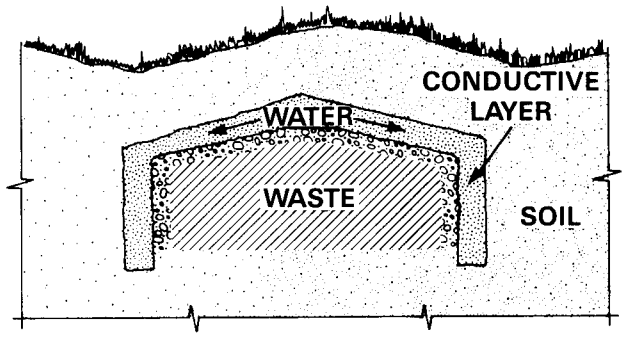


Fig. 2. Conductive layer barrier.

This system consists of a porous medium underlaid by a capillary break (rock layer). Infiltration barriers such as a conductive layer barrier or a clay layer barrier (or a combination thereof) must fail if subjected to substantial shearing caused by waste subsidence. Reestablishment of a layered system after subsidence failure is a difficult undertaking and is exacerbated by the increasing complexity of the layered system. The failure potential of in-ground layered systems during the subsidence period argues for development of an easily repairable surface barrier for use during that period. To that end, a procedure called "bioengineering management" was developed (4). The bioengineering management technique utilizes a combination of engineered enhanced run-off and moisture-stressed vegetation growing in an overdraft condition to control deep water percolation through disposal unit covers. An artist's conceptual drawing is shown in Figure 3.

FIELD EXPERIMENTS

In this section we will discuss experiments being conducted in large-scale lysimeters at a humid region site in Beltsville, Maryland (see Figure 4).

Bioengineering Management

In bioengineering management the necessary run-off is provided by features installed at or above the soil surface rather than within the profile. The procedure, described by Schulz et al. (4), was designated bioengineering management. Its principal advantage is that subsidence can easily be managed by relatively simple, inexpensive maintenance of the above-ground features rather

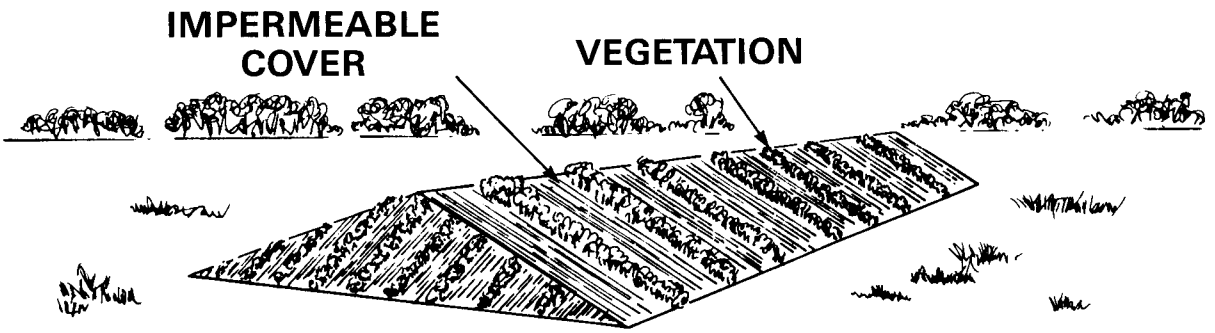


Fig. 3. Bioengineering management.

than by difficult reconstruction of below-ground layers. It should be noted that, after a length of time sufficient so that the organics have decayed and the waste containers have completely failed, subsidence will cease and a layered system could be then installed which could last over geological time periods.

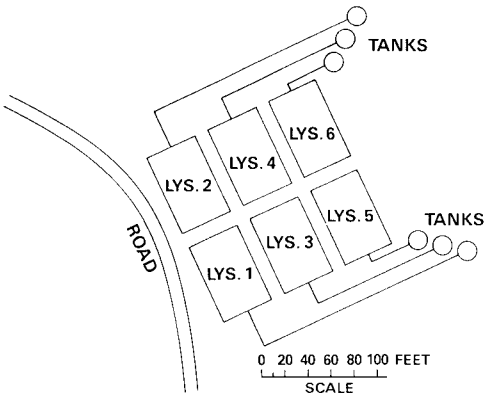
In essence, the bioengineering management technique utilizes a combination of engineered, enhanced run-off and stressed vegetation in an overdraft condition to control deep water percolation through disposal unit covers. To describe it further: if a waste burial site is selected so that incoming subsurface flow is negligible, then precipitation is the sole source of input water. In a simplified model, that water has three possible fates: (1) evapotranspiration, (2) run-off, and (3) deep percolation. Evapotranspiration has a definite limit, governed by energy input. Ideally, deep percolation should be zero, leaving only the run-off component available for unlimited manipulation. Positive control of run-off becomes difficult with the use of compacted porous media trench caps as the sole barrier to water infiltration. The compacted material tends to become more permeable with the passage of time, due to fractures caused by waste subsidence and from the inexorable process of root growth, followed by death and decay of the roots, thus creating water channels. Evapotranspiration cannot then use all of the infiltrating water, and water percolates downward to the waste. As stated before, evapotranspiration has a theoretical maximum dictated by solar energy input to the system; only run-off remains available for nearly unlimited management. This run-off can be surface or subsurface, as long as it occurs before water reaches the waste.

Surface run-off can be managed to as high as 100% by means of a perfect, leak-proof roof, which is expensive and hard to guarantee. Alternatively, adequate but not total run-off can be engineered rather inexpensively by using an impermeable ground cover over part of the surface to achieve high and controlled levels of run-off. Vegetation planted between areas of impermeable cover will extend over the cover to intercept incoming solar energy to evaporate water. Roots will extend under the cover in all directions to obtain water.

Such a system can be visualized by imagining a supermarket parking lot, where trees are planted in islands, surrounded by concrete curbs, within an extensive paved area. In this case, the trees are maintained in a drought environment due to the small soil surface available for infiltration of precipitation. The paving, along with the curbing around the trees, causes run-off of most precipitation. Aboveground, the tree's branches and leaves extend over the parking lot and intercept incident solar energy. Beneath the surface, the roots, in a drought state, explore outward under the paving for any available water. Utilizing this concept, it should be possible, by combining engineered run-off with vegetation, to maintain the soil profile in a potential overdraft condition on a yearly basis.

Initial investigations of the bioengineering management technique were carried out in lysimeters at Maxey Flats, Kentucky. Results obtained in seasonal 1984–1985 and 1985–1986 were reported by O'Donnell et al. (5). In that work, a fescue grass crop was used with an engineered cover of stainless steel. Following seasonal1985–1986 the grass cover was removed, a new stainless steel engineered cover was constructed, and Pfitzer junipers were planted in the lysimeters. After the junipers were established, percolation data were again collected in 1988 and reported by Schulz et al. (6). The woody junipers were excellent in preventing deep percolation of water in the lysimeter.

The encouraging initial results obtained in the Maxey Flats lysimeter experiment led to the establishment of a large-scale field demonstration at Beltsville, Maryland (Figure 4).



Lysimeter		Date Completed
1	Bioengineering management	5/87
2	Bioengineering management	5/87
3	Vegetated crowned soil cover	5/87
4	Rip-Rap over resistive layer barrier	10/88
5	Resistive layer barrier over conductive layer barrier	1/90
6	Vegetation over resistive layer barrier	4/89

Design type and completion dates of experimental lysimeters located at Beltsville, MD.

Fig. 4. Plan view showing placement of experimental lysimeters at Beltsville, MD.

Figure 5 is a photograph of lysimeter 1, bioengineering management, taken in January, 1994, 7 years after planting of the Pfitzer junipers. Alternating panels of aluminum and fiberglass were used as the hard cover. These plots, or lysimeters, are 70 ft long by 45 ft wide, and the bottoms are 10 ft below grade. Figure 6 shows a side view of construction details of lysimeters 1 and 2 (bioengineering management). The only difference between the two was the initial water level in the lysimeters. The water level was 90 cm above the bottom of lysimeter 1 and 190 cm above the bottom of lysimeter 2. The water level in the lysimeters simulates the water table in a flooded disposal cell. In addition to the two bioengineered lysimeters, two reference lysimeters (3 and 4) were initially constructed. They were similar to the former, except that they were merely planted with fescue grass. No hard cover was present, but surface slopes were similar to the two bioengineered lysimeters (i.e., a slope of 1:5). Performance data for the reference lysimeters are given in Figure 7.

The water level in the two reference plots or trenches (lysimeters 3 and 4) rose until it was near the surface. At that time, water was pumped from the lysimeters to keep them from running over. The graphs of the water tables (i.e., water levels) in the bioengineered plots (lysimeters 1 and 2) show an entirely different story, as evidenced in Figure 8. In both cases, the water table was eliminated. It appears that the bioengineering approach could prevent water infiltration to a disposal unit. It also could be used for a remedial action in dewatering existing problem sites such as Maxey Flats.

On February 4, 1988, lysimeter 4 was pumped out to prevent overflow. It was then discontinued as a reference lysimeter and converted to a rock-surfaced, resistive-layer barrier plot. Lysimeters 1 and 2 (bioengineered) and lysimeter 3 have been continued. A summary of run-off, evapotranspiration, and pumping from those three lysimeters is given in Figure 9.

Figure 9 shows that there was very little run-off from the grass-covered plot. Most of the precipitation was disposed of, via evapotranspiration, by the fescue crop, but this was not adequate to prevent the rise of the water table. Table 1 gives the run-off, evapotranspiration, and deep percolation in the bioengineered plots during the past 6 years. There was no deep percolation during this period. The evapotranspiration has been rising annually, probably as a result of the greater vegetative canopy intercepting a greater percentage of the precipitation. In 1988, 1989, 1990, 1991, and 1992 the runoff percentages were 80, 74, 70, 67 and 63, respectively (7). In 1993, the run-off decreased to 61% of the precipitation. During 1989, the water table was completely eliminated in both plots (Figure 8).

Table 1. Run-off, evapotranspiration and deep percolation from bioengineered plots.

Year	Run-off	Evapotranspiration	Deep Percolation
	— Percent of Precipitation —		
1988	80	20	0
1989	74	26	0
1990	70	30	0
1991	67	33	0
1992	63	37	0
1993	61	39	0

In addition to rainfall, run-off, and evapotranspiration measurements discussed above, neutron-probe soil-moisture measurements have been made continuously to monitor soil moisture changes in all six lysimeters depicted in Figure 4. The neutron probe measurements indicate whether there is a gain or loss of moisture from the soil profile or, perhaps, steady-state situation, where there is little or no net gain or loss of soil moisture during a year. A steady-state situation with relatively constant-moisture "dry" soil above waste would be highly desirable with a bioengineered cover.

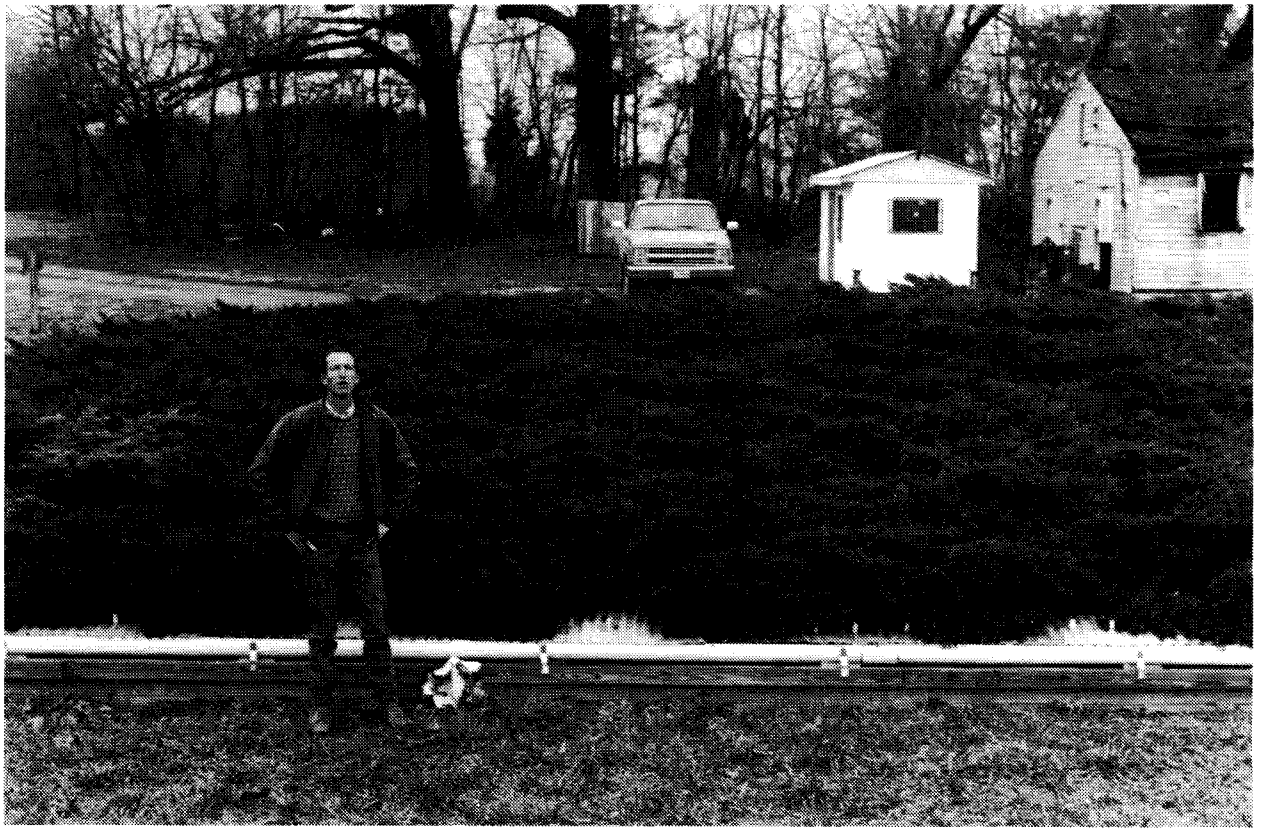


Fig. 5. Bioengineering plots at Beltsville, Maryland. Photo taken in January, 1994, 7 yr after planting Pfitzer junipers. Run-offis 61% of precipitation, evapotranspiration is 39% of precipitation; there is no deep percolation.

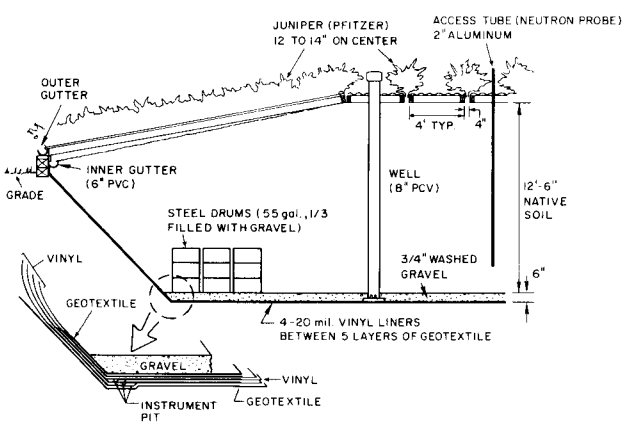


Fig. 6. Side view of bioengineered lysimeter. Surface run-off is collected from both engineered surface and soil surface. Soil moisture content measured with neutron probe. Water table measured in well.

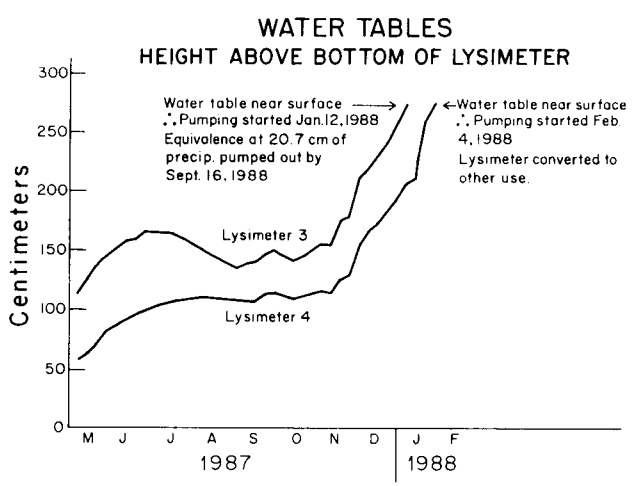


Fig. 7. Water table vs. time in reference lysimeters. Crowned surface is planted with fescue grass. Water table increased with time until pumping was necessary to keep trench from running over. Surface run-off was 8% of precipitation.

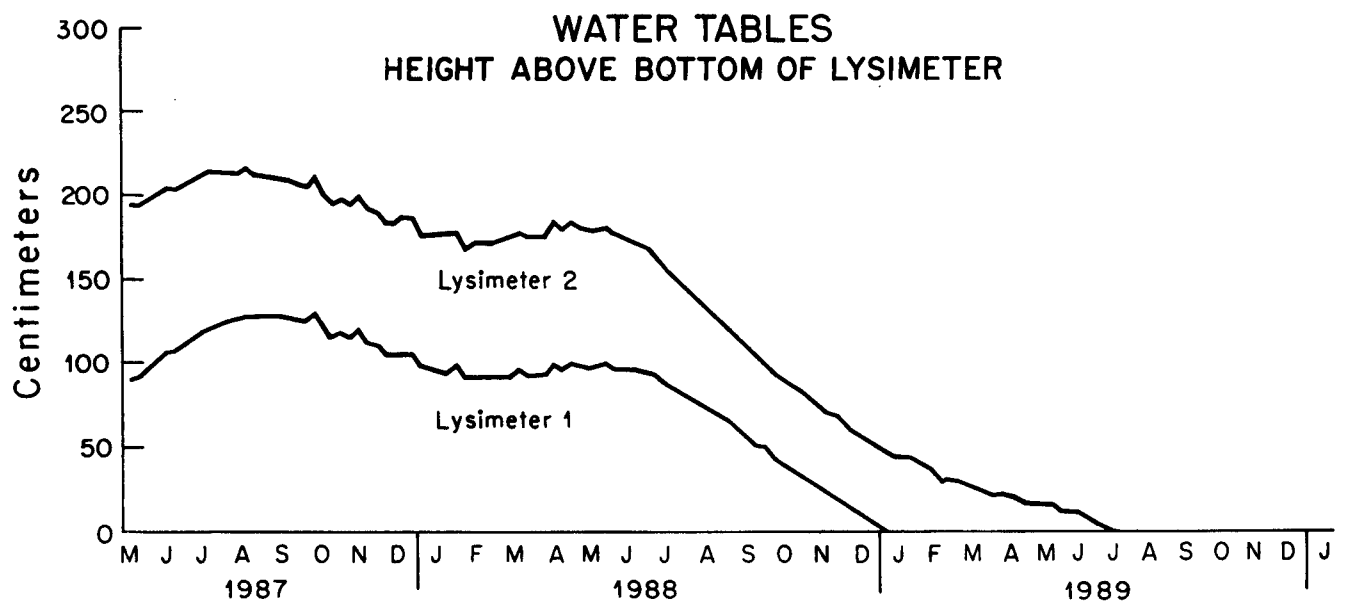


Fig. 8. Water table vs. time in bioengineered lysimeters. Decline of water-table levels with time shows bioengineered covers effectively prevented water percolation. Elimination of water table shows that this procedure could be used for remedial action ("drying out") of existing water-logged burial sites. Compare with Figure 7.

There would then be a large safety margin to protect the waste from infiltrating water.

Neutron probe apparatus, as supplied by the manufacturer, is calibrated against moisture measurements in sand. Such calibration is of unknown accuracy when applied to soil measurements. For this reason, the probe was calibrated using the same soil as in the lysimeters. Fourteen hundred pounds of soil were placed in a weighing lysimeter, and measurements were made over a 6 year period. Calibration data obtained using the weighing lysimeter are given in Table 2. The resulting curves, depicting the factory calibration and the weighing lysimeter calibration, are given in Figure 10. It is evident that use of the factory calibration on sand would result in a very large error in soil moisture determination.

Results of some neutron probe measurements are shown in Figure 11 for bioengineered lysimeters 1 and 2. The data are plotted as volumetric moisture content, as a function of soil depth, on specific dates. Only eight widely spaced measurement dates are shown, for clarity. From inspection of the figure it is seen that, at the start of the experiment in July, 1987, the moisture content of the soil increased with depthuntil the water table was reached, then became constant. By July, 1989, the water table had been eliminated from both lysimeters, and the soil profiles were drying out. However, the soil moisture content, although much lower in the soil profile than in July, 1987, still increased with depth. This same relationship was still evident in November, 1993, although the soil profile had become still drier.

In Figure 12 the neutron probe measurements of soil moisture are plotted as a function of time at various specific depths. Here, it is seen that at 61 cm (2 ft) the soil was dried out in the first year of the experiment. At this soil depth, a steady state of "dry" soil seems to have been reached. At 244 cm (8 ft), however, steady state has not yet been attained. During the past 6½ years, the soil moisture content has been decreasing and, indeed, still is. From the data shown in Figures 11 and 12, it is reasonable to conclude that a steady state of "dry" soil will eventually be obtained in the lysimeter. This would indicate that bioengineered closure, as described in this experiment, would maintain the cover over buried waste in a "dry," steady-state condition. This would not only prevent water from percolating down to the waste, but would do so with a large safety factor.

Resistive Layer Barrier

As previously mentioned, on February 4, 1988, lysimeter 4 was pumped out, discontinued as a reference

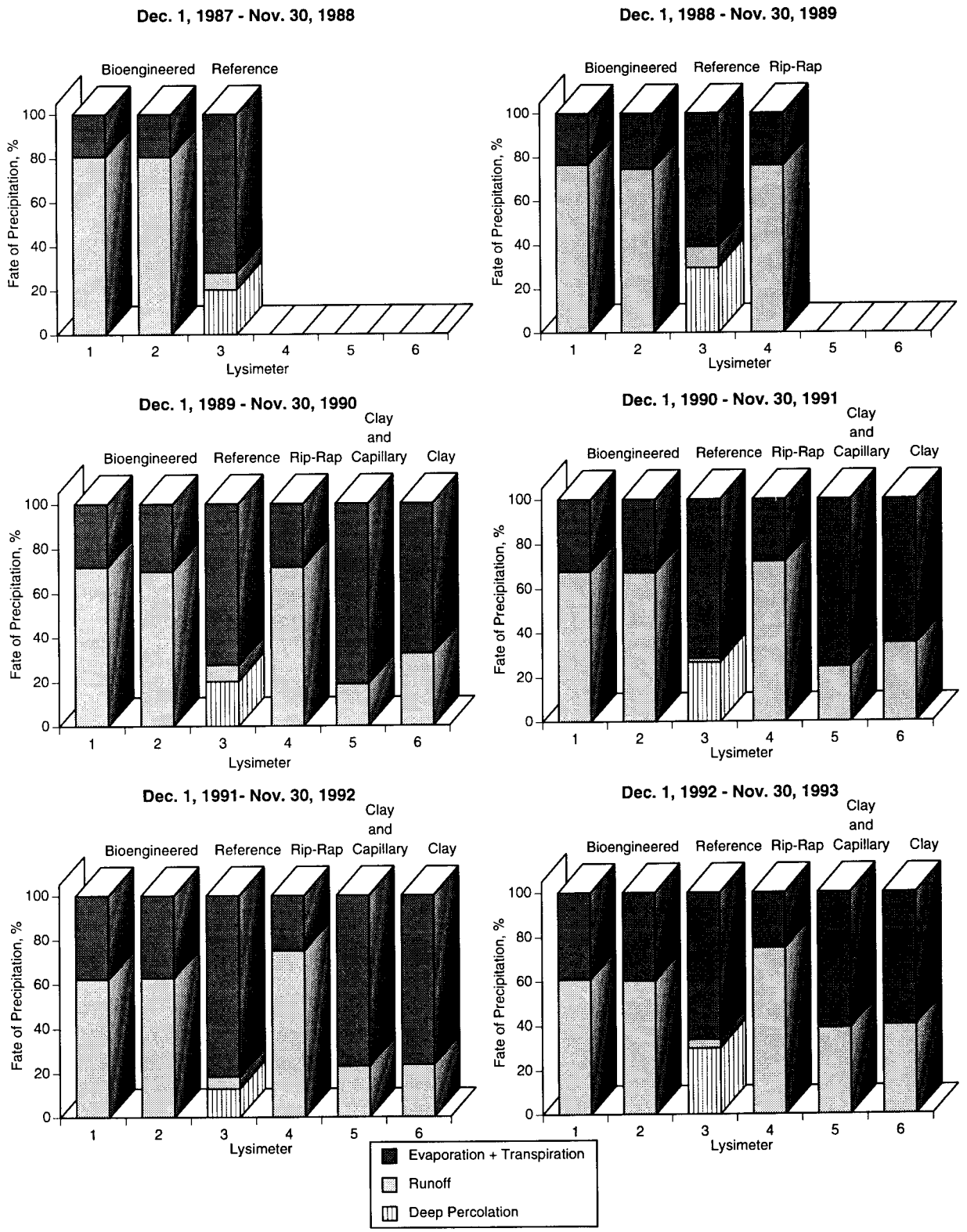


Fig. 9. Fate of precipitation in bioengineered, reference (soil with grass), UMTRA (clay with riprap), clay (clay with grass), and clay + capillary (clay and capillary layers with grass), lysimeters. Deep percolation is present in reference lysimeter. No deep percolation to date in any other cover system

Table 2. Calibration of neutron probe used in lysimeters 1,2,4,5 and 6. Calibration was carried out in a weighing lysimeter using the soil of the field lysimeters.

Date of Measurement	Counts / Std. Count	Moisture Content: Volumetric $\frac{cm^3\ H_2O}{cm^3\ Soil}\left(\frac{V}{V}\right)$	Moisture Content: Oven Dry Weight Basis % Moisture (Pw)
9-11-87	.191	.0109	.65
10-14-87	1.78	.256	15.6
10-23-87	1.72	.246	15.0
2-02-88	1.62	.223	13.6
5-27-88	1.52	.203	12.4
10-05-88	1.44	.183	11.2
11-30-88	1.38	.170	10.4
1-11-89	1.29	.159	9.7
3-02-89	1.23	.147	9.0
4-26-89	1.13	.132	8.0
6-14-89	1.04	.115	7.0
8-04-89	0.93	.097	5.9
10-11-89	0.84	.084	5.1
1-03-90	0.76	.072	4.4
7-09-90	0.73	.065	4.0
12-07-90	0.62	.052	3.1
5-22-91	0.56	.043	2.6
11-14-91	0.52	.040	2.4
4-28-92	0.50	.036	2.2
9-10-92	0.46	.033	2.0
1-18-93	0.44	.030	1.8
6-13-93	0.41	.025	1.5
9-17-93	0.37	.021	1.3
1-7-94	0.35	.020	1.2

Volume of soil in weighing lysimeter	382 liters
O.D. weight of soil in weighing lysimeter	628 kg
Bulk density of soil	1.65 g/cm^3
15 Atmosphere moisture (Pw)	3.1%
1/3 Atmosphere moisture (Pw)	7.1%
15 Atmosphere moisture (V/V)	0.051 g/cm^3
1/3 Atmosphere moisture (V/V)	0.117 g/cm^3
A.D. moisture % (Pw)	0.65%

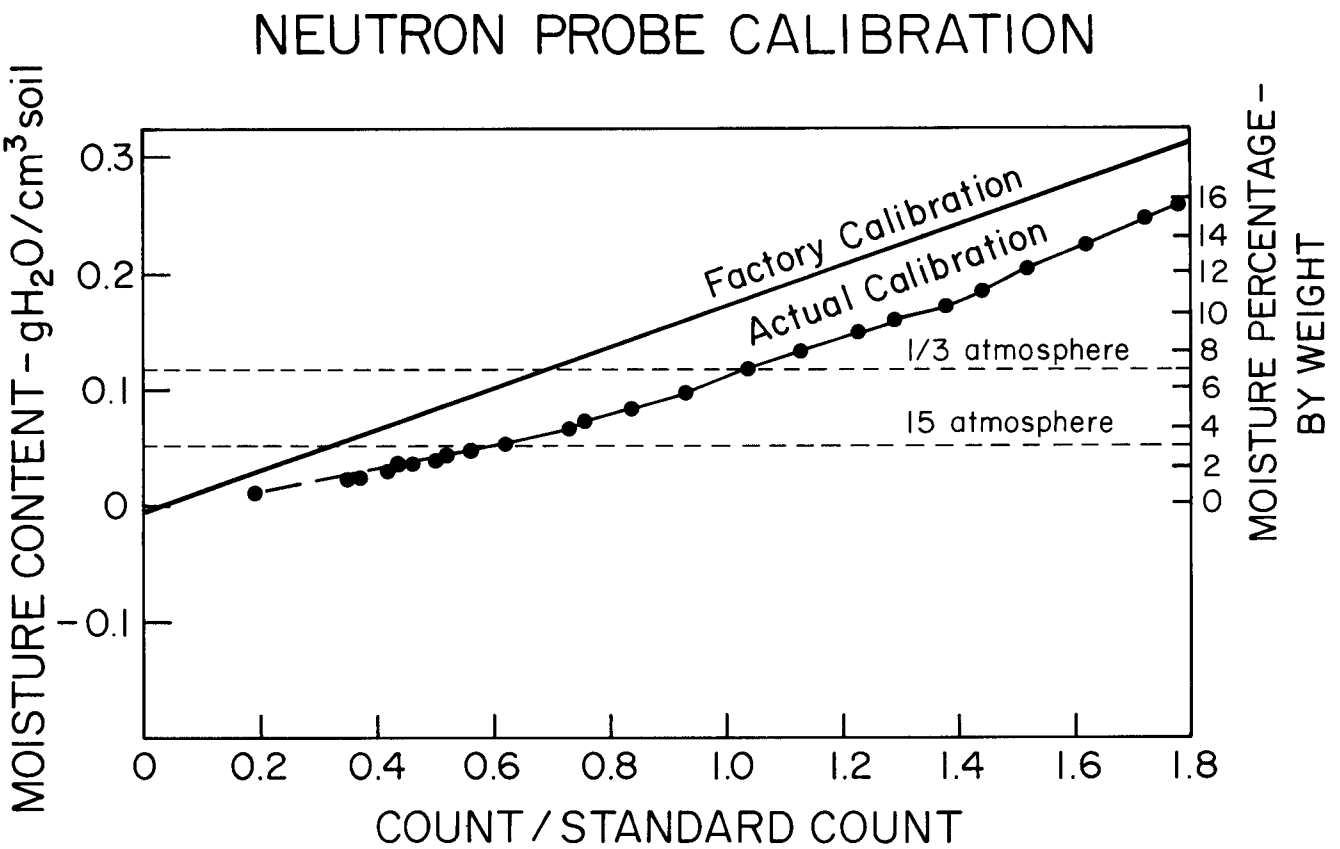


Fig. 10. Calibration of neutron probe using soil of bioengineered lysimeters. Calibration carried out in weighing lysimeter over a 6-yr period. Factory calibration was supplied by manufacturer of neutron probe and made against sand rather than soil.

lysimeter, and converted to a rock-surfaced, resistive-layer barrier plot. The primary reason for constructing that particular cover is the likelihood of such covers being used for uranium mill tailings. An end view of that plot or lysimeter is shown in Figure 13. This lysimeter was completed in the fall of 1988, and data collection (measuring performance) has begun. The most important information to be gained here will be the relative weighing of the advantages and disadvantages of rock surface vs. a vegetated surface.

In addition to the UMTRA or rock-surfaced, resistive-layer barrier plot, a vegetated resistive layer barrier plot was constructed. The primary purpose of this plot is for comparative measurements. Essentially, this plot is similar to the rock-surfaced plot except that topsoil replaces the rock layer, and the plot is planted with fescue grass. A diagram of this plot is given in Figure 14.

In Figure 9, the fate of precipitation in the UMTRA and grass-covered, clay-layer lysimeters is given. There was more than twice as much run-off from the rock-covered plot was as from the grass-covered plot. Although the data show no deep percolation through the clay layers to date in either lysimeter, there is little indication as to how much safety margin has been offered. Nor is it known how consistently such near-perfect clay barriers would be installed in a routine operation. That remains a problem for future consideration.

Another concern is the possible drying out of clay barriers. If this were to happen, the clay layer would not be as efficient a barrier for preventing radon escape as planned in the UMTRA application. In addition, drying out of the clay layer could lead to cracking, leading to subsequent leakage prior to resealing by wetting. Figure 15 gives the volumetric moisture content of clay in the rock-covered (lysimeter 4) and the grass-covered (lysimeter 6) plots. In no case did the clay layer dry out significantly. On the contrary, in the UMTRA or rock-covered plot, which was devoid of vegetation, there was a slight increase in moisture content with time, suggesting that some leakage of water through the clay layer may occur in the future. Lysimeter 6 has a clay layer and a grass cover. In this case, no increase

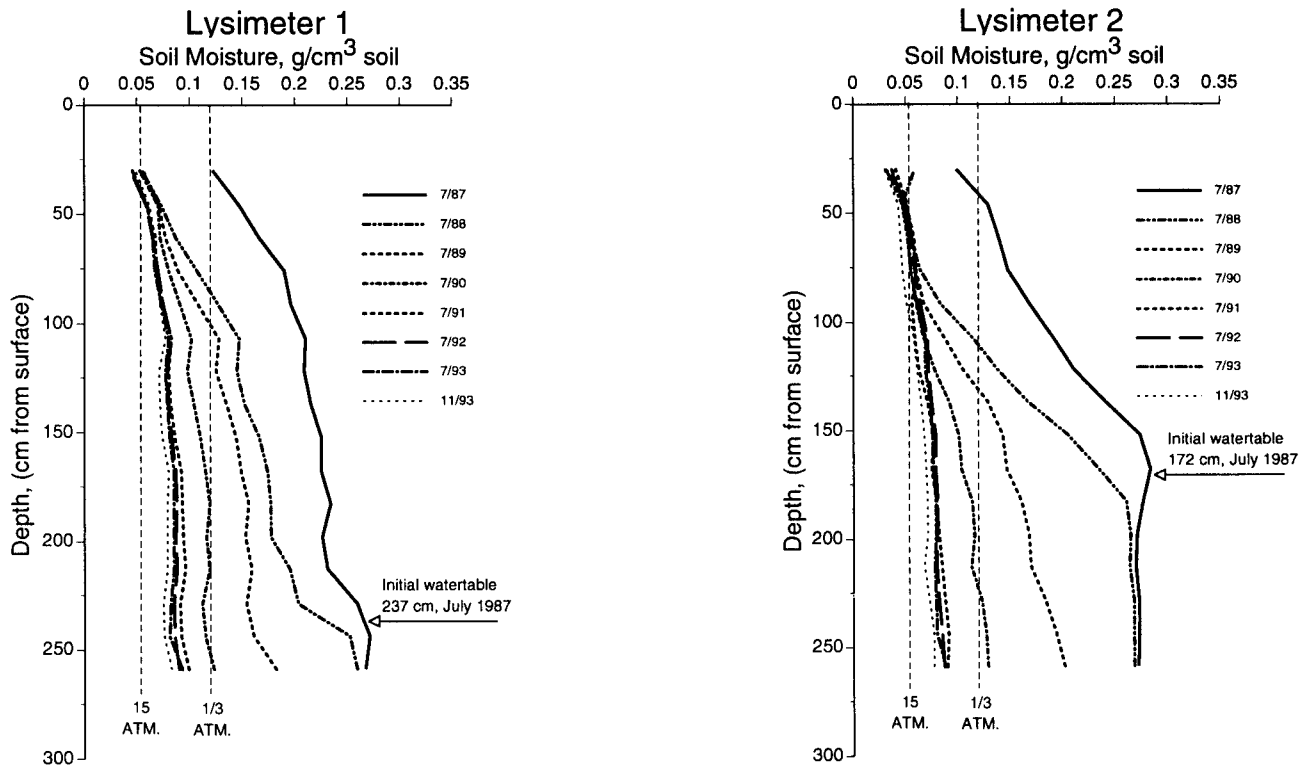


Fig. 11. Bioengineered covers. Volumetric soil moisture content plotted as a function of soil depth at seven different dates. By July, 1989, water table was eliminated from soil profiles. As of November, 1993, all soil profiles, although relatively dry, still showed slightly increasing moisture content with depth.

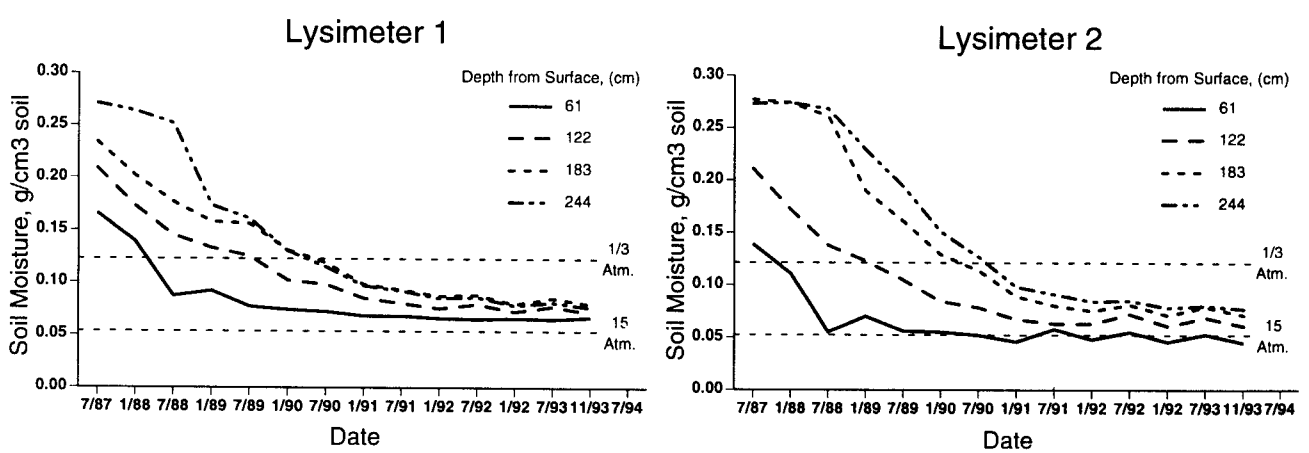


Fig. 12. Bioengineered covers. Volumetric soil moisture content plotted as a function of time at four different soil depths. At the 2-ft level, soil moisture was rapidly depleted during first year of experiment. At 8-ft level,moisture content continued to drop to present. Bioengineered closure would maintain soil over buried waste in "dry," steady-state condition, preventing water from infiltrating to waste, with large safety margin.

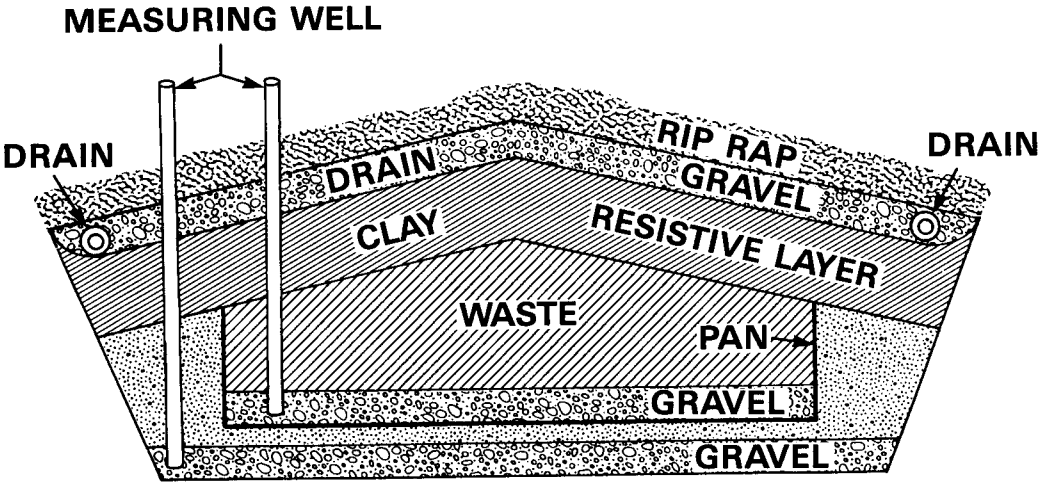


Fig. 13. Resistive-layer barrier with rock cover; no vegetation. Possible UMTRA cover. Possible advantages over vegetated, resistive-layer barrier: (1) Clay layer remains wet and more efficient barrier to escape of radon. (2)Initially, superior erosion protection. (3) No root penetration of waste. Major disadvantage: no plant transpiration, therefore requiring clay barrier of extremely low hydraulic conductivity. For clarity, most instrumentation and some details not shown. Plot (lysimeter) is 70 ft long by 45 ft wide; bottom is 10 ft below grade. Clay layer is 1½-2 ft thick. Slope is 1:5.

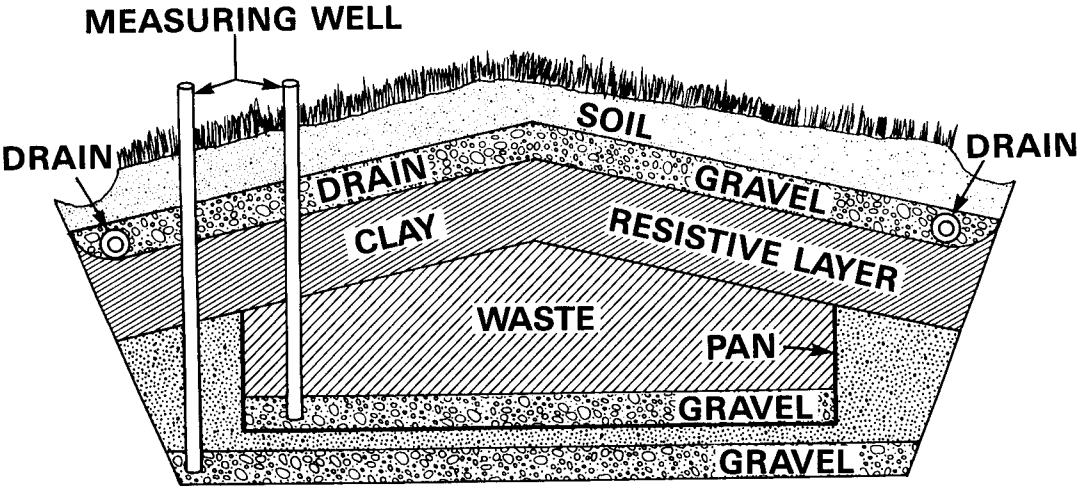


Fig. 14. Resistive-layer barrier with grass cover. Similar to UMTRA cover but has vegetation in place of riprap. See Figure 13.

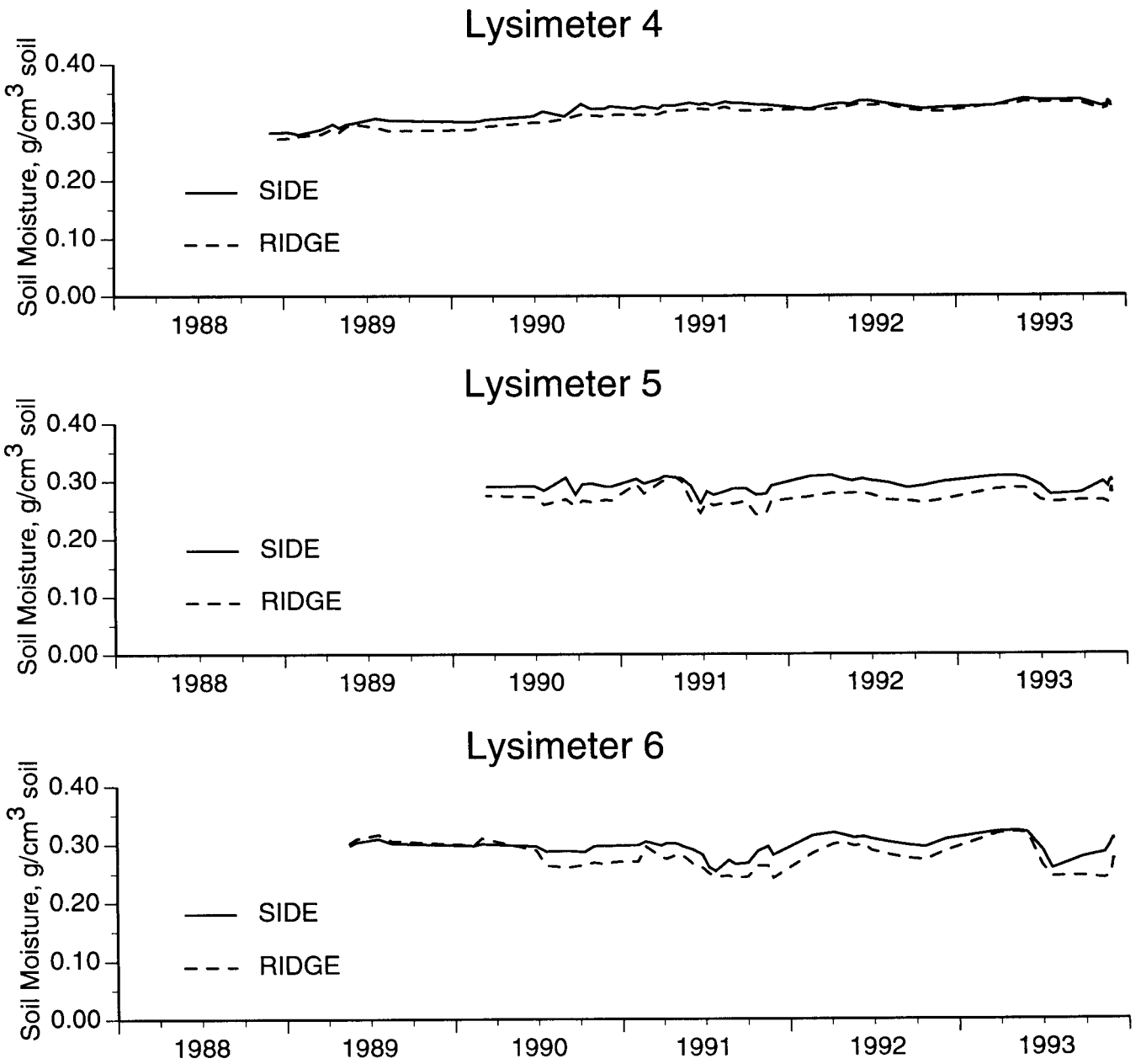


Fig. 15. Moisture content of clay layers with time. Lysimeter 4 cover system is clay layer covered with gravel and riprap. No vegetation is present, and clay shows very slight increase of water content with time. Lysimeter 5 has capillary (conductive-scavenging) layer underneath clay layer; plot is planted with grass. During 4-yr life of plot, largest variations in moisture content were during summer. Lysimeter 6 has clay layer with grass cover. As in lysimeter 5, largest moisture excursions were in summer.

in moisture content has been observed. On the contrary, to date the moisture content of the clay layer seems to be in a rather steady state, taken over the 5 year period of measurement.

Conductive Layer Barrier

If we consider the case of water flowing downhill in an unsaturated porous medium, we have the case shown in Figure 16. The "holes" shown in the diagram could be a rock layer, affording a capillary break or capillary discontinuity (Figure 17). Under appropriate conditions, water everywhere in these cross-sections will be under tension, and there will be no leakage. This might then serve as an excellent means of protecting waste by conducting water around the waste. Figure 16 simulates a conducting porous medium, such as a fine sandy loam soil, lying smoothly on top of a rock layer. Problems with water flow under saturated conditions could certainly arise where a less than smooth surface ends up being constructed as depicted in Figure 18. That is, what happens if imperfections are constructed so that "pockets" of soil extend down into the rock layer? Figure 18 represents that case. Again, there will be no leakage, provided conditions are such that the water in all parts of the conductive layer remains under tension.

The big question is, can conditions required to maintain the necessary soil water tension be practically maintained while using this procedure to effectively protect waste disposal units? To answer this question the apparatus schematically depicted in Figure 19 was constructed, i.e., a "soil beam." Several miniature soil beams (Figure 20) were constructed for use in the laboratory so that a variety of candidate conductive-layer materials could be quickly evaluated.

A number of materials were evaluated using the miniature soil beams. It was quickly established that it would be necessary to construct a resistive layer barrier above the conductive layer barrier to have a practical system. The standard was set that the resistive layer barrier have an easily achievable conductivity of not greater than 10^{-6} cm/sec. On this basis it was found that material such as fine sandy loam could provide an effective conductive layer barrier, that is, conduct around the waste 100% of water percolating through the resistive layer. However, the measurements showed that such materials would not provide the desired (factor of 10) safety margin.

Further investigations turned up a material, diatomaceous earth, that would fit these requirements. Measurements of tension vs. distance of flow are shown in Figure 21.

The results of this experiment in the 4.5 ft long beam suggest that, as long as the flow rate is no greater than 4.2 $\times 10^{-4}$ cm/sec, the soil water will remain under tension regardless of the soil beam length. These results show that with the use of diatomaceous earth for the conductive layer and following the easily achievable standard set above for the resistive layer, it should be possible to construct a barrier that would allow no water leakage to a waste disposal unit. However, before final selection of the diatomaceous earth as the conductive layer material, we believed it to be prudent to conduct tests in a

FLOW UNDER NEGATIVE MATRIC POTENTIAL

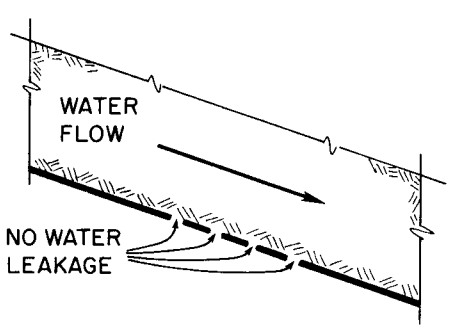


Fig. 16. Water flow in an unsaturated porous medium. A drop of water placed at one of holes shown wouldflow upward into soil.

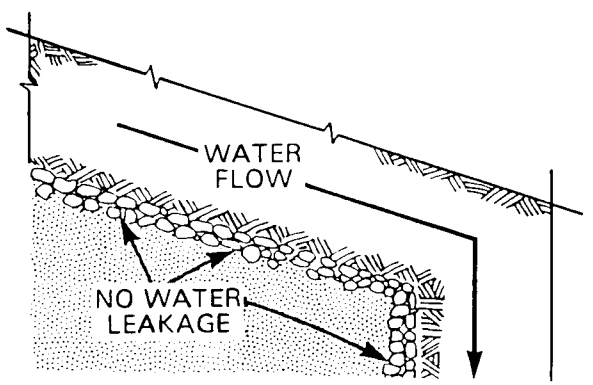


Fig. 17. Substitution of rock layer for holes shown in Figure 16. Voids between rocks act exactly like holes shown in Figure 16. They form capillary discontinuity, preventing leakage downward under influence of gravity.

FLOW UNDER NEGATIVE MATRIC POTENTIAL

CONDUCTIVE LAYER IMPERFECTLY CONSTRUCTED

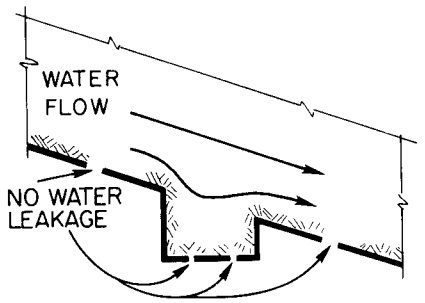


Fig. 18. Imperfectly constructed conductive layer with "pocket" extending down into rock (or capillary break) layer. No leakage if conditions required to maintain tension are met.

WATER PRESSURE DISTRIBUTION (VERTICAL)

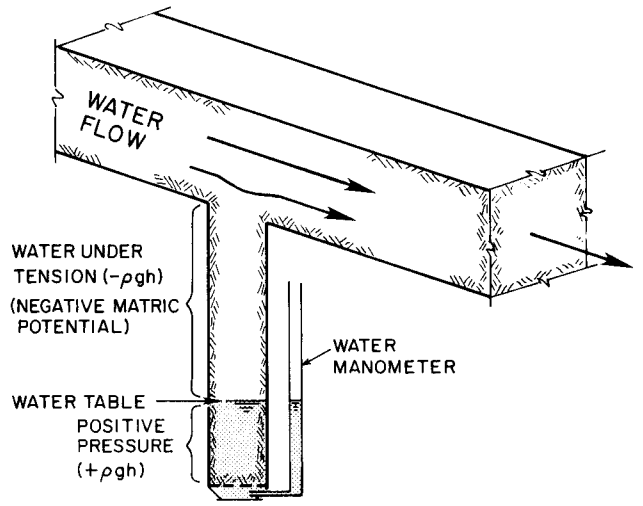


Fig. 19. Schematic of laboratory apparatus for measurement of water tension,using different materials and varying flow rates.

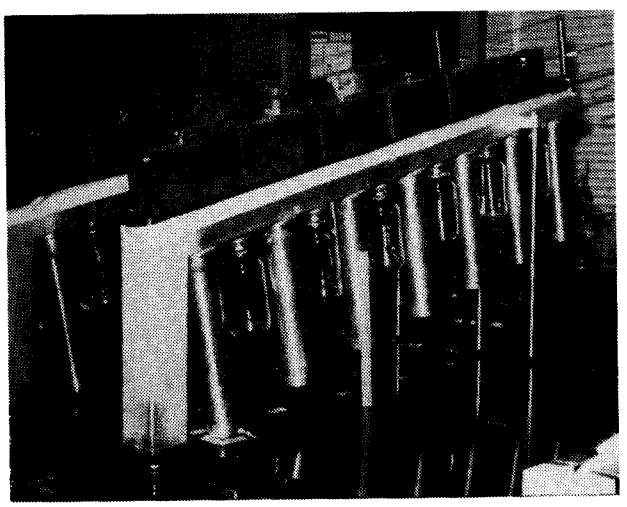


Fig. 20. Miniature soil beam used for evaluation of materials for possible use in conductive-layer barrier application. Soil beam has total length of 4.5 ft. Lead bricks were placed on top of test material to simulate overburden.

SOIL WATER TENSION AT VARIOUS FLOW RATES, (cm/sec)
TENSION vs HORIZONTAL DISTANCE FROM DISCHARGE POINT

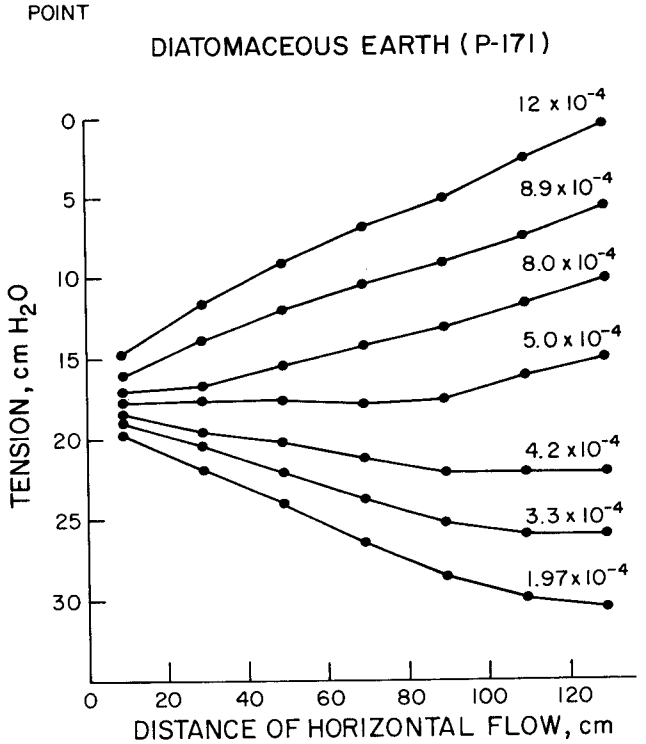


Fig. 21. Soil water tension at various flow rates, measured in miniature soil beam shown in Figure 20. Tension vs. horizontal distance from discharge point. Results suggest that,at 4.2×10^{-4} cm/sec or less, water would remain under tension at any beam length. Slope of beam is 1:5.

large-scale soil beam. The large beam, shown in Figure 22, has a soil beam length of 21 ft. As shown in Figure 23, a matric potential of about -15 to -20 cm of water is maintained over the entire 21 ft length of the beam when the flow rate does not exceed 3.1×10^{-4} cm/sec.

The studies carried out in the large soil beam closely confirmed the data obtained in the miniature beam. Accordingly, diatomaceous earth was used as the conductive layer material in the demonstration lysimeter (lysimeter 5). It has been estimated that purchasing and shipping the diatomaceous earth to a job site any place in the United States will add about \$0.50 per ft^3 of disposed waste. This is over the cost of using locally obtained soil, and based on waste being 10 ft deep.

Fig. 22. Large soil beam used for final selection of diatomaceous earth as conductive-layer material. Lead bricks were placed on top of diatomaceous earth to simulate overburden.

After the time-consuming task of selecting the conductive layer material was accomplished, a resistive layer barrier over a conductive layer barrier was constructed in lysimeter 5. It was completed in January, 1990. A local clay from Beltsville, Maryland, the Christiana Clay, was selected as the resistive layer barrier. Testing has shown this material more than meets specifications. A cross-section of the cover system is shown in Figure 24.

Performance of this cover is shown in Figures 9 and 15 (lysimeter 5). It has proven to be 100% effective in preventing water movement downward through the cover.

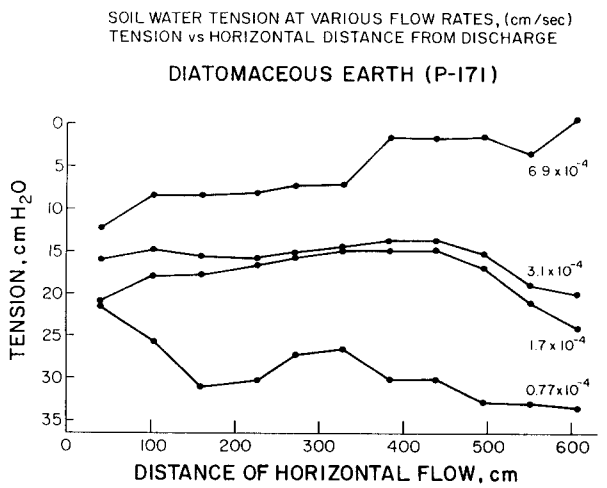


Fig. 23. Soil water tension at various flow rates, measured in large soil beam shown in Figure 22. That beam is 21 ft long and has slope of 1:5. At -15 to -20 cm, matric potential water flow rate is approximately 3×10^{-4} cm/sec. At this rate, unsaturated flow can be maintained over an infinite distance, confirming results of soil beam measurements (Figure 21).

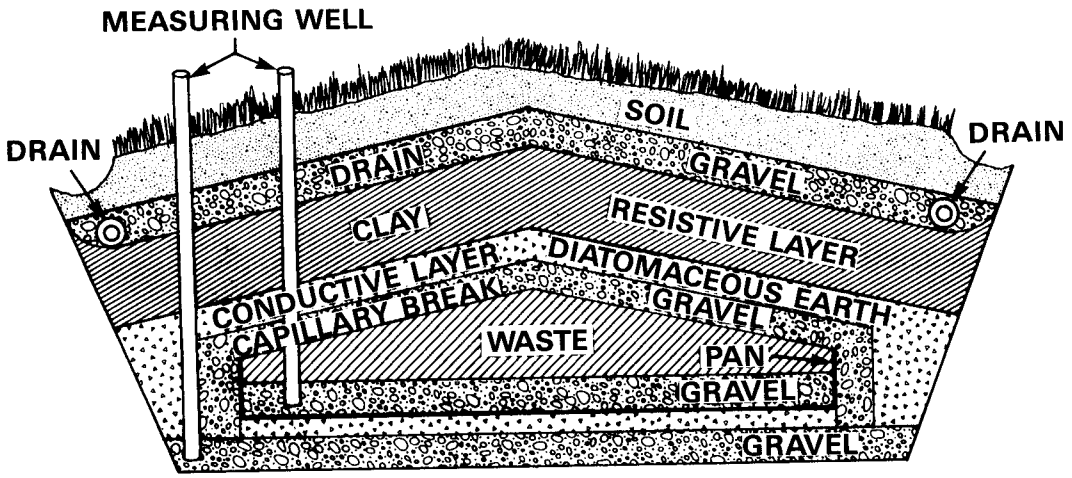


Fig. 24. Combination resistive-layer barrier over a conductive layer barrier. Clay-barrier (resistive layer barrier) needs only to protect to approximately 10^{-6} cm/sec. Conductive-layer barrier of diatomaceous earth readily transports percolating water around waste.

Further Studies of Conductive-Layer Materials

For The Beltsville study, diatomaceous earth was selected for the conductive-layer material, based both on performance and cost considerations. Based on these two considerations only, diatomaceous earth would still be the material of choice, particularly since it has a much lower bulk density than sand and is therefore less expensive to ship. However, the engineering properties of sand are better known, thus sand may be more attractive to some installers. Therefore, we have been conducting further studies with various sands. Results of studies of the unsaturated flow characteristics of four different sands are given in Figure 25. All these sands exhibit unsaturated flow rates that are about twice that of the diatomaceous earth at any given negative matric potential. The particle size distribution of the four sands is given in Table 3. The mortar sand, for example, had the narrowest particle size range, and the foundry sand had the widest particle size distribution, although the particle size distribution did not have an important effect on the flow rates reported in Figure 25. The Nevada dune sand and the Kelso dune sands are from large eolian deposits in the Nevada and California deserts, respectively. The Kelso deposit has been mined commercially. This work on the unsaturated flow characteristics of various materials is ongoing. Hydraulic properties will be studied over a larger range of matric potentials, further deposits will be located and investigated, and these investigations will be described in a future report.

APPLICATION

The three procedures described in the Introduction may be used singularly or in combination to protect disposal units from percolating water. The principles apply equally to above-ground or below-ground disposal. For example, a combination of covers (1) and (2), described in the Introduction, could be ideal for a stabilized, shallow land burial facility, whether it is above or below ground; e.g., the subsurface disposal could be in below-ground vaults, and the above-ground disposal units could be earth-mounded concrete bunkers. A combination of a resistive layer over a conductive layer in a concrete bunker or above-ground application is shown in Figure 26. The resistive (clay) layer is the primary barrier. The small amount of water passing through the clay layer will be diverted around the concrete bunker by the conductive layer. This cover over the concrete bunker can, in theory, be 100% effective, shielding the bunker from exposure to flowing water. This would result in a film of stagnant alkaline water at the gravel/concrete interface. The presence of this high pH, stagnant water would tend to protect the concrete from degradation over a long period. A resistive layer above must leak somewhat due to the imperfections in construction when using compacted porous material (clay).

Table 3. Particle size distribution of the four sands used in unsaturated flow studies reported in Fig. 24.

Nevada Dune Sand			
US Mesh	Size (microns)	% Retained, Per Sieve	% Retained, Cumulative
30	600	1.8	1.8
45	335	24.2	26.0
80	180	47.2	73.2
140	106	24.9	98.1
200	75	1.5	99.6
230	63	0.1	99.7
Pan	<63	0.3	100.0

Kelso Dune Sand			
US Mesh	Size (microns)	% Retained, Per Sieve	% Retained, Cumulative
30	600	0.0	0.0
45	335	13.7	13.7
80	180	61.0	74.7
140	106	20.5	95.2
200	75	2.4	97.6
230	63	0.0	97.6
Pan	<63	2.4	100.0

Mortar Sand			
US Mesh	Size (microns)	% Retained, Per Sieve	% Retained, Cumulative
30	600	0.7	0.7
45	335	9.2	9.9
80	180	76.6	86.5
140	106	11.5	98.0
200	75	0.6	99.6
230	63	0.0	99.6
Pan	<63	1.4	100.0

Foundry Sand, MX65			
US Mesh	Size (microns)	% Retained, Per Sieve	% Retained, Cumulative
30	600	1.7	1.7
40	425	9.2	10.9
50	300	20.9	31.8
70	212	26.5	58.3
100	150	24.7	83.0
140	106	12.1	95.1
200	75	1.7	96.8
270	53	3.1	99.9
Pan	<53	0.1	100.0

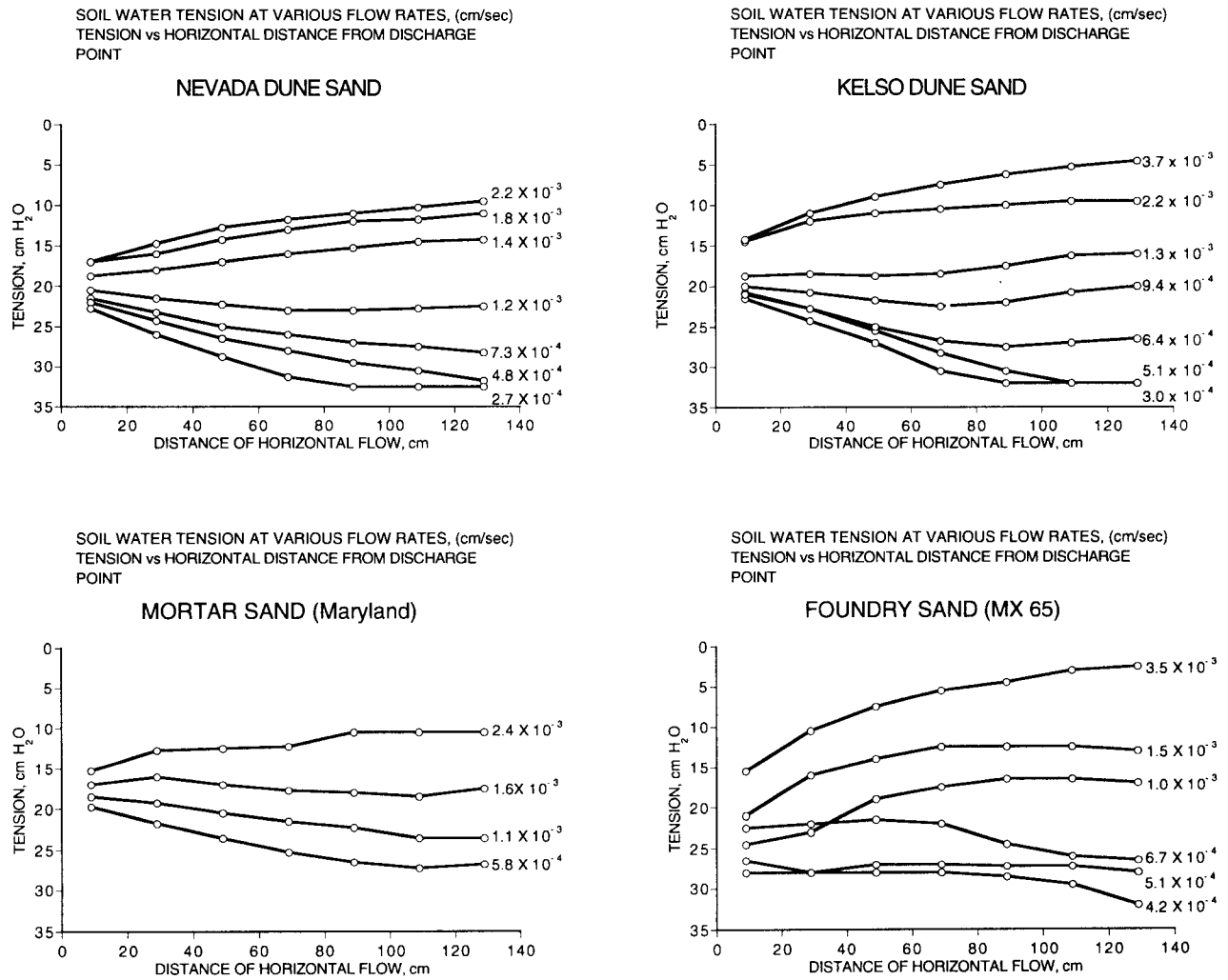


Fig. 25. Unsaturated flow characteristics of four sands. Soil water tension at various flow rates, measured in miniature soil beam shown in Figure 20. Tension vs. horizontal distance from discharge point. Results suggest that, at about 10^{-3} cm/sec or less, water would remain under tension at any beam length. Slope of beam is 1:5.

The bioengineering concept could be advantageous for either a tumulus or shallow land burial unit that would be likely to exhibit subsidence. If desired, and after subsidence has ceased, a combination of covers (1) and (2) could be constructed with geological materials to give extremely long-term isolation without further maintenance. Another possible application of a combination of covers (1) and (2) described in the Introduction is shown in Figure 27. Here, high-level waste is emplaced in a tunnel excavated in rock. If a fracture were present in the rock, and fracture flow occurred, the combination of a resistive layer and a conductive layer could provide excellent isolation of the waste from flowing water. Figure 28 depicts an application where only very low flow rates need be protected against (essentially, dropwise fracture flow). Here, the system could be simplified so that only a conductive layer with a capillary break is necessary.

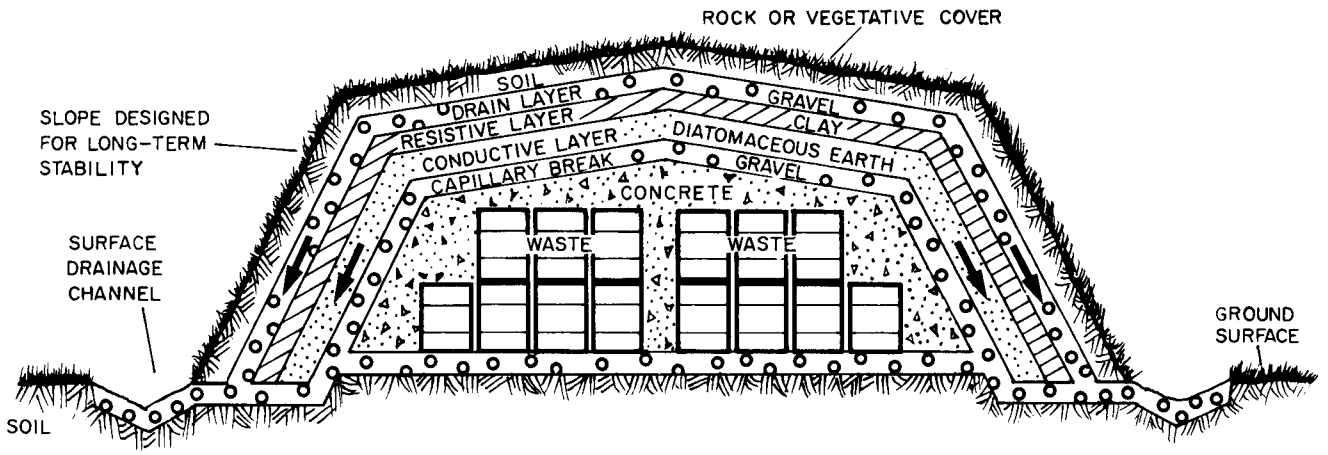


Fig. 26. Resistive-layer barrier overlaying a conductive-layer barrier as might be used with an earth-mounded concrete bunker. Resistive (clay) layer is primary barrier to water passage downward. Conductive layer (diatomaceous earth) scavenges and conducts any water percolating through clay layer around concrete structure to drains. Diatomaceous/gravel interface is capillary break. Concrete is exposed only to a stagnant, alkaline film of water, greatly retarding degradation of concrete over time. Only geological materials already over 1 million yr old are used in construction, other than concrete, so life of cover will far exceed that of concrete, even though this cover system can be expected to significantly increase structural life of concrete.

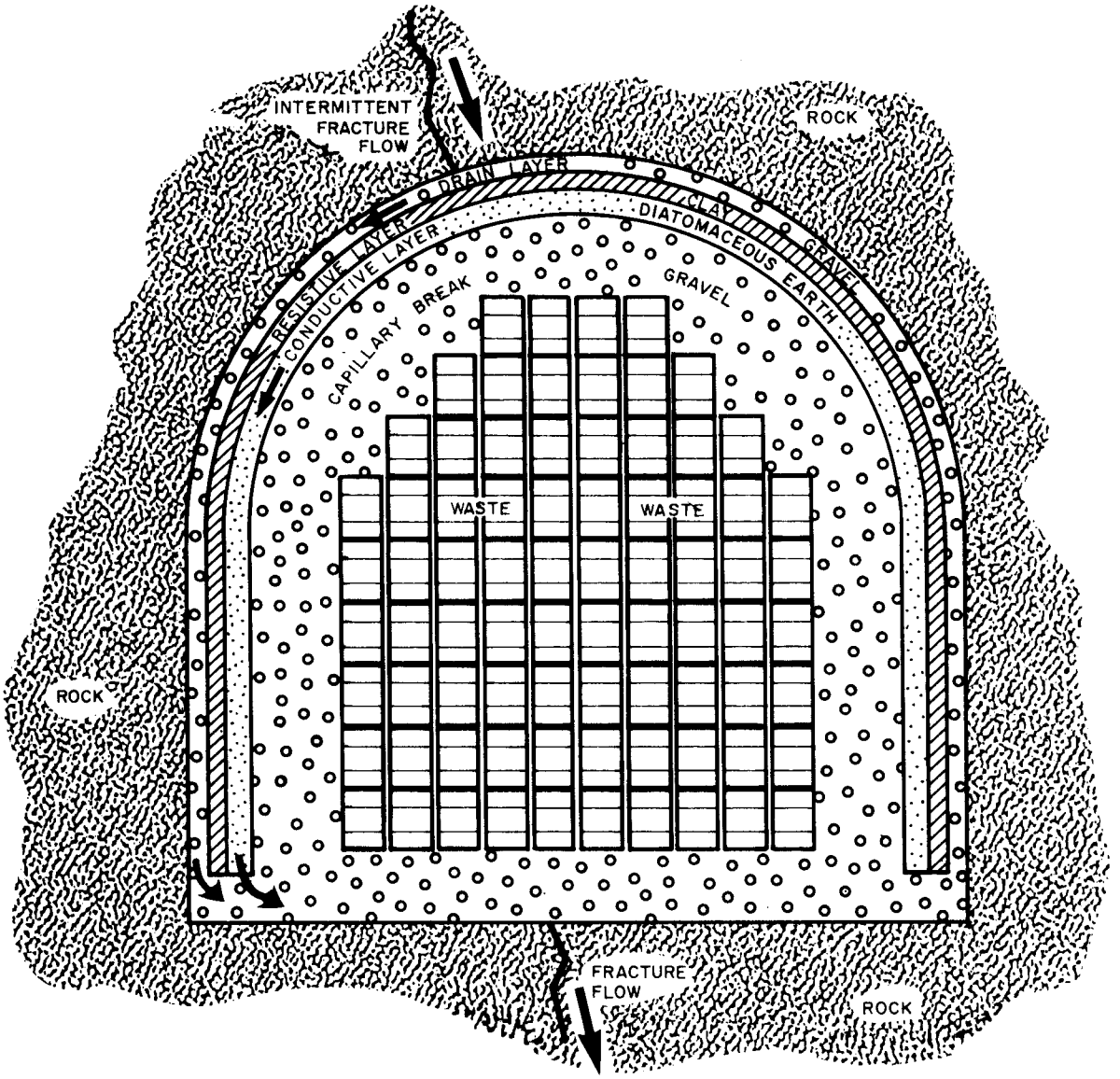


Fig. 27. Artist's concept of resistive and conductive layer barriers to protect high-level waste from water flowing through rock fracture. Resistive (clay) layer diverts almost all fracture flow water. Conductive layer (very fine sand or diatomaceous earth) scavenges small quantities of water that pass through clay layer. Conductive layer transports scavenged water, under tension, around waste.

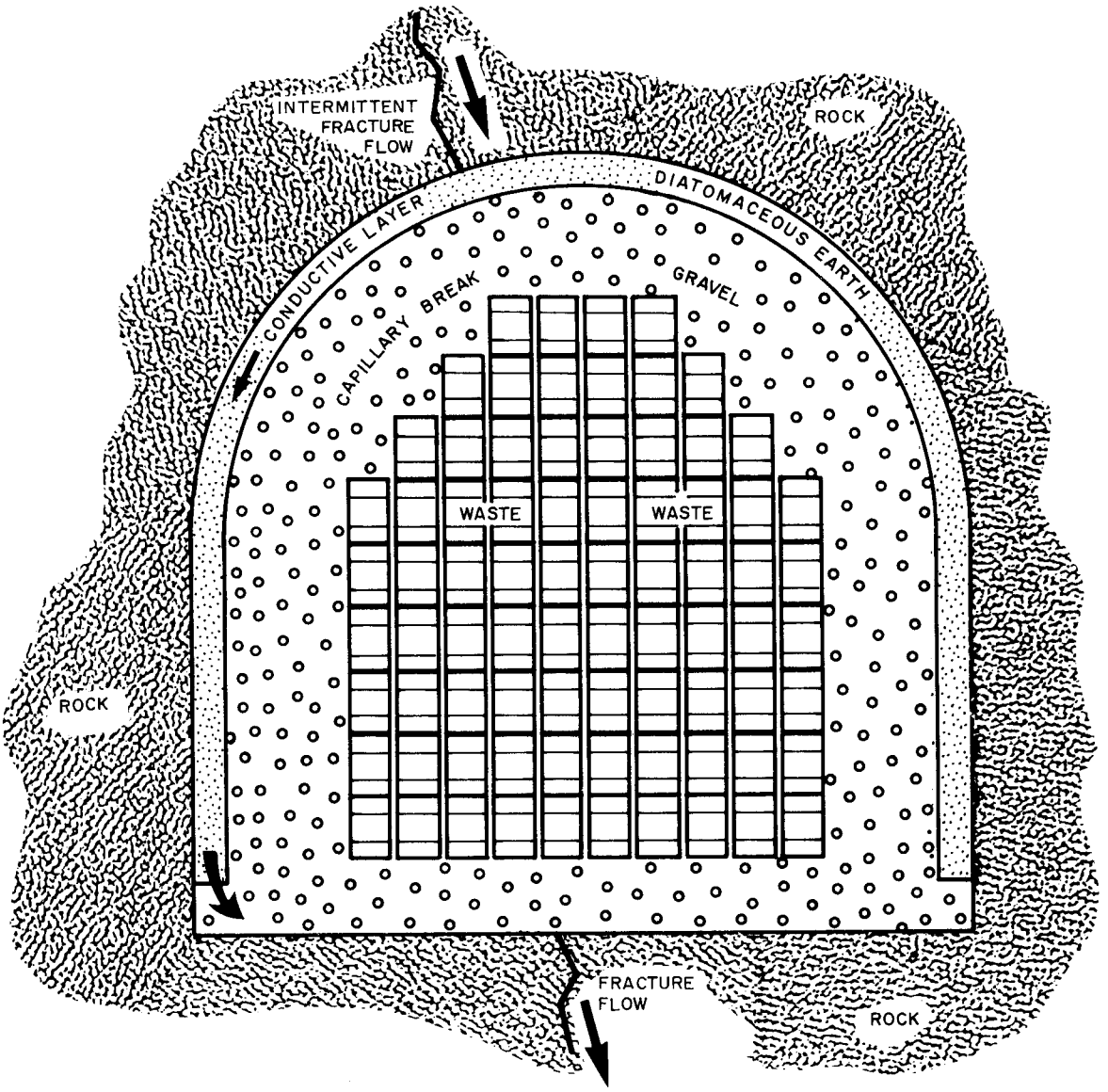


Fig. 28. Simplified case of Figure 27. If fracture flow is slow conductive layer transports all water around waste; clay layer is then not needed.

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

The project objective is to assess means for controlling waste infiltration through waste disposal unit covers in humid regions. Experimental work is being performed in large scale lysimeters (70'x45'x10') at Beltsville, MD and results of the assessment are applicable to disposal of LLW, uranium mill tailings, hazardous waste, and sanitary landfills. Three concepts are under investigation: (1) resistive layer barrier, (2) conductive layer barrier, and bioengineering water management. The resistive layer barrier consists of compacted earth (clay). The conductive layer barrier is a special case of the capillary barrier and it requires a flow layer (e.g. fine sandy loam) over a capillary break. As long as unsaturated conditions are maintained water is conducted by the flow layer to below the waste. This barrier is most efficient at low flow rates and is thus best placed below a resistive layer barrier. Such a combination of the resistive layer over the conductive layer barrier promises to be highly effective provided there is no appreciable subsidence. Bioengineering water management is a surface cover that is designed to accommodate subsidence. It consists of impermeable panels which enhance run-off and limit infiltration. Vegetation is planted in narrow openings between panels to transpire water from below the panels. This system has successfully dewatered two lysimeters thus demonstrating that this procedure could be used for remedial action ("drying out") existing water-logged disposal sites at low cost.

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hazardous waste disposal
toxic waste disposal
sanitary landfill
hydrology
capillary barrier
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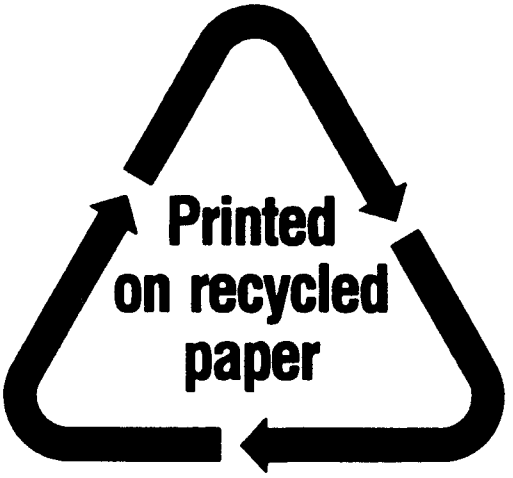

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