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Control of Water Infiltration Into Near Surface LLW Disposal Units

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 21.34 m x 13.72 m x 3.05 m (70 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 should 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 tritiated water), and those present in anionic form or neutral complexes, will essentially move with the flow of water; others, present as 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**

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 Fig. 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.

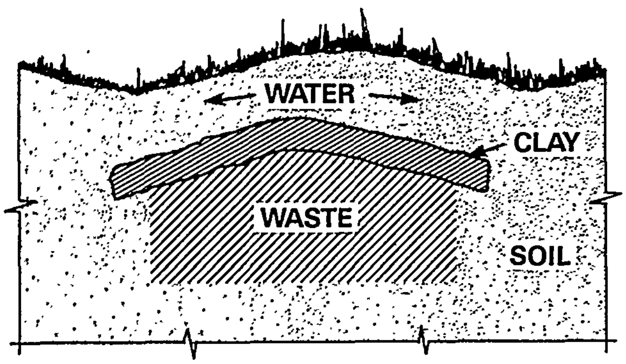


Fig. 1. Resistive layer barrier.

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 Fig. 2.

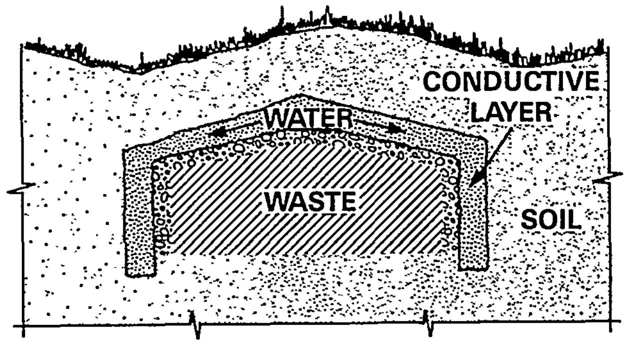


Fig. 2. Conductive layer barrier.

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 Fig. 3.

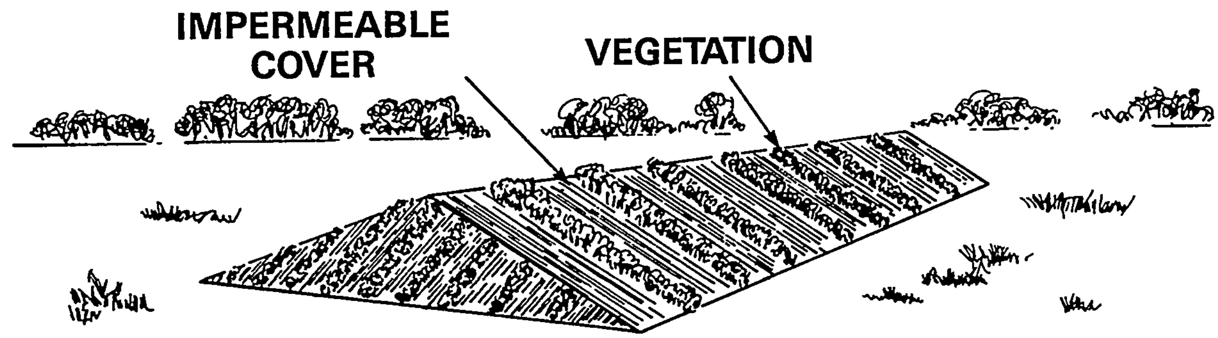
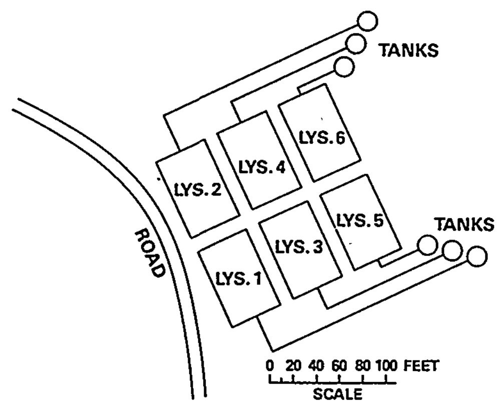


Fig. 3. Bioengineering management.

EXPERIMENTAL AND DEMONSTRATION

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

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 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 seasonal 1985–1986 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 (Fig. 4). Figure 5 is a photograph of lysimeter 1, bioengineering management, taken in January, 1996, nine years after planting of the Pfitzer junipers. Alternating panels of aluminum and fiberglass were used as the hard cover. These plots, or lysimeters, are 21.3 m (70 ft) long by 12.7 m (45) ft wide, and the bottoms are 3.05 m (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 Fig. 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 Fig. 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 Fig. 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 I gives the run-off, evapotranspiration, and deep percolation in the bioengineered plots during the past 8 years. There was no deep percolation during this period. Until seasonal 1993-1994 the evapotranspiration had been rising annually, probably as a result of the greater vegetative canopy intercepting a greater percentage of the precipitation. In 1988, 1989, 1990, 1991, 1992, 1993 and 1994 the run-off percentages were 80, 74, 70, 67, 63, 61 and 61 respectively (7). In 1995, the runoff decreased to 58% of the precipitation. During 1989, the water table was completely eliminated in both plots (Fig. 8).

Table I. 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
1994	61	39	0
1995	58	42	0

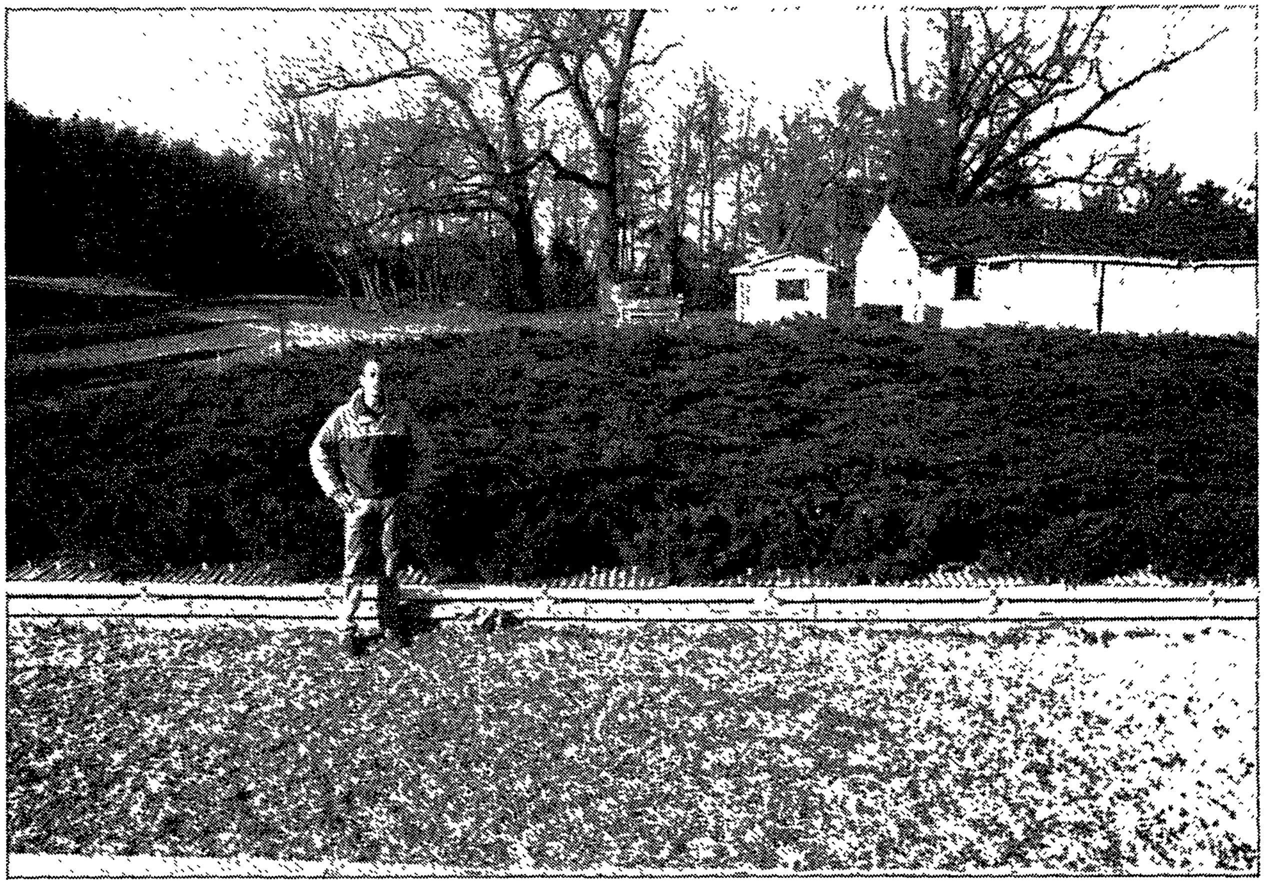


Fig. 5. Bioengineering plots at Beltsville, Maryland. Photo taken in January, 1996, 9 yr after planting Pfitzer junipers. Run-off is 58% of precipitation, evapotranspiration is 42% of precipitation; there is no deep percolation.

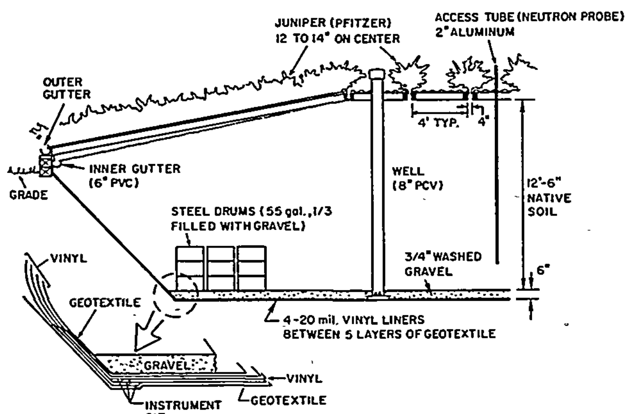


Fig. 6. Side view of bioengineered lysimeter. Surface run-off is collected from both engineered surface and soil surface. Soil moisture content measured with neutron probe. Water table is measured in well.

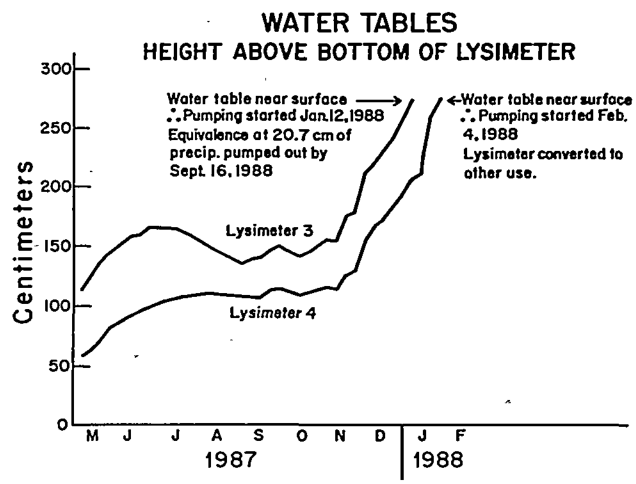


Fig. 7. Water table vs. time in reference lysimeters. Crowned surface is planted with fescue grass. Water table increased with time until pumping was necessary to keep trench from running over. Surface run-off was 8% of precipitation.

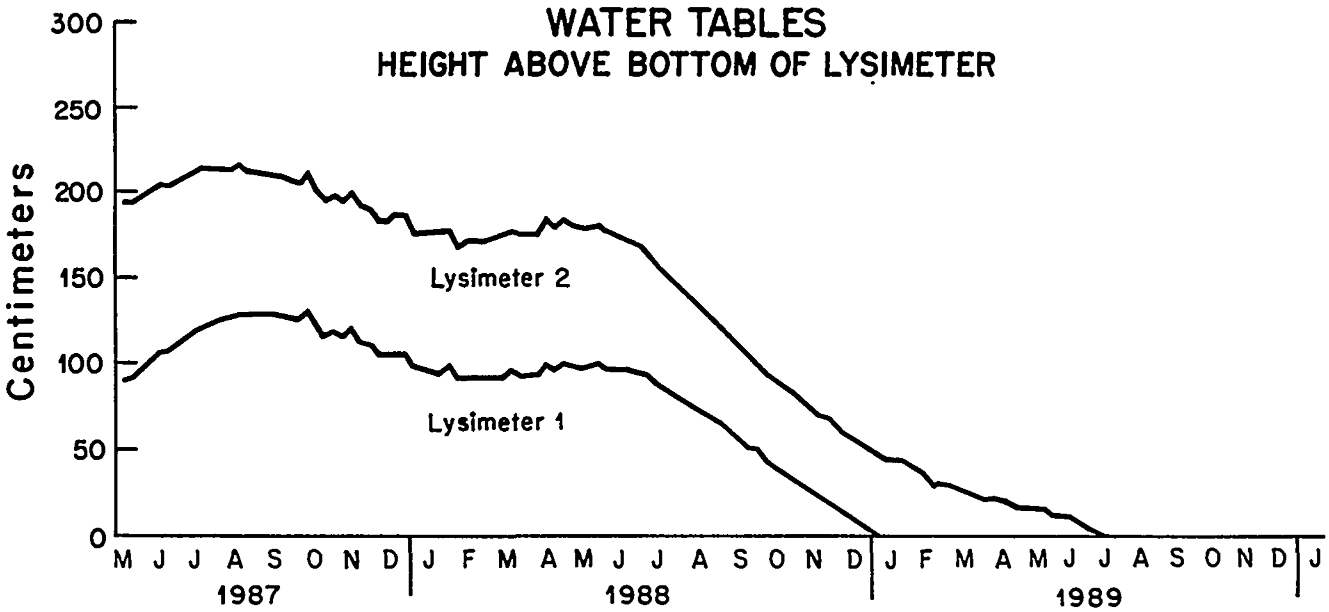


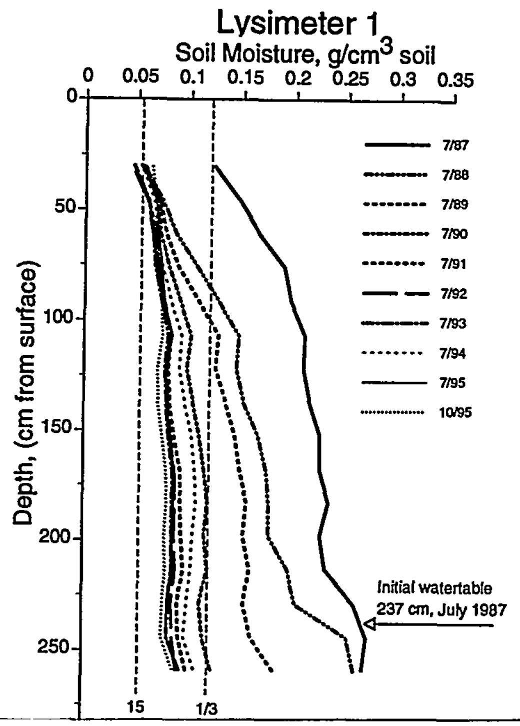
Fig. 8. Water table vs. time in bioengineered lysimeters. Decline of water-table levels with time shows bioengineered covers effectively prevented water percolation. Elimination of water table shows that this procedure could be used for remedial action ("drying out") of existing water-logged burial sites.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

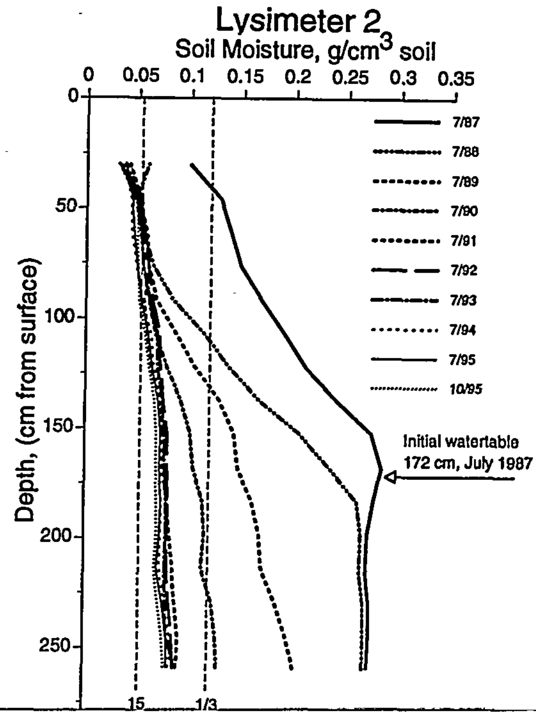
In addition to rainfall, run-off, and evapotranspiration measurements discussed above, neutron-probe soil-moisture measurements have been made continuously to monitor soil moisture changes in all six lysimeters depicted in Fig. 4. The neutron probe measurements will indicate whether there is a gain or 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. 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. Six hundred and twenty-eight kilograms (1400 lbs) of soil were placed in a weighing lysimeter, and measurements were made over a eight year period. Calibration data obtained using the weighing lysimeter are given in Table II. The resulting curves, depicting the factory calibration and the weighing lysimeter calibration, are given in Fig. 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 Fig. 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 ten 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 depth until 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 October, 1995, although the soil profile had become still drier.

Figure 12 shows the moisture content of the soil profiles in lysimeters 1 and 2 at the end of each seasonal year. Following the complete removal of the water tables during the 1987-1989 period, the soil profiles were dried out further during the ensuing years. However, an unanticipated result turned up in lysimeter 1 at the end of seasonal 1993-1994. The moisture content of the soil profile increased slightly. To shed light on that result, the moisture content in the soil profiles at four depths were plotted monthly along with monthly rainfall data (Fig. 13). Here we see seasonal cyclical variations in moisture content in the soil profiles, with peak moisture concentrations occurring in the early spring, following periods of significant rainfall and minimal evapotranspiration. That cycling is both obvious and expected.





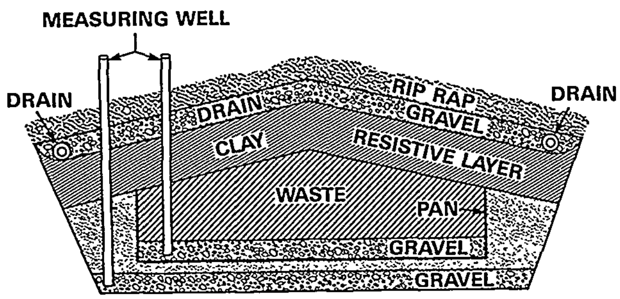
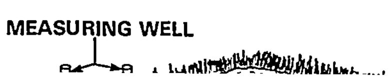


Fig. 14. Resistive-layer barrier with rock cover; no vegetation. Possible UMTRA cover. Possible advantages over vegetated, resistive-layer barrier: (1) Clay layer remains wet and more efficient barrier to escape of radon. (2) Initially, superior erosion protection. (3) No root penetration of waste. Major 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 21.34 m (70 ft) long by 13.72 m (45 ft) wide; bottom is 3.05 m (10 ft) below grade. Clay layer is 46-61 cm (1½-2 ft) thick. Slope is 1:5.



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 16 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 would occur in the future. That first leakage occurred during the past year, seasonal 1994-1995. Lysimeter 6 has a clay layer and a grass cover. In this case, no increase 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 7 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 Fig. 17. The "holes" shown in the diagram could be a rock layer, affording a capillary break or capillary discontinuity (Fig. 18). 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 18 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 Fig. 19. That is, what

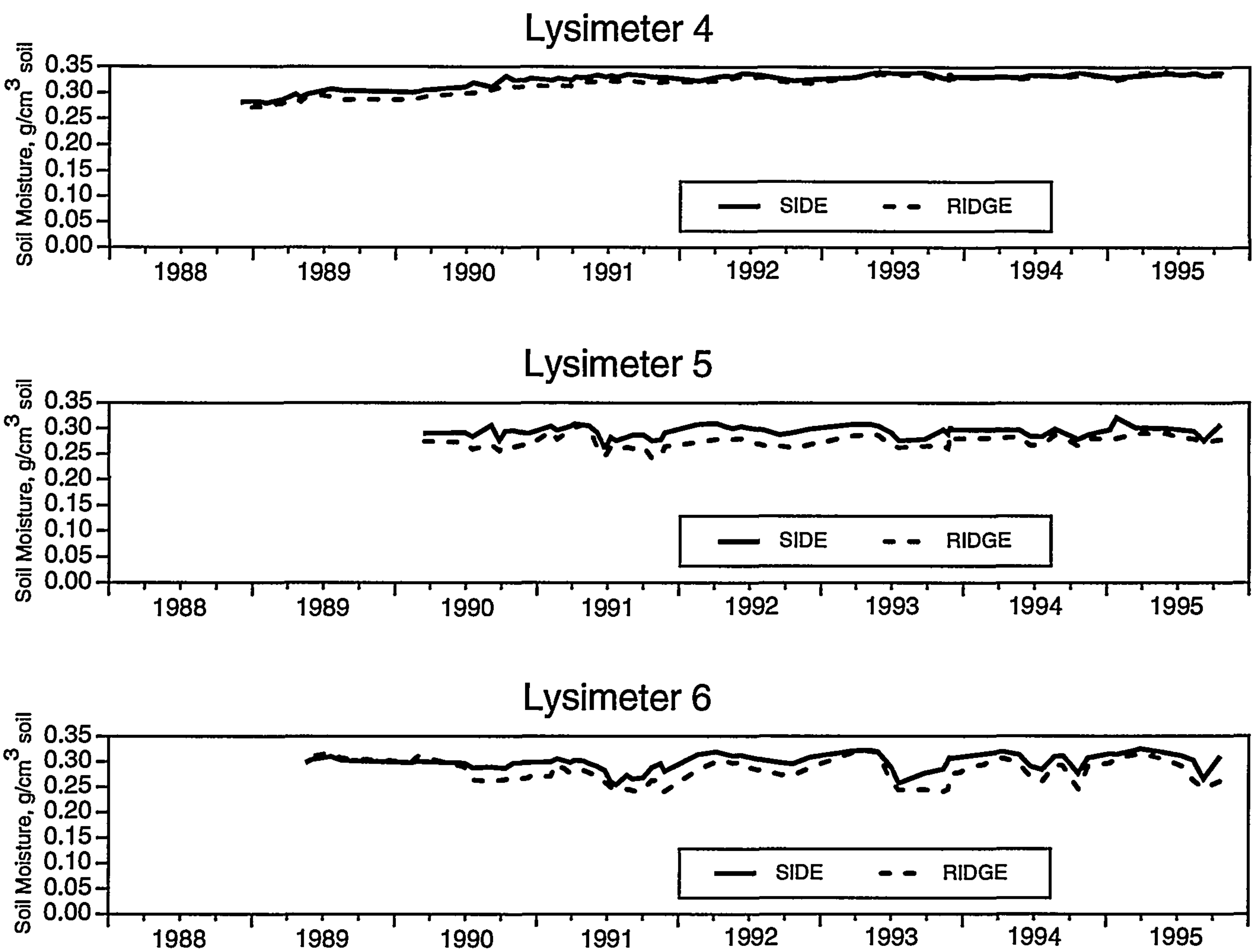


Fig. 16. Moisture content of clay layers with time. Lysimeter 4 cover system is a clay layer covered with gravel and rip-rap. No vegetation is present, and clay shows a very slight increase of water content with time. Lysimeter 5 has a capillary (conductive-scavenging) layer underneath clay layer; plot is planted with grass. During six-year life of plot, largest variations in moisture content were during summer. Lysimeter 6 has clay layer with a grass cover. As in lysimeter 5, largest moisture excursions were in summer.

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 Fig. 22.

The results of this experiment in the 137 cm (4.5 ft) long beam suggest that, as long as the flow rate is no greater than 4.2×10^{-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 large-scale soil beam. The large beam, shown in Fig. 23, has a soil beam length of 6.4 m (21 ft). As shown in Fig. 24, a matric potential of about -15 to -20 cm of water is maintained over the entire 6.4 m length of the beam when the flow rate does not exceed 3.1×10^{-4} cm/sec.

FLOW UNDER NEGATIVE MATRIC POTENTIAL

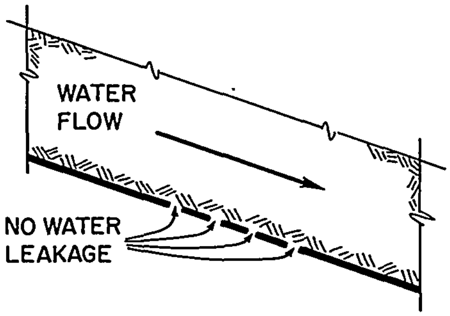


Fig. 17. Water flow in an unsaturated porous medium. A drop of water placed at one of the holes shown would flow upward into the soil.

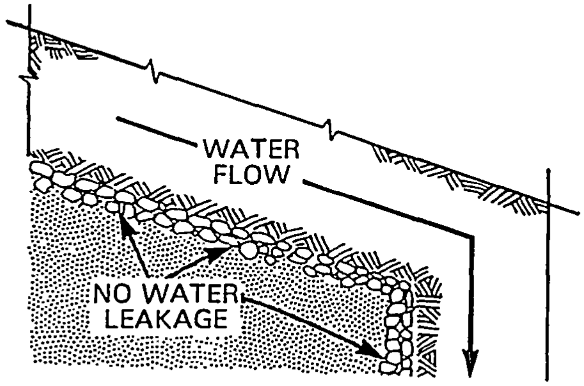


Fig. 18. Substitution of rock layer for holes shown in Fig. 17. Voids between rocks act exactly like holes shown in Fig. 17. They form a capillary discontinuity, preventing leakage downward under the influence of gravity.

FLOW UNDER NEGATIVE MATRIC POTENTIAL

CONDUCTIVE LAYER IMPERFECTLY CONSTRUCTED

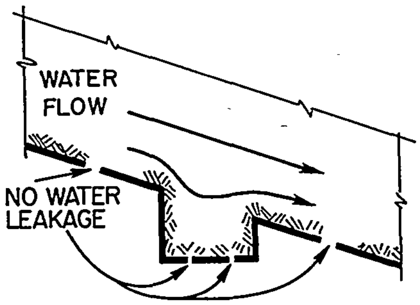


Fig. 19. Imperfectly constructed conductive layer with "pocket" extending down into rock (or capillary break) layer. No leakage if conditions required to maintain tension are met.

WATER PRESSURE DISTRIBUTION (VERTICAL)

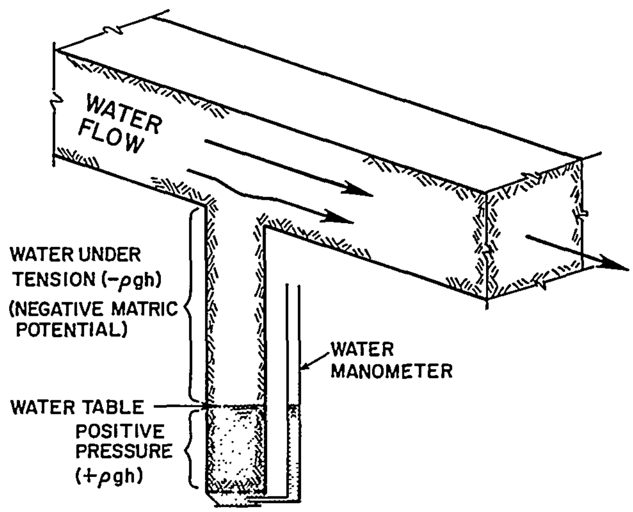


Fig. 20. Schematic of laboratory apparatus for measurement of water tension using different materials and varying flow rates.

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 3.05 m (10 ft) deep.

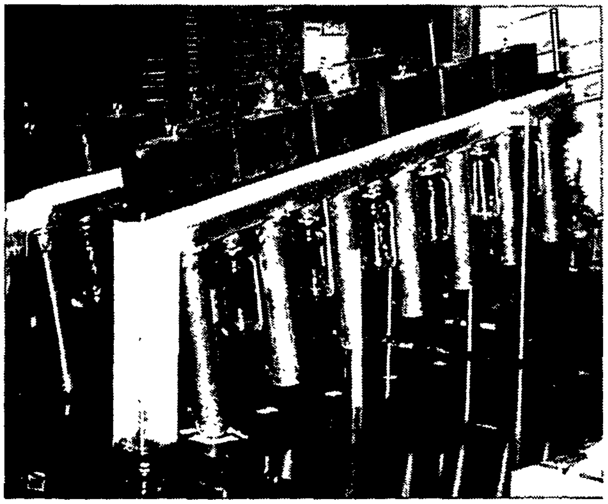


Fig. 21. Miniature soil beam used for evaluation of materials for possible use in conductive-layer barrier application. Soil beam has total length of 137 cm (4.5 ft). Lead bricks were placed on top of test material to simulate overburden.

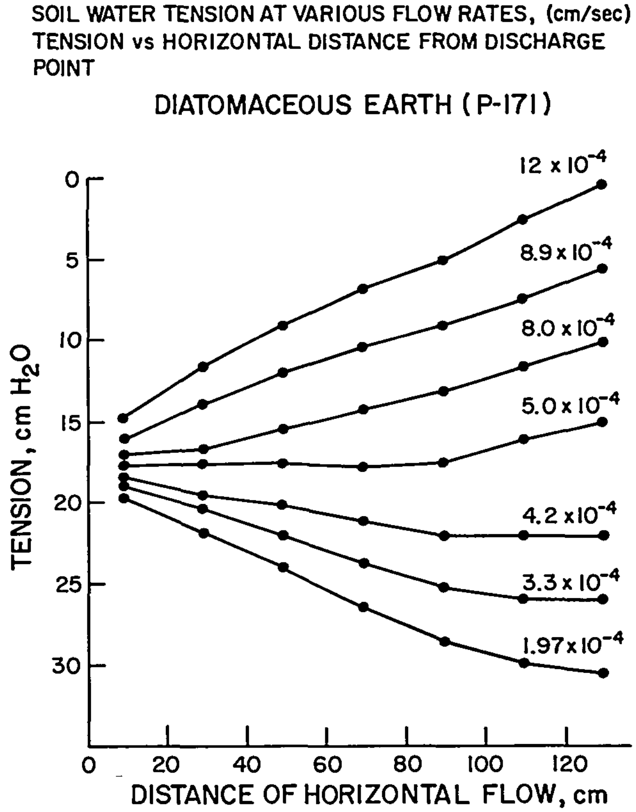


Fig. 22. Soil water tension at various flow rates, measured in miniature soil beam shown in Fig. 21. Tension vs. horizontal distance from discharge point. Results suggest that, at 4.2 × 10^{-4} cm/sec or less, water would remain under tension at any beam length. Slope of beam is 1:5.

Fig. 23. 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.

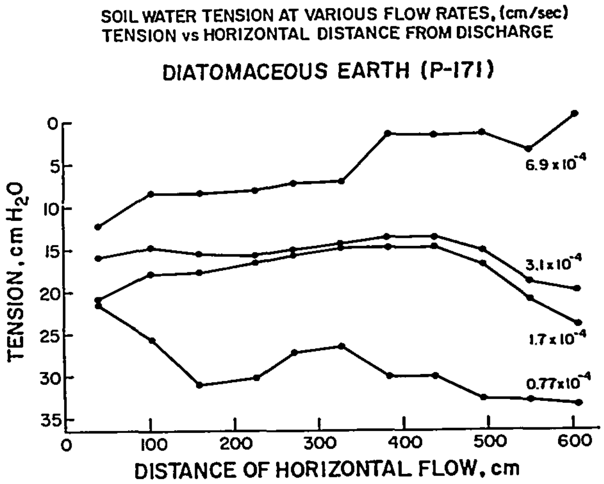


Fig. 24. Soil water tension at various flow rates, measured in large soil beam shown in Fig. 23. That beam is 6.4 m (21 ft) long and has slop of 1:5. At −15 to −20 cm, matric potential water flow rate is approximately 3 × 10^{-4} cm/sec. At this rate, unsaturated flow can be maintained over an infinite distance, confirming results of soil beam measurements (Fig. 22).