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

The 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"45"10') at Beltsville, MD, and 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. They are: (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. 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, a resistive layer barrier/conductive layer barrier system. This latter system would then give long-term effective protection against water entry into waste and 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 to the waste, the cover will be "sensitive," i.e., 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 in the protection of 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 was disposed of in a rock formation with a fracture present, this system could be used to divert possible fracture flow water around the waste.

INTRODUCTION

Infiltration of water into the waste is the foremost problem associated with near surface disposal of LLW. Up to this time, disposal unit covers have generally been constructed from soil materials. In the 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, and 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 this work to examine and demonstrate various approaches of 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.

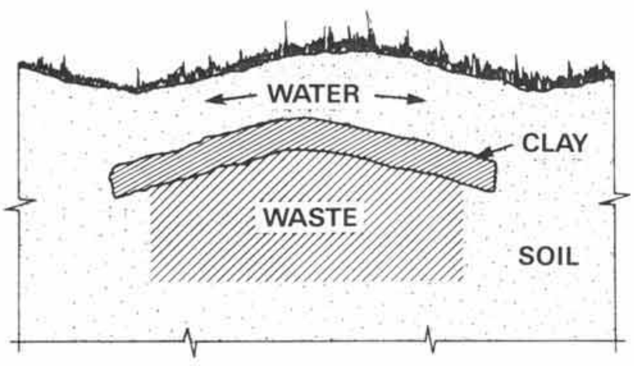


Fig. 1. Resistive layer barrier.

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.

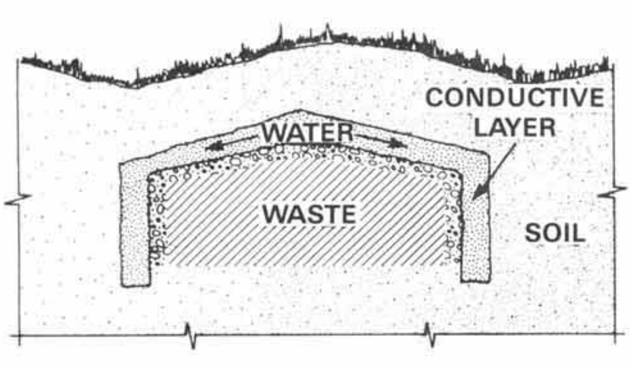


Fig. 2. Conductive layer barrier.

This system consists of a porous medium underlain 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 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-of 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.

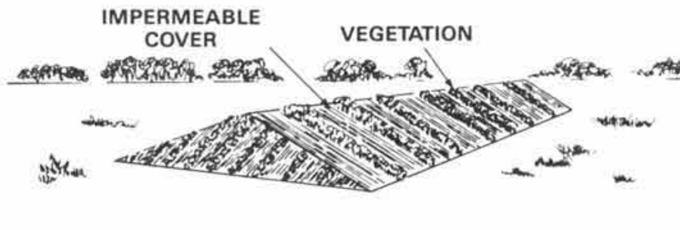
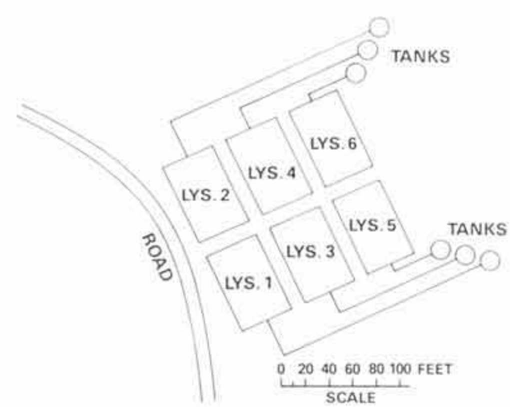


Fig. 3. Bioengineering management.

EXPERIMENTAL AND DEMONSTRATION

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

Bioengineering Management

Bioengineering management is a procedure where the necessary run-off is provided by features installed at or above the soil surface rather than within the profile. The procedure has been described by Schulz et al. (4) and was designated bioengineering management. The principal advantage of the bioengineering management system is that subsidence can be easily managed by relatively simple, inexpensive maintenance of the above-ground features rather than difficult reconstruction of below-ground layers. It should be noted, that after a sufficient passage of time, so that the organics have decayed out and the waste containers have completed failure, subsidence will cease and a layered system could be then installed which could last over geologic 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 is then not adequate to 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 percent (perfect leak-proof roof, expensive and hard to guarantee). Alternately, 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 conceiving in one's mind a supermarket parking lot where trees are planted in islands among an extensive paved area with the islands having curbing around them. 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, KY. Results obtained in seasonal 1984–85 and 1985–86 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 1985–86 the grass cover was removed, a new stainless steel engineered cover was constructed and Pfitzer junipers were planted in the lysimeters. After establishment of the junipers, percolation data was again collected in 1988 and reported by Schulz et al. (6). The performance of the woody junipers was excellent in preventing deep percolation of water in the lysimeter.

The encouraging initial results obtained in the Maxey Flats lysimeter experiment has led to the establishment of a large-scale field demonstration at Beltsville, Maryland. Figure 4 shows the placement of the experimental lysimeters and Fig. 5 is a photograph of lysimeter 1, bioengineering management, taken in January 1993, six years after planting of the Pfitzer junipers. Alternating panels of aluminum and fiber glass 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. Fig. 6 shows a side view of construction details of lysimeters 1 and 2 (bioengineering management). The only difference between the two was the initial level of the water tables. The water table was 90 cm above the bottom in lysimeter 1 and 190 cm above the bottom in lysimeter 2. In addition to the two bioengineered lysimeters, two reference lysimeters were initially constructed. The reference lysimeters were similar except that they were merely cropped with fescue grass. They were labeled lysimeter 3 and 4. No hard cover was present but surface slopes were similar. Performance data of the reference lysimeters are given in Fig. 7.

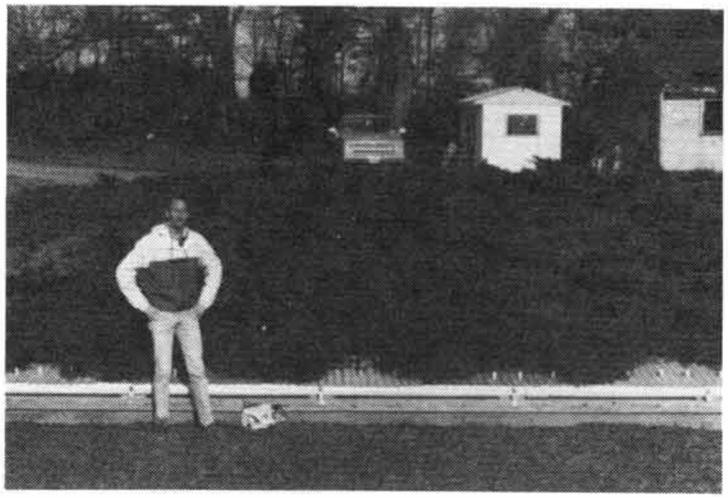


Fig. 5. Bioengineering plots at Beltsville. Photo taken in January of 1993, six years after planting of Pfitzer junipers. Run-off is 63% of precipitation, evapotranspiration is 37% of precipitation and there is no deep percolation.

The water table in the two reference plots or trenches, lysimeters 3 and 4, i.e., the plots cropped to fescue, rose until near the surface. At that time pumping of water from the water table was initiated to keep the plots (trenches) from running over. The graphs of the water tables in the bioengineered plots (lysimeters 1 and 2) show an entirely different story as evidenced in Fig. 8. Here, in both cases, the water table has been eliminated. It appears that the bioengineering approach not only could be used to 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

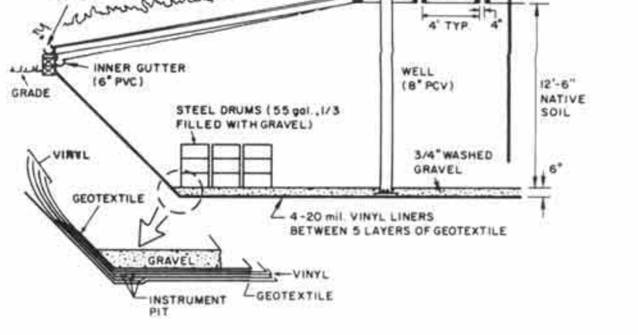


Fig. 6. Side view of bioengineered lysimeter. Surface run-off is collected from both engineered surface and soil surface. Soil moisture content is measured with neutron probe. Water table is measured in well.

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. The bulk of the precipitation was disposed of by evapotranspiration by the fescue crop but this was not adequate to prevent the rise of the water table. Table gives the run-off, evapotranspiration and deep percolation in the bioengineered plots during the past four years. There was no deep percolation during this period. The evapotranspiration has been rising annually. The annual rise in evapotranspiration is probably caused by the greater vegetative canopy intercepting a greater percentage of the precipitation. In 1988, 1989, 1990 and 1991 the run-off percentage was 80, 74, 70 and 67(7). In 1992 the run-off had decreased to 63% of the precipitation. During 1989 the water table was completely eliminated in both plots as shown in Fig. 8.

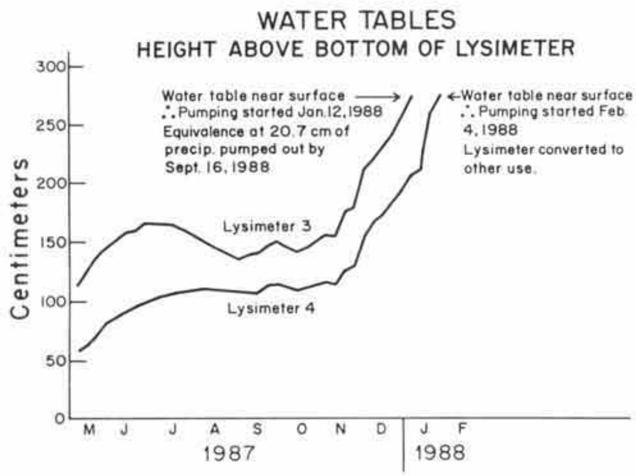


Fig. 7. Water table vs. time in reference lysimeters. The crowned surface is cropped with fescue grass. Water table increased with time until pumping of water table was necessary to keep trench from running over. Surface run-off was 8% of precipitation.

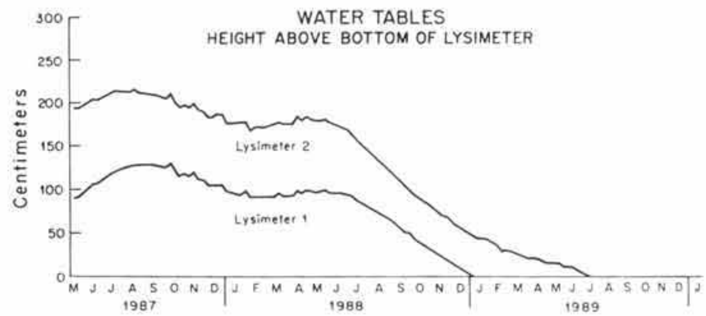


Fig. 8. Water table vs. time in bioengineered lysimeters. Decline of water table levels with passage of time shows bioengineered covers were very effective in preventing water percolation. Elimination of water table shows that this procedure could be used for remedial action ("drying out") of existing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

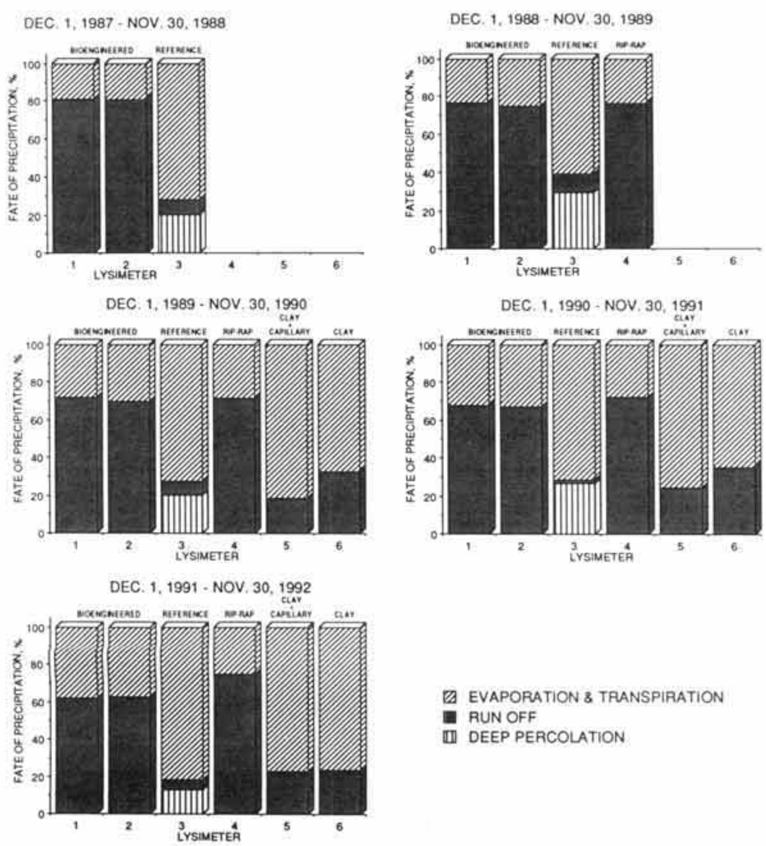


Fig. 9. Fate of precipitation in bioengineered, reference (soil with grass), UMTRA (clay with riprap), clay (clay with grass), and clay + capillary (clay and capillary layers with grass), lysimeters. Deep percolation is present in reference lysimeter. No deep percolation has occurred to date in all other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

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

TABLE II
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.

		Moisture Content Volumetric	Oven Dry Weight Basis
Date of Measurement	Counts Std. Count	$\frac{cm^3\ H_2O}{cm^3\ oil}\ \left(\frac{V}{V}\right)$	% 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
Volume of soil in weighing lysimeter			382 liters
O.D. weight of soil in weighing lysimeter			628 kg
Bulk density of soil			1.64 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%

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 a 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 exist a large safety margin in protecting the waste from infiltrating water.

Neutron probe apparatus, as supplied by the manufacturer, are calibrated against moisture measurements in sand. Such calibration will be of unknown accuracy when applied to soil measurements. For this reason, calibration of the probe was carried out using the same soil used in the lysimeters. Fourteen hundred pounds of soil were placed in a weighing lysimeter and measurements made over a four-year period. Calibration data obtained using the weighing lysimeter is given in Table II. The resulting curves depicting the factory calibration and the weighing lysimeter calibration are given in Fig. 10. From 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 is plotted as volumetric moisture content as a function of soil depth on specific dates. Only seven 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 of 1987, the moisture content of the soil increased with depth until the water table was reached, then became constant. By July of 1989, the water table had been eliminated from both lysimeters, the soil profiles were drying out but the soil moisture content, although much lower in the soil profile than in July of 1987, still increased with depth. This same relationship was still evident November of 1992, although the soil profile had become still drier.

In Fig. 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 the two-foot depth (61 cm) 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 eight feet, however, steady state has not yet been attained. During the past 5½ years, the soil moisture content has been decreasing and indeed, still is. From the data shown in Figs. 11 and 12, it is reasonable to conclude that a steady state of "dry" soil will be eventually obtained in the lysimeter. This would evidence that bioengineered closure as described in this experiment would maintain the cover over buried waste in a "dry" steady-state condition and thus 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 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 Fig. 13. This lysimeter was completed in the fall of 1988 and data collection, i.e., 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 surface resistive layer barrier plot, construction of a vegetated resistive layer barrier plot was carried out. 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 to fescue grass. A diagram of this plot is given in Fig. 14.

In Fig. 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 as the grass-covered plot, but in both cases there has been no deep percolation through the clay layers to date. Although the data show no deep percolation through the clay layers to date in both lysimeters, that data in itself gives little clue as to how much safety margin has been offered. Also it is not known how consistently such near perfect clay barriers would be installed in routine operation. That remains a problem for future consideration. Another concern is that of possible drying out of clay barriers. If the clay layer were to dry out, it 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 of the layer, 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, devoid of vegetation, there is a slight increase in moisture content with passage of time, suggesting that some leakage of water through the clay layer may be observed in the future. 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 four-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.

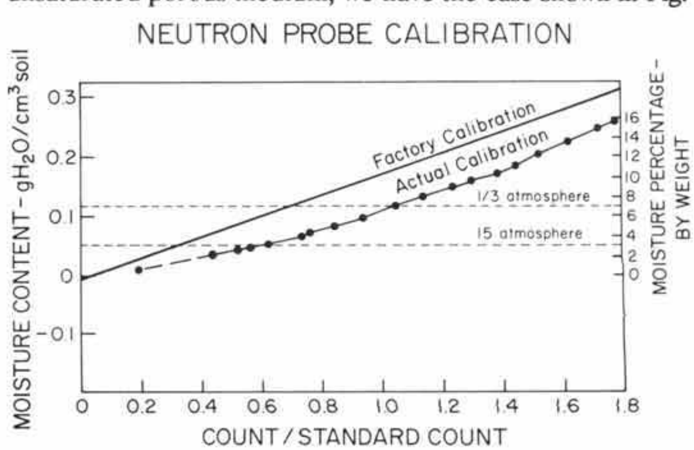


Fig. 10. Calibration of neutron probe using soil of bioengineered lysimeters. Calibration was carried out in a weighing lysimeter over a four-year period. Factory calibration was supplied by manufacturer of neutron probe and was made against sand rather than soil.

16. The "holes" shown in the diagram could be a rock layer affording a capillary break or capillary discontinuity. This is illustrated in Fig. 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 smoothly laying 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. 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 an apparatus schematically depicted in Fig. 19 was constructed.

The apparatus constructed to make the necessary measurements were called soil beams. Several "mini-soil beams" were constructed for use in the laboratory so a variety of candidate conductive layer materials could be quickly evaluated. A photograph of a laboratory scale "mini-soil beam" is shown in Fig. 20.

A number of materials were evaluated using the mini-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 soil 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.

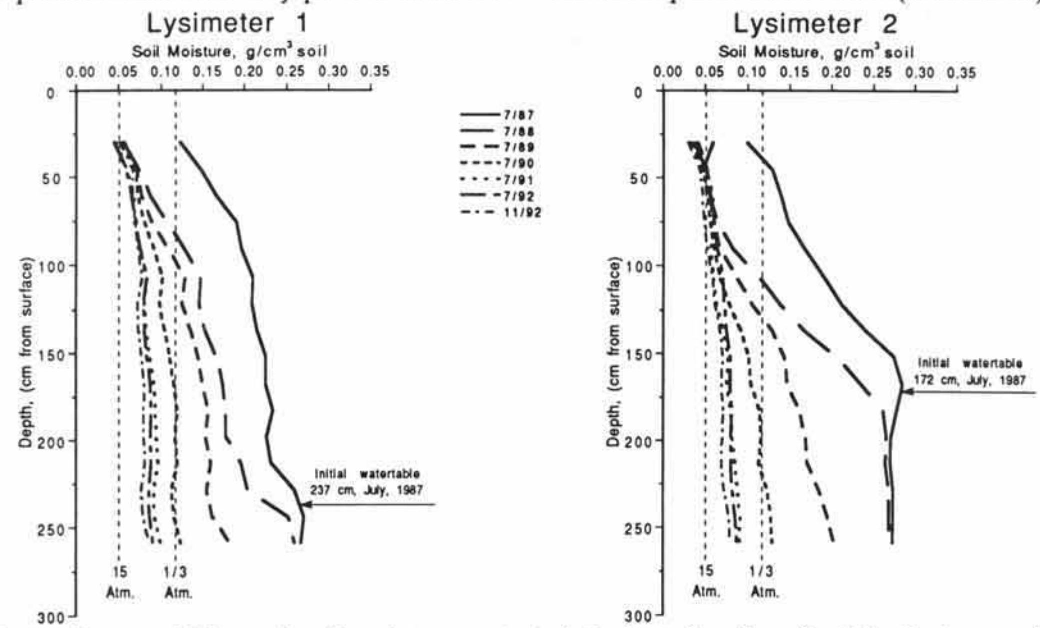


Fig. 11. Bioengineered covers. Volumetric soil moisture content plotted as a function of soil depth at seven different dates. By July of 1989 water table had been eliminated from soil profiles. As of November 1992 entire soil profiles, although relatively dry, still showed slightly increasing moisture content with depth.

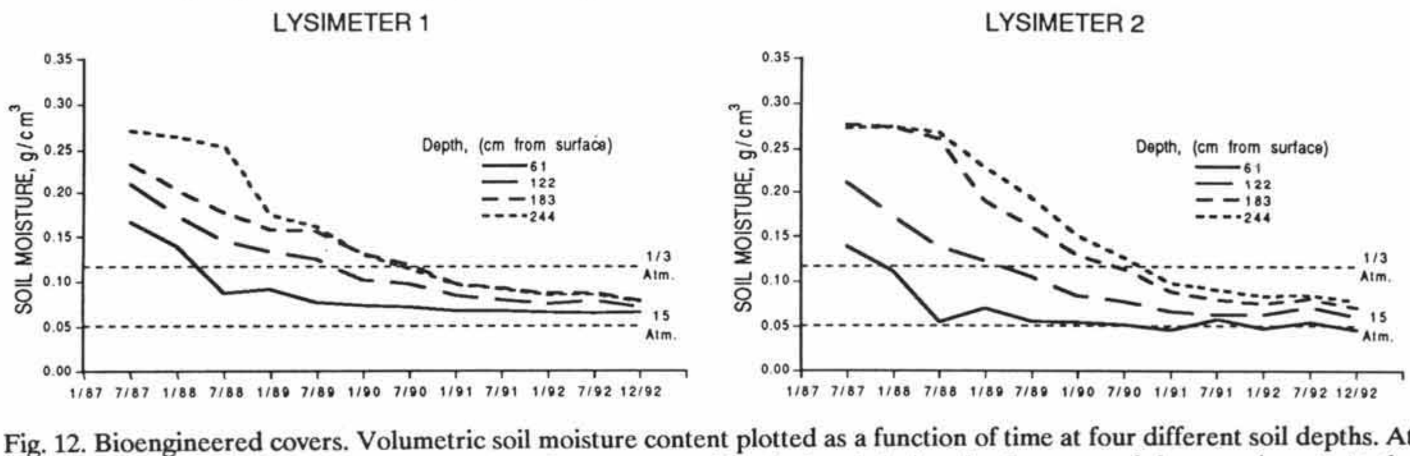


Fig. 12. Bioengineered covers. Volumetric soil moisture content plotted as a function of time at four different soil depths. At the two-foot level (61 cm) the soil moisture was rapidly depleted during the first year of the experiment. At the eight-foot level (244 cm) the moisture content has continued to drop to date. The bioengineered closure would maintain the soil over buried waste in a "dry" steady-state condition and not only prevent water from infiltrating to the waste, but would do so with a large safety margin.

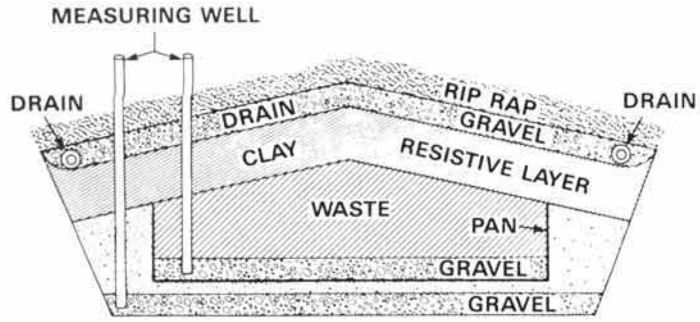


Fig. 13. Resistive layer barrier with rock cover. No vegetation. Possible UMTRA cover. Possible advantages over vegetated resistive layer barrier: 1) Clay layer remains wet and more efficient barrier to escape of radon. 2) Initially, superior erosion protection. 3) No root penetration of waste. Major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

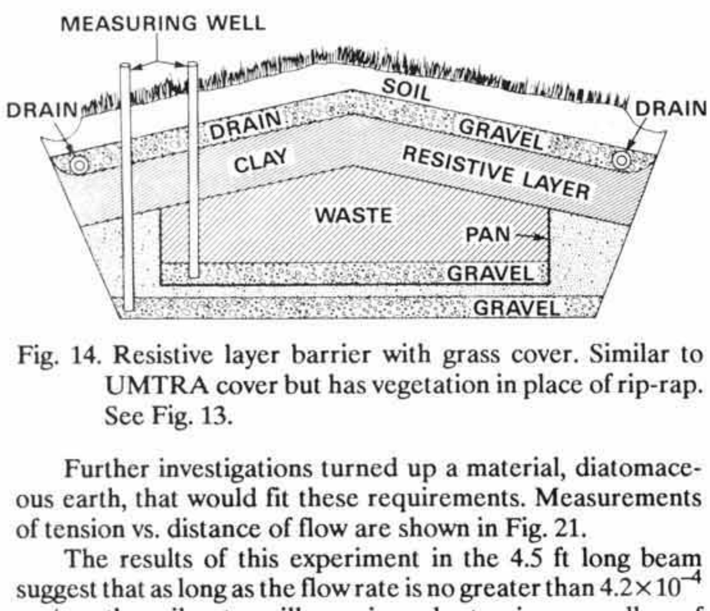


Fig. 14. Resistive layer barrier with grass cover. Similar to UMTRA cover but has vegetation in place of rip-rap. See Fig. 13.

Further investigations turned up a material, diatomaceous earth, that would fit these requirements. Measurements of tension vs. distance of flow are shown in Fig. 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 4.2×10^{-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 was made, it was felt prudent to conduct tests in a large-scale soil beam. A large beam was constructed and used for this purpose. The large beam is shown in Fig. 22 and has a *soil beam* length of 21 ft. As shown in Fig. 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 verified closely the data obtained in the mini-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 U.S. will add about $0.50 per cubic

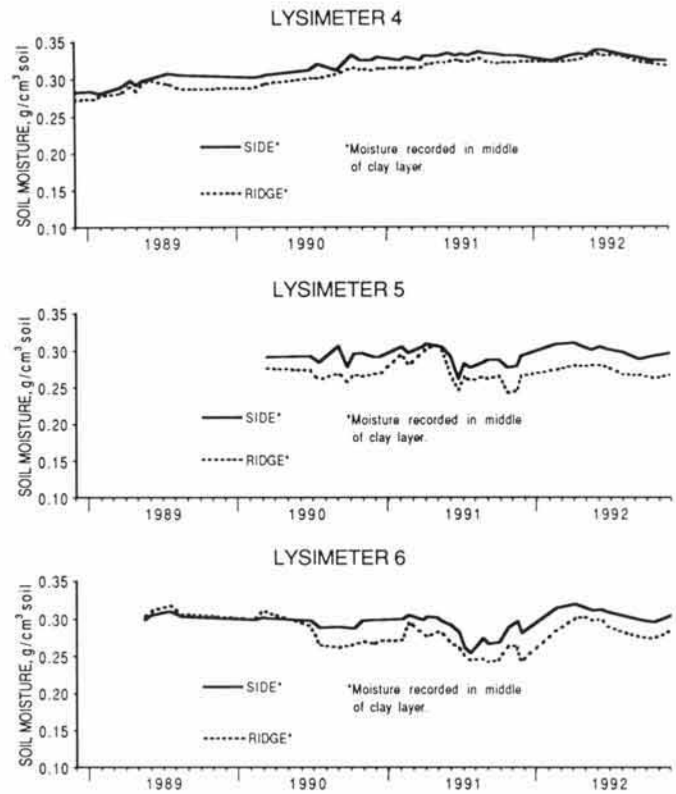


Fig. 15. Moisture content of clay layers with the passage of time. Lysimeter 4 cover system is a clay layer covered with gravel and rip-rap. No vegetation is present and the clay is showing a very slight increase of water content with time. Lysimeter 5 has a capillary (conductive-scavenging) layer underneath a clay layer and the plot is cropped to grass. This plot has been underway for nearly three years and the largest variations in moisture content take place during the summer months. Lysimeter 6 has a clay layer with a grass cover. As in lysimeter 5 the largest moisture excursions have taken place in the summer months.

FLOW UNDER NEGATIVE MATRIC POTENTIAL

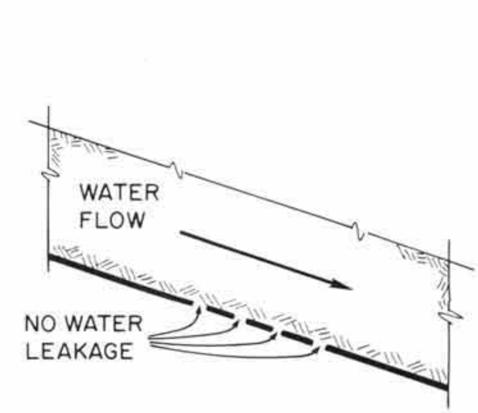


Fig. 16. Water flow in an unsaturated porous medium. If a drop of water were to be placed at one of the holes shown, it would flow upward into the soil.

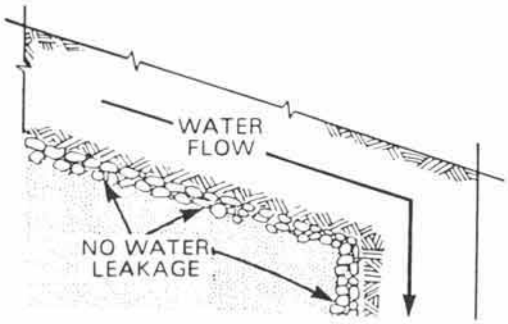


Fig. 17. Substitution of rock layer for holes shown in Fig. 16. Voids between rocks act exactly like holes shown in Fig. 16 in forming a capillary discontinuity, therefore preventing leakage downward under the influence of gravity.

feet of disposed waste. This is over the cost of using locally obtained soil and based on waste being 10 ft deep.

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 Fig. 24.

Performance of this cover, to date, is shown in Figs. 9 and 15, lysimeter 5. The cover system has proven to be 100% effective in preventing water movement downward through the cover.

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 diatomaceous earth 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 possibly making sand more attractive to some installers. Therefore during the past year we have been conducting further studies with various sands. A large deposit of wind transported (eolian) sand has been identified that has hydraulic properties at least as desirable as those of diatomaceous earth. This work is on-going and will be described in detail in a future report.

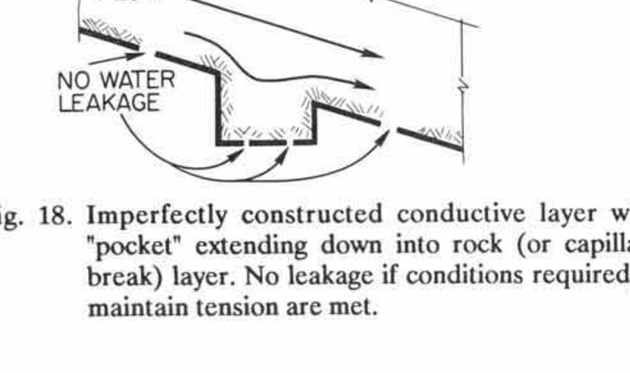


Fig. 18. Imperfectly constructed conductive layer with "pocket" extending down into rock (or capillary break) layer. No leakage if conditions required to maintain tension are met.

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 of this article 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 unit could be earth-mounded concrete bunkers. A drawing showing a combination of a resistive layer over a conductive layer in a concrete bunker or above-ground

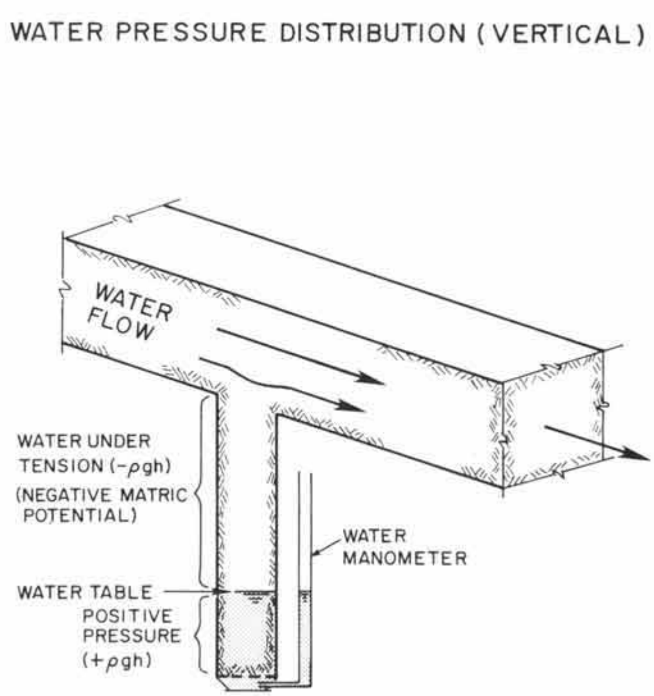


Fig. 19. Schematic of laboratory apparatus for measurement of water tension using different materials and varying flow rates.

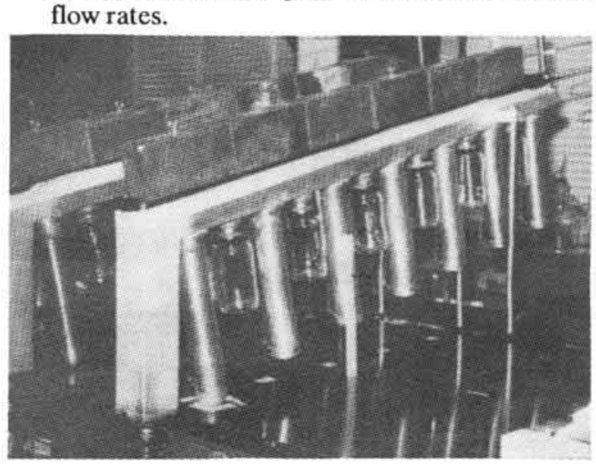


Fig. 20. Mini-soil beam used for evaluation of materials for possible use in conductive layer barrier application. This soil beam has a total length of 4.5 ft. Lead bricks were placed on top of the test material to simulate overburden.

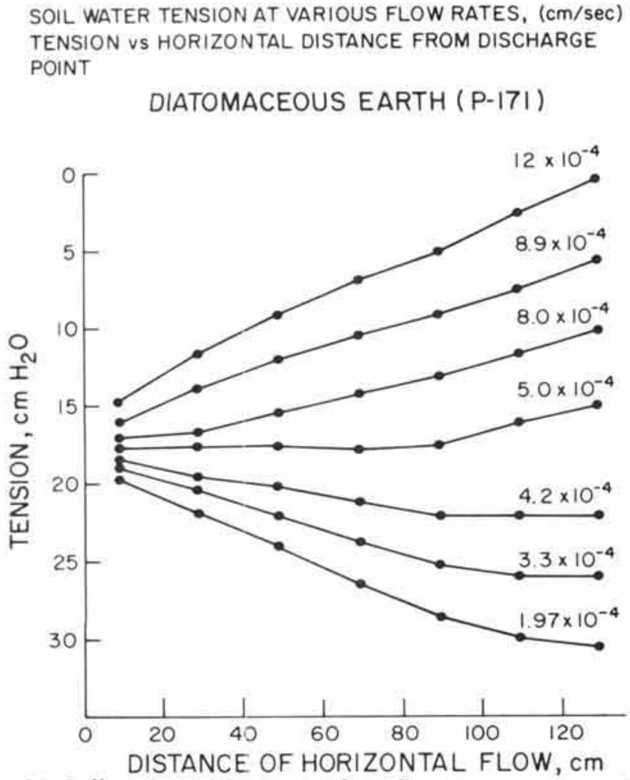


Fig. 21. Soil water tension at various flow rates, measured in mini-soil beam shown in Figure 20. Tension vs. horizontal distance from discharge point. Results suggest that at rates of 4.2×10^{-4} cm/sec or less, water would remain under tension at any beam length. Slope of beam is 1:5.

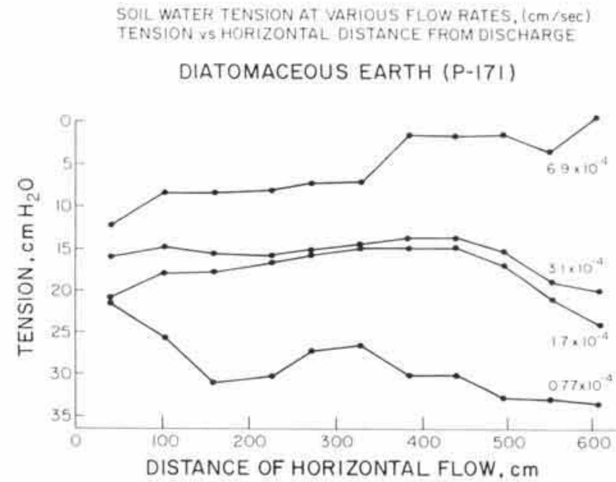


Fig. 23. Soil water tension at various flow rates, measured in large soil beam shown in Figure 22. That beam is 21 ft. long and has a slope of 1:5. At -15 to -20 cm, matric potential water flow rate is approximately 3×10^{-4} cm/sec. At this flow rate unsaturated flow can be maintained over an infinite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

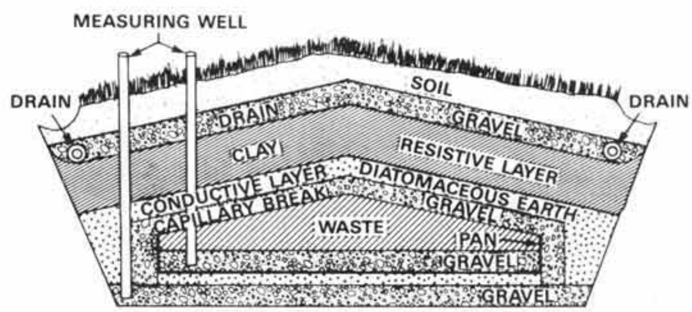


Fig. 24. Combination resistive layer barrier over a conductive layer barrier. The clay barrier (resistive layer barrier) needs only to provide protection to approximately 10^{-6} cm/sec. Conductive layer barrier of diatomaceous earth will readily transport percolating water around waste.

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.

application is shown in Fig. 25. 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 be, in theory, 100% effective. The concrete structure would thus be shielded 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 nature of construction of compacted porous material (clay).

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

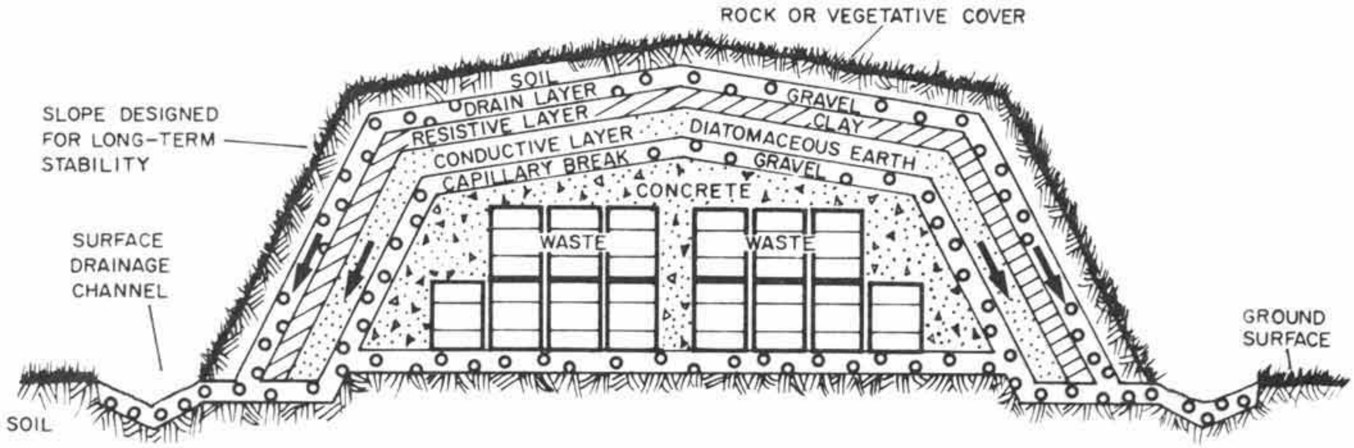


Fig. 25. Resistive layer barrier overlaying a conductive layer barrier as it might be used with an earth-mounded concrete bunker. The resistive (clay) layer is the primary barrier to water passage downward. The conductive layer (diatomaceous earth) will scavenge and conduct any water percolating through the clay layer around the concrete structure to drains. The diatomaceous/gravel interface is the capillary break. The concrete is exposed only to a stagnant, alkaline film of water which will greatly retard the degradation of the concrete over a very long time period. Only geological materials already over one million years old are used in construction, other than the concrete, so the life of the cover will far exceed that of the concrete, even though this cover system can be expected to significantly increase the structural life of the concrete.

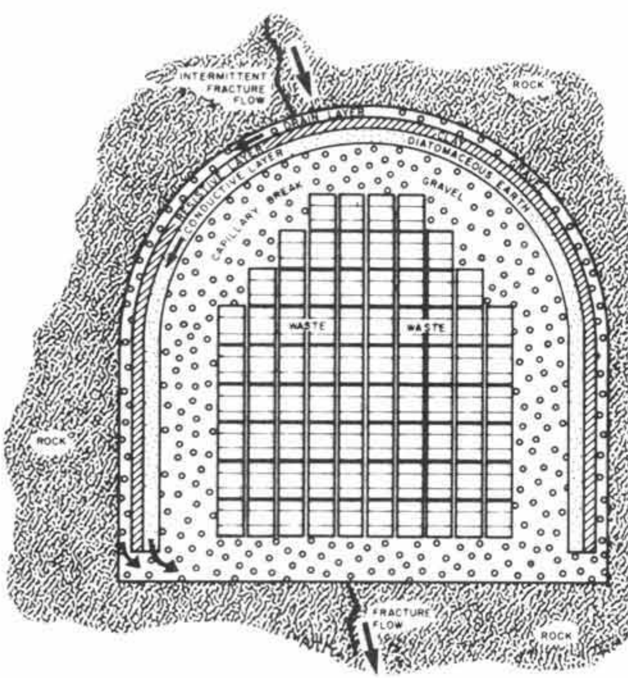


Fig. 26. Artist's concept of resistive and conductive layer barrier to protect high level waste from water flowing through a *rock fracture*. Resistive (clay) layer will divert all but a small amount of fracture flow water. Conductive layer (very fine sand or diatomaceous earth) will scavenge the small quantities of water that will pass through the clay layer. The conductive layer will transport the scavenged water, under tension, around the waste.

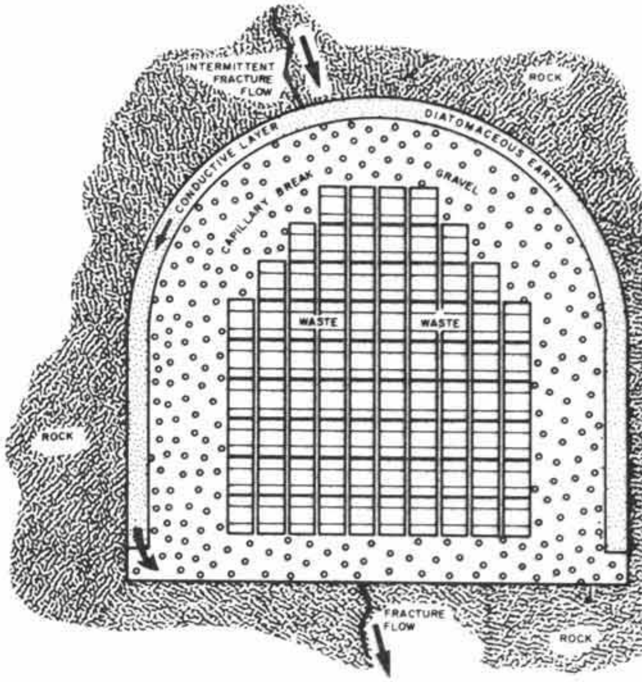


Fig. 27. Simplified case of Fig. 26. If fracture flow is slow (i.e. dropwise) conductive layer will transport all water around waste. Clay layer will then not be needed.

constructed with geological materials to give extremely long-term isolation without further maintenance (8). Another possible application of a combination of covers (1) and (2) described in the introduction of this article is shown in Figure 26. Here high level waste is emplaced in a tunnel excavated in rock. If a fracture was 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 27 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.

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