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Control of Water Infiltration Into Near Surface LLW Disposal Units

Task Report - A Discussion

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Prepared for
U.S. Nuclear Regulatory
Commission

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ABSTRACT

The principal pathway for water entry into LLW disposal units in the humid eastern United States is through their covers. Most of that water is derived from precipitation. On a long term basis, precipitation has three possible fates: (1) some water will be returned to the atmosphere by evaporation and plant transpiration; (2) some water may run-off laterally; and (3) some may percolate below the root zone of the vegetation. Since deep percolation is undesirable in a waste isolation system, it is required that the sum of run-off plus evapotranspiration approach or equal precipitation. It should be noted that the run-off can be surface or sub-surface so long as the lateral transport occurs before the water can contact the waste.

If deep percolation is to be close to zero, then only two parameters are left for possible control, evapotranspiration and run-off. Evapotranspiration, however, has a very definite maximum. The energy available for evaporation is incident solar radiation and is not subject to control. Thus only run-off is subject to unlimited management.

Two types of sub-surface features that may be constructed to enhance run-off are: (1) the "resistive layer" barrier, and (2) the "conductive layer barrier". The "resistive layer" barrier is the well known compacted soil or compacted clay layer and depends on compaction of permeable porous material to obtain low flow rates. The "conductive layer" barrier is a special case of the capillary barrier. Use is made of the capillary barrier phenomenon not only to increase the moisture content above an interface but to divert water away from the waste. During such diversion the water is at all times at negative capillary potential or under tension in the "flow layer". The use of capillary barrier concept is perhaps most readily apparent upon consideration of the "outflow law" (Richards, 1950) which explains the existence of dry caves present in porous materials and also why gopher holes do not fill up during a rainstorm. This is because, that as long as the soil moisture has a path to follow so that water pressure remains negative (less than atmospheric) no water will enter the cavity. That is, outflow from a soil to a cavity or rock layer occurs if the pressure in the soil water exceeds atmospheric. A conductive layer barrier has a theoretical efficiency approaching 100%. But on both a theoretical and practical basis, such a barrier can work only under relatively low water flows. On the other hand, the resistive layer barrier works most efficiently at higher precipitation rates. Based on these two considerations, a very effective barrier system might be constructed by placing a "resistive barrier" over a "conductive barrier". A note of caution: such a system must fail if appreciable subsidence takes place.

An alternate procedure called "bioengineering management" utilizes engineered features at the surface (as opposed to the subsurface) to ensure adequate run-off. The engineered features are combined with stressed vegetation, that is vegetation in an overdraft condition, to control deep percolation. Investigation on that procedure in lysimeters designed to give full water budget data are encouraging.

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ACKNOWLEDGEMENT

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INTRODUCTION

Water is referred to by chemists as the universal solvent. The entry of this "universal solvent" into all of the major low level radioactive waste disposal sites (1-8) located in the humid regions of the United States is a noteworthy occurrence. 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 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. To date, tritium migration has been found in all six of the major LLW sites referred to above (9). The object of the present paper is to discuss pathways of water entry to waste placed in near surface, low level disposal units and to suggest likely fruitful areas of investigation.

WATER PATHWAYS TO THE WASTE

Essentially there are three directions from which water can approach emplaced waste. One direction is from above; generally the source being precipitation. Isolation of waste from precipitation water will be the principal topic in this presentation. A second direction of water movement to waste could originate from upward movement of water by a rising water table. A third direction could be lateral movement, also of free water, or groundwater. The best solution to problems two and three is very simple. Do not locate a LLW disposal unit where a groundwater table may be a problem. It is just not reasonable. If, in spite of these considerations such a siting should be made, the area must be artificially drained. An enormous drainage literature exists and procedures are well established. Drainage of agricultural lands has been carried out for centuries. Extensive drainage is routinely done in all sorts of engineering projects such as road and airport construction. Since such an extensive body of knowledge and experience is in existence on the subject of land drainage, engineering procedures are well known and results are predictable.

In contrast to problems related to land drainage, which has received extensive investigation, means of reducing infiltration has received relatively little study. To the contrary, agricultural studies along these lines are directed to means of increasing infiltration, not decreasing it. In the agricultural case, water run off is generally to be reduced, thus increasing irrigation efficiency. Probably the relative lack of emphasis on studies relating to means of reducing infiltration has contributed to the lack of success in prevention of water entry into humid area LLW trenches. For this reason the discussion in this paper will concentrate on the infiltration-percolation pathway of water entry into near surface low level waste disposal units.

Before examining the water pathway problem, it is interesting to note that the lack of success in keeping buried waste isolated from water has led to the expenditure of considerable effort on improved packaging as a preventative effort. Concrete, especially, has received much attention along these lines (10-17). Questions of long term stability of concrete surrounded by acid soil, cost, etc. suggest that concrete may not be the best solution. Isolation using natural materials should not yet be given up on but should be investigated further, especially in the areas that have received relatively little attention.

Up to this time, LLW disposal unit covers have been constructed from soil materials. The covers have proved unsuccessful from the standpoint of exclusion of water from waste buried in humid regions. Quite to the contrary, the trench covers have been the principal pathway for water passage to the waste (5, 8, 18-24). To provide a basis for a discussion of what might be done to improve on this situation, we shall next review some of the principles describing water transport through porous media such as soils or clays.

SOIL WATER MOVEMENT

In 1856 Darcy (25) published an article describing flow of water in filter beds. From this came Darcy's law: The flow rate through a porous media is proportional to the head loss and inversely proportional to the length of the flow path. The equation resulting from this law may be written in many ways but we will write it here:

$$v = K \frac{P_1 - P_2}{s} \qquad (1)$$

where v is the flow velocity, K is the hydraulic conductivity, and P_1 and P_2 are inlet and outlet pressures of the porous body of length s. It can be noted that this equation closely resembles the Pouseulle equation describing flow of water through capillary tubes. Darcy's law is also quite analogous to Ohm's law which describes electrical current flow through a wire. Other analogies between water flow through porous media and electrical flows become apparent upon examination of later articles such as that of Buckingham (26).

By the 19th century it was already known that all soil water is not free to move under the influence of gravity. King (27) and Briggs (28) were cognizant of various states of water in soils. "Gravity water" was described as water in soil free to move under the influence of gravity. "Capillary water" was water held in capillary spaces under the influence of surface tension. "Hygroscopic water" was film water and not free to move under gravity or capillary forces. It is interesting to note that the "capillary water" concept can furnish an explanation for the capillary barrier concept for protecting wastes from percolating water. The displacement of capillary water under the influence of gravity was described by Briggs (28) in 1897.

When air is introduced into a porous media, the saturated media becomes an unsaturated media. Air replaces water and the cross section available for liquid flow is reduced and flow will be reduced accordingly. In 1907, Buckingham (26) incorporated this reduction of conductivity into a flow equation. Later Richards (29), and Childs and Collis George (30, 31) showed that Darcy's law basically also applied to the movement of soil moisture under unsaturated conditions and hence the following simple equation can be written:

$$v = k \frac{P_1 - P_2}{s} \qquad (2)$$

where k is the capillary conductivity and $P_1 - P_2$ represents the difference of the combined gravitational and capillary forces in the soil.

It should be further noted that K in equation (1) will be fairly constant for a given soil, but k in equation (2) will vary with moisture content.

Another difference to be noted in the use of equations (1) and (2) is that in unsaturated conditions, flow may take place in any direction and in the case of upward flow, the gravitational force must be subtracted from capillary force to obtain $P_1 - P_2$.

Darcy's law and the equations derived from it then form a foundation for describing protection that may be afforded to waste isolated by a compacted clay layer. Such a clay layer is, in essence, a resistance layer, i.e. a layer of material that offers resistance to water flow. The greater the resistance of the layer the better the performance in isolating waste from water flow.

A quite different concept is that of the capillary barrier. The capillary barrier concept depends on the observation that water will not flow into a cavity from an unsaturated porous media such as soil. In this concept a relatively low resistance to flow (or high hydraulic conductivity) is essential for the barrier to give good performance in isolating waste from water infiltration. In 1930 Zunker (32) discussed a field drainage case where a layer of fine textured soil is underlain with coarse material. The transition zone from fine to coarse texture acts like a perched water table in the fine textured material. Zunker presented an explanation for the phenomena based on capillary forces. Richards and Joffe (33) reported in 1939 that zero pressure (or zero soil moisture tension) are the required boundary conditions for outflow from the bottom of a soil column. In 1950 Richards (34) published an article titled "Laws of Soil Moisture". Here he put forth his Outflow Law: Outflow of free water from soil occurs only if the pressure in the soil water exceeds atmospheric pressure. The outflow law applies to drains and explains why dry caves exist and why gopher holes do not fill up with water during a period of rainfall. As long as the soil moisture has a path to follow so that the water pressure remains negative (or less than atmospheric), no water will enter the cavity. This principle has obvious interesting implications for isolating wastes from percolating waters.

ISOLATION OF WASTE FROM PERCOLATING WATER

On a long term basis, precipitation falling onto an area has three possible fates. (1) Some water will be returned upward to the atmosphere by evaporation and plant transpiration (evapotranspiration). (2) Some water may run-off laterally. (3) The third possible fate of the water over a long term period is deep percolation. Since deep percolation is undesirable in a waste isolation system, it is required that the sum of run-off plus evapotranspiration approach or equal precipitation. It should be noted that the run-off can be surface or sub-surface so long as the lateral transport occurs before the water can contact the waste.

If deep percolation is to be close to zero, then only two parameters are left for possible control, evapotranspiration and run-off. Evapotranspiration, however, has a very definite maximum when considered over an extended area. The energy available for evaporation of water is incident solar radiation and is not subject to control. About 588 calories are required to evaporate each gram of water in the field, so we can see that evapotranspiration has a maximum. By definition, a humid area is one in which precipitation exceeds evapotranspiration. This leaves only one degree of freedom, that is, only run-off is subject to unlimited management. As stated earlier, that run-off may be surface or sub-surface so long as the lateral transport of water takes place so that the water does not reach the waste.

METHODS FOR CONTROLLING WATER MOVEMENT

THE RESISTIVE LAYER BARRIER

The major burial sites in the humid areas of the United States have, to date, consisted of trenches partly filled with wastes, then trench caps have been constructed using compacted soil materials. A trench cap constructed from compacted clay or soil could be termed a resistive layer since the function of the cap is to provide a low hydraulic conductivity or high resistance to water flow through the layer to the emplaced waste. Such a "resistive layer" or compacted clay layer can have a low hydraulic conductivity and afford a high degree of protection to waste. Water movement through such a layer can be described by adaptations of Darcy's law. However, as noted earlier in this paper, all of the major waste sites located in the humid U.S. have reported some water movement into trenches and the caps are the major pathway (5, 8, 18-24).

It should be noted that it is the nature of compacted porous material to allow some water passage. All such materials have a measurable hydraulic conductivity. In addition, trench caps tend to become more permeable to water with the passage of time. This can be ascribed to two occurrences.

(1) Subsidence:

Subsidence of the waste which causes shear failure of the clay layer is a serious problem and is one that is not easily managed. Waste compaction will not solve the problem as organics will still decay with time, creating voids leading to subsidence. The subsidence problem can be managed by one of two ways. One is to prevent subsidence by construction of very expensive vaults or containers or by reduction of the waste to a compact inorganic material that would not undergo further volume reduction with the passage of time. The other way could be by simply managing the subsidence as it occurs. This second practice has been followed to date but with limited success in preventing water infiltration to buried wastes. As the cap subsides it is simply repaired.

(2) Plant root penetration:

The growth of plant roots results in increased hydraulic conductivity of disposal unit covers with passage of time. Roots increasingly penetrate clay or compacted soil layers and upon death and decay of the roots, channels or macropore paths are formed (18). Bio-barriers have been suggested to prevent such root penetration (35), but it is unlikely that the suggested rock or cobble barrier will prove effective in stopping root penetration over long periods of time in humid areas. Roots are perfectly able to penetrate gravel or rock for long distances if the rock is kept wet.

In summary, the restrictive layer barrier, with either continued maintenance or extraordinary initial measures can be expected to provide an effective but not perfect barrier to water passage. Lateral run-off of water caused by the restrictive layer barrier can be through a gravel drainage layer above the clay layer or may be at the soil surface.

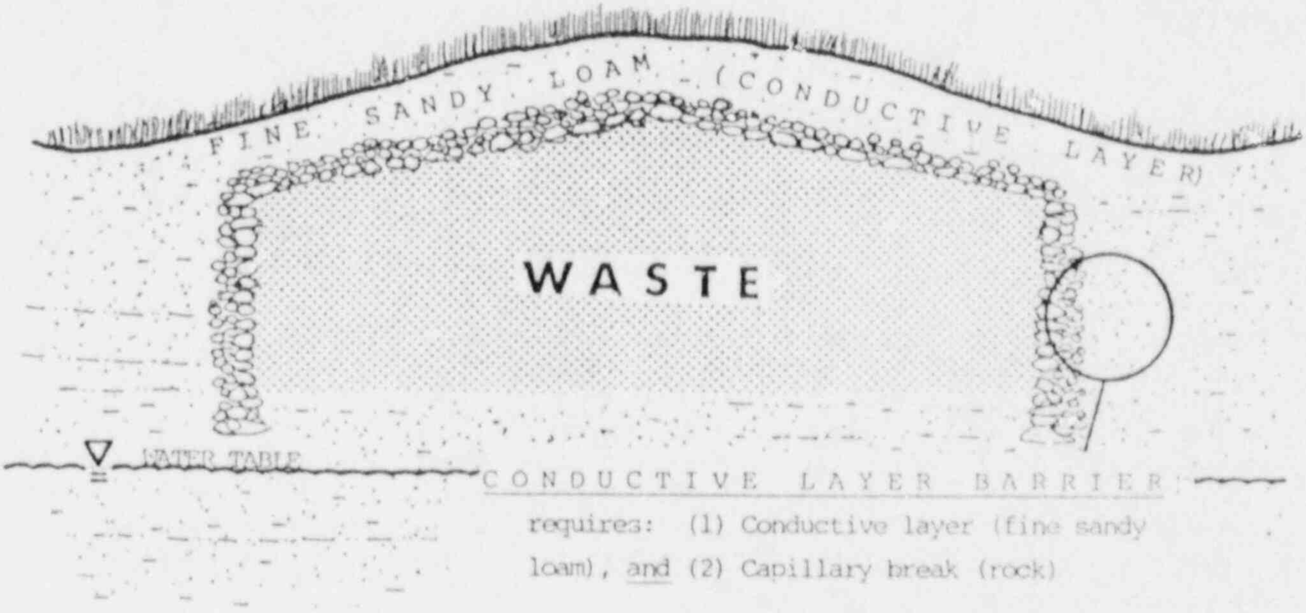
THE CONDUCTIVE LAYER BARRIER

The conductive layer barrier is a special case of the capillary barrier. Use is made of the capillary barrier phenomenon not only to increase the moisture content above an interface but to divert water away from the waste. During such diversion the water is at all times at negative capillary potential or under tension. (Note: the energy status of water present in unsaturated porous media is alternatively referred to as capillary potential, hydraulic potential and more recently as matric potential. All of these terms are still in use and are defined differently, but the differences are not important to this discussion).

The use of the capillary barrier concept is perhaps most readily apparent upon consideration of the "outflow law" (34) described earlier in this paper. This law, along with the explanation based on capillary considerations by Zunker (32), readily explain the existence of dry caves present in porous materials and also why gopher holes do not fill up during a rainstorm. As was mentioned earlier, as long as the soil moisture has a path to follow so that the water pressure remains negative (less than atmospheric) no water will enter the cavity. That is, outflow from a soil only occurs if the pressure in the soil exceeds atmospheric. Perhaps the same principles can be applied to isolate waste from water where the waste is disposed of in a near surface facility. Such disposal could be either above or below grade.

Cartwright, et al. (9) described results from a field experience at Sheffield where the layering sequence resulted in a wick effect so that extra moisture is retained in the upper fine grained layer, thus making it more available for evapotranspiration. This is probably not the most important attribute of a capillary barrier system. In many cases the waste itself will serve as the cavity so that a capillary break (barrier) is established. It should be noted that merely increasing the water holding capacity of the soil above the waste will not, in itself, prevent water from infiltrating the waste. If this were the case, simply making the cover thicker would suffice. By definition, in a humid area precipitation exceeds evapotranspiration. As mentioned earlier, only by increasing run-off to the point that E.T. will use the rest of the water, will percolation be prevented.

In the special case of waste isolation, the capillary barrier needs only to provide sub-surface run-off to divert water from the waste. If the water is shunted around the waste to a porous unsaturated zone below the waste, our goal of waste isolation from percolating water will be achieved. (See Figure 1).



CONDUCTIVE LAYER BARRIER

requires: (1) Conductive layer (fine sandy loam), and (2) Capillary break (rock)

Figure 1 CONDUCTIVE LAYER BARRIER
(simplest case)

For a well drained soil the soil itself will act as a conductor. As long as the soil is unsaturated water will not enter a drain (the rock layer). This system will work best when there are slow percolation rates. Water will be conducted through the fine sandy loam layer (above the rock layer) to the water table or to drains which should be located below the waste. Drains are not shown in this diagram. If percolation rates are high, a resistive layer barrier should be added as shown in the following figure.

In addition to the work at Sheffield a number of investigators have suggested or tried to use the capillary barrier concept to protect waste from water infiltration (35-58). Simulations have perhaps worked best, followed with decreasing success with laboratory models, then field experiments. Some of the field experiments have met with little success (9); some showed some promise (38, 52, 58). The most successful field demonstration was reported by Rancon (55). However, in this most successful case, the trench cap was less than three meters wide, therefore this experiment does not yield conclusive proof that the concept will be useful to isolate waste of greater lateral dimensions. Probably the usefulness of the capillary barrier-conductive layer barrier concept has not yet been given a definitive trial.

In designing a conductive layer barrier system, one condition is paramount. The rock layer must be clean or free of fines so as to form the necessary "cavity", or the outflow law does not apply. The second condition is that the conductive layer above and around the "cavity" must be conductive. That is, that layer must have a reasonable hydraulic conductivity in the negative moisture potential range of -10 cm to -200 cm of water. Third, the water being transported in the capillary layer must have somewhere to go. Ideally, this will be into an unsaturated region below the waste. If the conductive layer terminates at a drain located at or above the elevation of the waste, the capillary potential of the water must rise to zero at that point (outflow law), and water may seep into the waste.

In the various reports on the capillary barrier referred to above, it has been stated that it is very important that the fine/coarse grained interface be very sharp. This is not necessarily so. A graded interface made of several particle size layers or other filter materials may be superior. It is absolutely essential that large amounts of fine materials do not penetrate long distances into the "cavity". A diffuse barrier of a few centimeters thickness has a penalty of only that of gravity. That is, a "pocket" of fine material extending 5 cm into the "cavity" will have a 5 cm water pressure disadvantage only. If water at the plane of the top of "pocket" has a capillary potential of -6 cm, no water will drip off of the bottom of the pocket. That water will still have a potential of -1 cm.

A conductive layer barrier has a theoretical efficiency approaching 100%. But on both a theoretical and practical basis, such a barrier can work well only under relatively low water flows. On the other hand, the restrictive layer described earlier, works most efficiently (that is, diverts a higher percentage of infiltrating water) at higher precipitation rates. Based on these two considerations, it seems reasonable that a very effective barrier system might be constructed by placing a "restrictive barrier" over a "conductive barrier". (See Figure 2 and 3). A note of caution: Such a system must fail if appreciable waste subsidence takes place.

CONDUCTIVE LAYER BARRIER
requires: (1) Conductive layer (fine sandy loam), and (2) Capillary break (rock)

Figure 2. CONDUCTIVE LAYER BARRIER USED IN CONJUNCTION WITH A RESISTIVE LAYER BARRIER

The resistive layer barrier functions best with high percolation rates. It's purpose here is to reduce the amount of water that reaches the conductive layer barrier. As noted in Figure 1, the conductive layer barrier functions most efficiently with slow percolation rates. As long as the conductive layer remains unsaturated water will not enter the rock layer. Under unsaturated conditions water will be conducted through the fine sandy loam layer (above the rock layer) to the water table or to drains which should be located below the waste. Drains are not shown in this diagram.

CONDUCTIVE LAYER BARRIER

requires: (1) Conducting layer (fine sandy loam), and (2) Capillary break (rock)

Figure 3. USE OF THE CONDUCTIVE LAYER BARRIER AT A SITE CONTAINING LOW PERMEABILITY STRATA

In the case shown above, the conductive layer barrier conducts water to the water table or to drains (not shown) that should be located below the waste. As long as the conductive layer remains unsaturated, water can not pass into the rock layer.

BIOENGINEERING MANAGEMENT

As noted several times in this paper, infiltration barriers such as capillary barriers or clay layer barriers (or a combination thereof) must fail if subjected to substantial shearing caused by waste subsidence. Re-establishment of a layered system after subsidence failure is a difficult undertaking and would be especially onerous if this remedial action had to be taken repeatedly.

In this section we will examine 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., (59) and was designated bioengineering management. The principle 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 and 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 sub-surface 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, 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 similarly to a supermarket parking lot where trees are planted in islands among an extensive paved area with the island 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.

Investigations of the bioengineering management technique are underway in lysimeters at Maxey Flats (Figures 4 - 6) and large scale field plots (Figures 7, 8, 9) at Beltsville, MD (59). To date, results have been reported on the lysimeter experiments and are quite encouraging. (See Figure 10). Data acquisition has been initiated at Beltsville but not yet reported. The installations at both the Maxey Flats and Beltsville sites afford complete water balance accountability.

MAXEY FLATS

FIGURE 4 . Lysimeter installation, 1983. System gives complete accountability of all rain water falling on soil surface of each lysimeter. Amount of water striking soil surface is known from rainfall measurements. Over a sufficiently long time period, the water striking the surface has three fates: 1) surface run-off, measured by collection in surface run-off sump and pumping collection tank; 2) deep percolation to the water table, measured by maintaining constant water table level by pumping to storage tank; and 3) surface evaporation and plant transpiration. Surface evaporation and plant transpiration = rainfall - (surface run-off + deep percolation).

FIGURE 5. Lysimeter with engineered run-off system installed. Lysimeter has two surface run-off measurement capabilities. The soil surface run-off is collected in a sump and pumped out to a measuring tank. The engineered run-off is measured similarly. 1984.

FIGURE 6. Lysimeter with Kentucky fescue grass one year after addition of enhanced run-off system. Grass has grown up between gutters and provides substantial evapotranspiration. 1985.

BELTSVILLE, MARYLAND

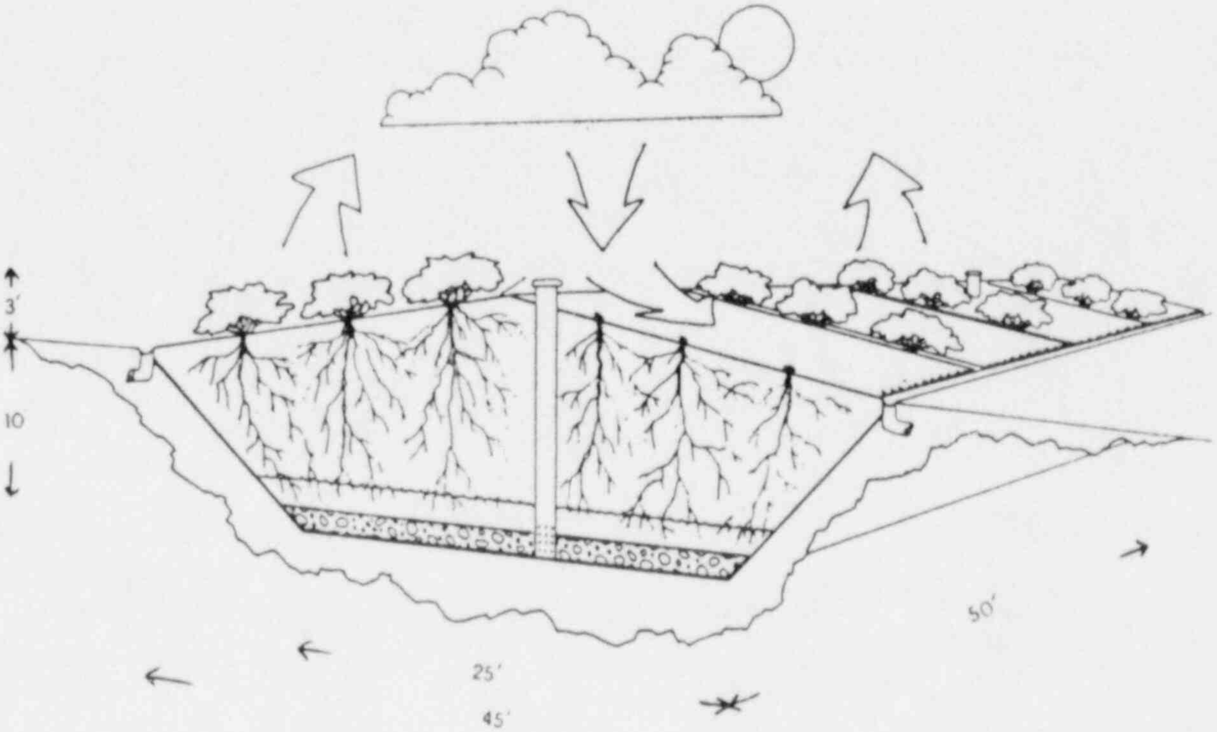


FIGURE 7. Large lysimeter for complete water balance measurements. Precipitation, surface run-off, percolation and evapotraspiration will be measured. Diagram shows positive run-off feature which, in this case, is provided with corrugated panels. Junipers are planted between panels and are grown to extend over panels to provide potential evapotranspiration greater than infiltration on an annual basis. The soil mass acts as a reservoir to sustain the plants in dry periods, and acts as a sponge during wet periods.

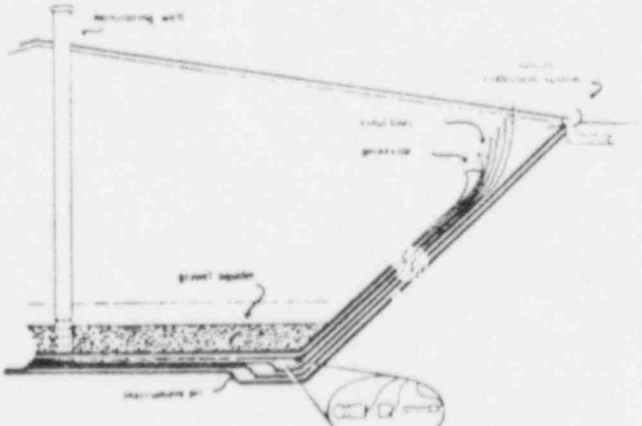


FIGURE 8. Detail of cell construction. There are 4 layers of 20 mil PVC liners and 5 layers of geotextile to serve as water barriers to isolate the cell. Three discrete barrier partitions are thus created. Leakage through any partition is monitored.

BELTSVILLE, MARYLAND

FIGURE 9. Large-scale bioengineering management lysimeters. Each cell (lysimeter or plot) is 14 m x 21 m with Pfitzer Juniper growing through the 4-inch gaps between panels. The light appearing panels are corrugated aluminum and the darker panels are corrugated green fiberglass panels. Two crowned lysimeters behind the bioengineered lysimeters are cropped to fescue grass for comparative purposes. Two lysimeters at the rear are reserved for future work.

RESULTS OF MAXEY FLATS LYSIMETER EXPERIMENTS

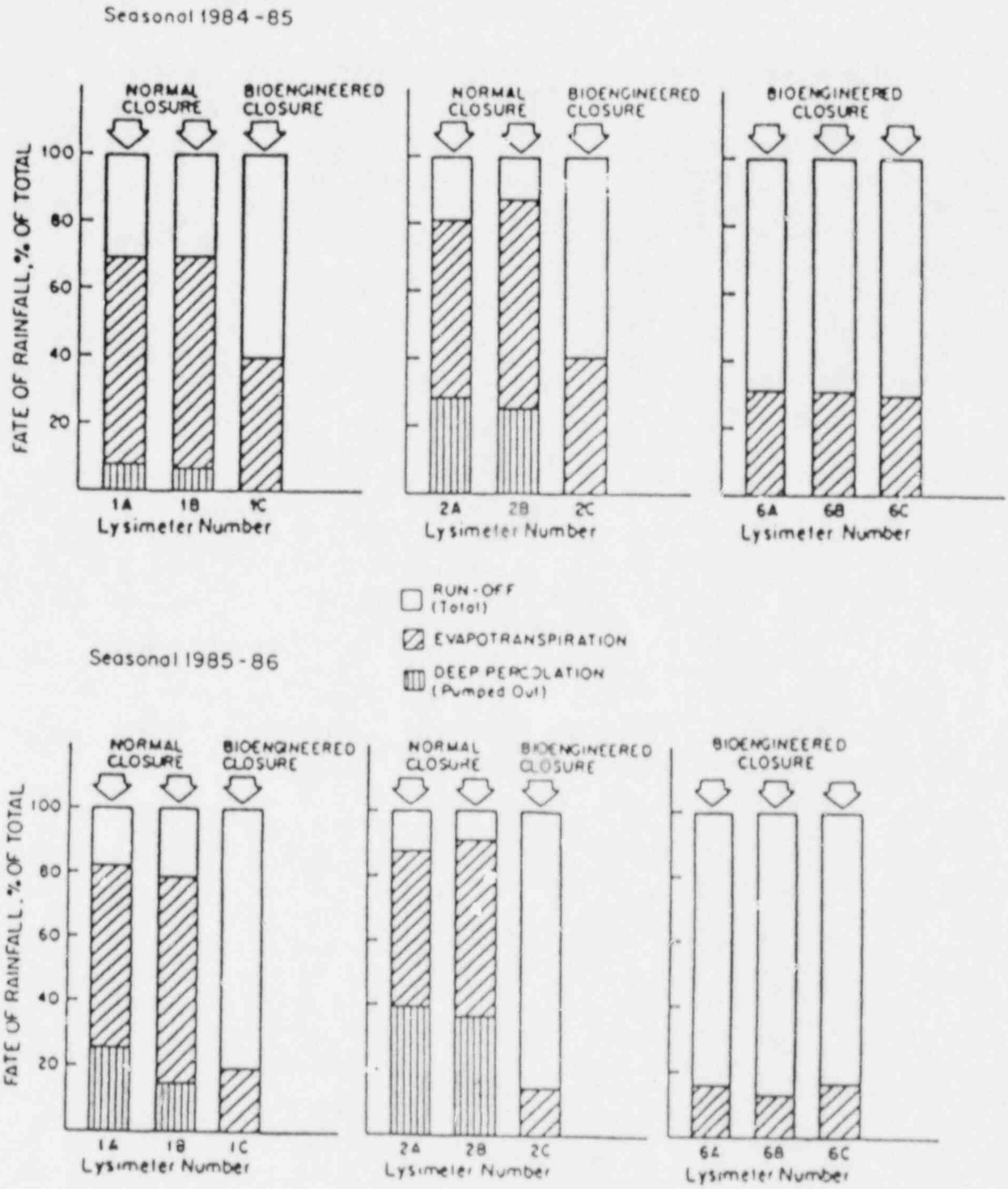


FIGURE 10. Fate of water entering the system. Evapotranspiration, total surface run-off, and deep percolation given as a percent of precipitation for the seasonal years 1984-1985 and 1985-1986. One of the essential requirements of a bioengineered closure system is that substantial evapotranspiration be maintained after the installation of an engineered run-off system; that requirement was readily met. (Ref. 59)

PRESENT OUTLOOK AND RECOMMENDATIONS

The thesis has been developed in this paper that solely run-off can be subject to unlimited manipulation. Necessary run-off can be surface or sub-surface.

A procedure named "bioengineering management" has been described which used engineered features at the surface to ensure adequate water run-off. Investigation on that procedure is underway, and results to date are encouraging.

Two types of sub-surface features that may be constructed to enhance run-off are described. One is the "restrictive layer" barrier, and the other is the "conductive layer" barrier.

The "restrictive layer" barrier is the well known compacted clay layer and depends on compaction of permeable porous materials to obtain low flow rates. Flow through a restrictive layer is described by Darcy's law (1856). 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.

The "conductive layer" barrier is based on the capillary barrier concept and has but little been investigated. No definitive full scale field experiments have been carried out in the humid regions. It is in this relatively unplowed ground that the greatest advances might take place in the near future, and is where new effort should be directed.

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13. ABSTRACT (200 words or less)

The principal pathway for water entry into LLW disposal units in the humid eastern United States is through their covers. Two types of sub-surface features that may be constructed to enhance run-off (surface or sub-surface run-off) and thus reduce percolation are: (1) the "resistive layer" barrier, and (2) the "conductive layer barrier". The "resistive layer" barrier is the well-known compacted soil or compacted clay layer and depends on compaction of permeable porous material to obtain low flow rates. The "conductive layer" barrier is a special case of the capillary barrier. Use is made of the capillary barrier phenomenon not only to increase the moisture content above an interface but to divert water away from the waste. During such diversion the water is at all times at negative capillary potential or under tension in the "flow layer". A very effective barrier system might be constructed by placing a "resistive barrier" over a "conductive barrier". A note of caution: such a system must fail if appreciable subsidence takes place. An alternate procedure called "bioengineering management" utilizes engineered features at the surface (as opposed to the subsurface) to ensure adequate run-off. The engineered features are combined with stressed vegetation, that is, vegetation in an overdraft condition, to control deep percolation.

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