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BIOLOGICAL INTRUSION BARRIERS FOR LARGE-VOLUME WASTE-DISPOSAL SITES

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ABSTRACT

Intrusion of plants and animals into shallow land burial sites with subsequent mobilization of toxic and radiotoxic materials has occured. Based on recent pathway modeling studies, such intrusions can contribute to the dose received by man. This paper describes past work on developing biological intrusion barrier systems for application to large volume waste site stabilization. State-of-the-art concepts employing rock and chemical barriers are discussed relative to long term serviceability and cost of application. The interaction of bio-intrusion barrier systems with other processes affecting trench cover stability are discussed to ensure that trench cover designs minimize the potential dose to man.

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INTRODUCTION

The purpose of this paper is to summarize state-of-the-art methods for designing large volume waste cover systems that limit biological intrusion into waste. The need for such systems is based upon past experience at a varity of waste disposal sites where transport of toxic and radiotoxic elements by plants and burrowing animals has occured (1,2,3,4).

An examination of some of the factors affecting waste site integrity (5) shows that water - and biota-related processes account for most occurrences of contaminant transport from the waste repository. For example, major concerns at shallow land burial sites for low-level radioactive waste include excess erosion of the trench cover, excess percolation of water into the trench contributing to waste leaching and subsidence, and intrusion of plant roots and burrowing animals into the waste (Fig. 1). While plants and animals can mobilize buried waste, they also play a vital role in the dynamics of water movement in soil cover profiles. In the Western U.S., plants may transpire nearly all of the annual precipitation back to the atmosphere (6).

Although vegetation is important in controlling the water balance in the cover profile, deep-rooted plants can access radionuclides and bring them to the soil surface. Radionuclides in plant tissue can be ingested by herbivores or nectar-collecting organisms such as honey bees. At Los Alamos, New Mexico, one of the pathways of tritium transport away from a controlled low-level waste site is via the soil moisture-plant nectar-honey bee-honey pathway (2), however radiation doses to humans that might consume this honey are very small. Tumbleweeds growing on low-level waste sites are a principal transport vector for ^{90}Sr at Hanford, Washington (3).

The importance of preventing buried waste from reaching the ground surface is illustrated by a pathway model of plutonium behavior in terrestrial ecosystems (Fig. 2). Radionuclides buried below the ground surface can be absorbed by plant roots and deposited in above ground tissue. However, when the radionuclides are present in surface soils, as is the case at several waste sites, physical resuspension of soil particles (especially the clays) by wind and water can deposit contaminated soil particals on plant surfaces (i.e., leaves, stems, and fruiting bodies). Field studies (7) with plutonium, as well as other radionuclides, show that for every picocurie taken up by plant roots, at least 10 (and often 100 to 1000) picocuries can be deposited on foliage surfaces. Of course, most herbivores consume those radionuclides whether they are on or in the plant. Even in the case of humans, who presumably wash vegetable crops before consumption, as much as 50% of their radionuclide intake from consuming certain garden vegetables may be from very small soil particles (clays) not removed from crop surfaces by standard household food washing procedures (8).

The importance of animal burrowing activities within a trench cover is generally disregarded except in those cases where problems have arisen (1,9). Trench covers are disturbed soil systems, often loosely compacted and are readily invaded by native plants and animals. Burrowing animals utilize the void spaces left after trench backfilling as natural tunnels and nesting sites (10).

Burrowing activities by animals play an important role in chemical cycling in the soil profile. The vertical transport of Fe, Se, Al, Ca, Mg, U, Ra, and Th from deep soil layers to the surface by the mechanical action of rodents (11, 12) has given rise to the statement that burrowing rodents serve as nutrient pumps that bring insoluble materials to the soil surface for weathering (13, 14). As mentioned before, soil and chemicals brought to the surface are more readily avalable for resuspension and transport by physical processes.

Although burrowing animals can gain access and transport waste to the ground surface, less obvious interactions with the cover and trench backfill may be of greater importance. For example, pocket gophers inhabiting a low-level waste site at Los Alamos excavated about 12,000 kg of soil per ha from a trench cover during a one year period (15). Displacement of that amount of soil created about 8 m^3 of void space in the cover or about 2800 m of tunnel system. Soil disturbance of a similar or greater magnitude, caused by burrowing animals, has been documented in many parts of the Western U.S. (16, 17, 18, 19, 20). Tunnel systems created by pocket gophers in Colorado have been shown to increase rates of water infiltration (by decreasing soil bulk density) into the soil profile by a factor of two over similar but undisturbed profiles (21, 22). Compared with undisturbed vegetated soil surfaces, soil cast to the surface by burrowing activity can be subject to accelerated erosion (17).

Burrowing animals may greatly alter the integrity of engineered, multi-layer soil profiles by penetrating through such profiles and/or by vertically displacing the layers. In native ranges, under high population densities, pocket gophers are estimated to turn over 15 to 25% of the soil surface in a single year (19, 20).

REQUIREMENTS OF BIO-INTRUSION BARRIERS

Desirable features of a bio-intrusion barrier system include:

- being effective at minimizing plant root and burrowing animal intrusion into the soil profile,
- serviceable over the lifetime of the site,
- does not adversely alter other processes affecting waste site integrity (e.g. erosion, percolation), and
- cost effectiveness.

Several approaches have been suggested to reduce the bio-intrusion potential at waste disposal sites. Most of those approaches rely on physical or chemical barriers to prevent plant roots and/or burrowing animals from accessing the waste. Examples of physical barrier systems include natural geologic materials such as rocks or man-made barrier materials such as hypalon sheeting or asphalt emulsions. Chemical barrier systems include the use of biotoxins.

Past studies with man-made physical intrusion barriers lead to questions about the serviceable life of such materials under field conditions. One analysis suggests that materials such as asphalt, hypalon and concrete have a field life of no more than 25 years (23).

The two approaches that have received the most attention based on their potential for meeting the requirements of an effective bio-intrusion barrier are the use of multi-layered rock materials and controlled release chemical toxins. The following discussion describes some of the experimental date supporting the use of those approaches for preventing biological intrusion.

MULTI-LAYERED ROCK INTRUSION BARRIERS

Initial studies at Hanford, Washington on the use of rock bio-intrusion barrier systems demonstrated the effectiveness of cobble (3.8 - 7.6 cm diameter) over conventional waste cover profiles in preventing plant and animal intrusion into simulated waste (24). Subsequent laboratory studies (24) indicated that improved performance of the rock barrier was obtained by adding gravel (0.3 -0.6 cm diameter) over the rock to retard the rate of soil movement downward into the large air spaces between the rock. The air spaces between the rock, which lack water and nutrients, account for the effectiveness of this barrier material in limiting plant root intrusion. Additionally, the rocks, if of sufficient mass, also prevent the burrowing of most small mammals that would occupy a waste site.

Follow-up studies were initiated at Los Alamos, New Mexico under funding from DOE's National Low-Level Waste Management Program and Environmental Research Division, to further evaluate the use of geologic materials as bio-intrusion barriers under different soil, climate, and vegetation regimes than at Hanford (25, 26). Important questions which were addressed in those studies were:

> How do cobble, cobble-gravel and bentonite clay barrier systems perform compared to a conventional waste cover consisting of crushed tuff and topsoil?
>
> What are optimum barrier-soil thickness combinations?

Waste cover profiles were constructed at small scale as shown in (Fig 3) to evaluate the effect of the following variables in limiting biological intrusion:

- top soil thickness,
- barrier thickness,
- barrier type, and,
- plant species.

A plant available tracer (CsCl) was used to indicate barrier failure (Fig. 3). Three fast-growing, deep rooted plant species were used to stress the various cover profiles to evaluate plant species effects on barrier performance. Pocket gophers were released on larger scale cover profiles containing the various barrier materials to evaluate the effect of the barriers in limiting burrowing with depth (25).

Based on a log-linear contingency table analysis, the type of vegetation, bio-barrier material, and soil and bio-barrier thickness were all statistically significant factors ($P<0.05$) affecting root penetration; barley was much more effective in penetrating cobble and cobble-gravel systems than were alfalfa or sweet clover (Table 1).

Crushed tuff, the sandy backfill material used in covering low-level waste sites at Los Alamos, offers little resistance to plant roots, regardless of plant species and soil-barrier thickness combinations (Table 2). In as little as 101 days (14 wk), plant roots had intruded through 69 of the 72 cover profiles that contained crushed tuff as a barrier material. The pattern of high root intrusion through crushed tuff was consistent throughout the remainder of the study, further demonstrating the need for an effective root intrusion barrier.

The clay, cobble, and cobble-gravel barrier systems were all much more effective than crushed tuff in limiting root intrusion even at minimum soil and barrier thickness combinations as shown by the data for the cobble-gravel barrier material in Table 3. For example, 172 days after seeding, 97% (70/72) of the crushed tuff barriers had been intruded by plant roots while corresponding values for clay, cobble, and cobble gravel, respectively, were 55, 42, and 40%. Thus, the latter 3 barrier systems resulted in about 2 times more protection against root intrusion than the sandy backfill over one growing season. Increasing soil and barrier thickness greatly improved performance of the clay, cobble, and cobble-gravel root barrier systems (Table 3). Maximum soil-barrier thickness combinations (1.5 m total) for the cobble and cobble-gravel barrier materials generally reduced root intrusions to less than 25%.

Although clay, cobble and cobble-gravel barrier systems work equally well in this short-term experiment, some problems were encountered with the use of bentonite clay and cobble as barrier materials. Bentonite clay, which was saturated with water before use, was subject to shrinking causing by depletion of water from the clay. Visual observation of exposed root profiles in the lysimeter suggested that removal of water from the clay by plant roots was the cause of that shrinkage.

Examination of profiles containing cobble barriers suggested that the large pore spaces between the rocks gradually become filled with soil overburden. As such, cobble may not be effective over long periods of time because the soil between the rocks will provide a pathway for root growth. The 2-cm-diameter gravel which was placed over the cobble in the cobble-gravel system greatly retarded the rate of soil migration the air into spaces between the cobble rock.

Results of the animal intrusion experiment demonstrated that cobble, cobble-gravel and bentonite clay were equally effective in preventing animal intrusion with depth (25). Crushed tuff, however, was readily used for turneling and offered little resistance to burrowing activity.

For reasons discussed previously, bentonite clay would probably not be effective as an animal intrusion barrier due to the plant associated drying and shrinking of the clay barrier. Additionally, Cobble, although effective in preventing animal burrowing may not be a viable long-term plant root intrusion barrier. Although visual examination of soil excavated by the gophers suggested that burrowing occurred in the gravel overlaying the cobble, tunnels could not be maintained in this loosely aggregated material. The latter result, along with those of the plant root intrusion study, indicate that cobble-gravel may be an effective biological intrusion barrier when used applied at a 1 meter thickness. However, at least four considerations related to the use of cobble-gravel barrier systems remain, They are,

1) performance of cobble-gravel intrusion barrier systems over extended time frames,

2) performance at field scale under natural precipitation regimes with native vegetation,

3) performance under various degrees of subsidence, and

4) effect on water balance (percolation into the cover profile).

Experiments to address those topics are currently underway at Los Alamos and Hanford (27); preliminary results (26) show that the effect of a vegetated (barley, ~80% ground cover) cobble-gravel cover system (60 cm topsoil, 100 cm cobble-gravel) on the infiltration of water into simulated waste has not been different that a vegetated trench cover comprised of crushed tuff and topsoil (60 cm topsoil, 100 cm crushed tuff). Acute additions of as much as 5 cm of precipitation had no effect on the moisture content of the backfill underlying both cover systems indicating that the combination of 60 cm topsoil and heavy vegetation cover provides sufficient water storage capacity and transpiration potential to prevent percolation of water through the barrier. Increasingly larger additions of water are now being applied to those experiments to determine when infiltration of water through the rock barrier will occur.

CHEMICAL BIO-INTRUSION BARRIERS

A major impediment to the use of toxins in preventing plant and animal intrusion into waste sites has been the need to control the rate of release of the toxins to increase the useful life of the chemicals under environmental conditions (27,28). A further requirement is that the toxins be placed in a configuration which does not greatly decrease plant density and, thus, contribute to water related problems (i.e. erosion, leaching).

Pilot studies on the use of herbicides to prevent plant root intrusion (27,29) identified trifluralin and oxyzalin as being effective in preventing root growth while maintaining normal vegetative ground cover and root growth above the buried toxin. However, the degradation and leaching of these compounds under the conditions of the pilot experiments was rapid.

By encapsulating the herbicide in a polymer, the herbicide is protected from degradation which occurs when it is applied to soil directly. For instance, the results indicate that the half-life of trifluralin in Ritzville silt-loam is approximately 50 days (29). Thus, even with high application rates, the directly applied herbicide will be ineffective within a few years. On the other hand, when trifluralin is encapsulated within a polymeric pellet, degradation (by biological and chemical means) occurs only following release of the trifluralin from the surface of the device. Thus, the trifluralin remaining within the device is protected until it is able to diffuse to the surface of the device.

A number of studies to investigate the release of trifluralin from a variety of polypropylene and polyethylene carrier/delivery systems indicated that theoretical serviceable lifetimes of approximately 100 years were achievable (27).

The studies investigated the effects of pellet size, trifluralin concentration, carbon black filler, and polymer type on optimum performance. Results of these tests indicated that an optimum pellet was cylindrical (9 mm in diameter and 9 mm long), formed of polyethylene, and impregnated with 24% trifluralin and 18% carbon black. When placed on 5 cm centers (0.04 pellets/ cm^2) the release of trifluralin from the pellets was sufficient to prevent root intrusion. The minimum concentrations in the soil required to inhibit root growth for 13 varieties of plants ranged from 0.3 to 6.4 $\mu g/g$ (Table 4).

The 9 mm x 9 mm pellets described above were placed in the overburden over uranium tailings at the Grand Junction site in August 1981. They are placed 76 cm below the soil surface. Following emplacement for an eight month period, core samples were taken at the site, the soil in the region of the pellets was carefully divided into horizontal sections, and the sections individually analyzed to determine the concentration of the trifluralin in each section. The results (27) are shown in Table 5. These results indicate that trifluralin does not move significantly through the soil profile; concentrations in the immediate region of the device exceed that necessary to prevent root intrusion through the pellet-loaded zone. While pellets placed on 2.5 cm centers provide an extra measure of protection in preventing root intrusion, the devices placed on 5 cm centers provide concentrations of trifluralin exceeding the minimum effective level. In this case, trifluralin is being released from the device at approximately the same rate that it is being destroyed by biological and chemical degradation. Experiments in the laboratory indicate that this equilibrium level is reached approximately 30 days after the device is placed in the soil.

COST OF BARRIER SYSTEMS

Projected cost of application of the cobble-gravel and chemical barrier systems described in this paper are presented in Table 5. A one meter thick cobble-gravel barrier applied at Los Alamos cost about $100K/ha including delivery of materials to the site. The chemical barrier system is estimated to cost substantcially less than the rock barrier ($10K versus $100K) although the chemical materials are not yet commercially available.

Advantages of the rock barrier system are that it is effective against both plant and animal intrusion and it is not subject to rapid deterioration. Based on preliminary studies, the rock barrier does not alter water balance relationships when coupled with optimum topsoil type and depth and plant cover. Potential disadvantages include cost and disruption by subsidence.

The advantages of the chemical toxin as a plant root barrier is that it is easy to apply, relatively inexpensive and, based on theoretical considerations, should be effective for a hundred years. The serviceability life of the controlled-release system can be varied by adjusting the size and trifluralin concentration of the polymer carrier/delivery system.

Disadvantages of the controlled release system are that serviceability life of the device have not been field tested and that animal burrowing and subsidence may disrupt the barrier system sufficiently to cause barrier failure. The presence of trifluralin contaminated beads on the soil surface may retard above ground herbage growth contributing to water related problems. Consequently placement depth within the cover profile is an important issue which is not as yet, resolved.

SUMMARY AND CONCLUSIONS

The need to develop effective long-term methods for limiting plant and animal intrusion into large volume waste disposal sites has been recognized as an important adjunct to designing disposal facilities that minimize transport of contaminants into biological pathways. Present state-of-the-art methods on preventing biological intrusion involve use of multi-layered rock materials or chemical toxins that inhibit root growth. Although many questions remain about long-term effectiveness of those systems, they clearly outperform conventional waste cover materials. Field studies at Los Alamos and Hanford will resolve most of the remaining questions about the use of these materials as biological intrusion barriers.

Layered rock barriers, such as the cobble-gravel system described in this paper, offer long-term effectiveness if soil can be prevented from entering the air spaces between the rock. The 2-cm-diameter gravel has been shown to reduce infiltration of soil particles downward into the rock over the short-time period of one year. Consideration should be given to employing rock barriers that incorporate graded rock sizes from bottom to top to eliminate soil movement into the large rock air spaces.

Effective layered rock barriers also require the use of adequate depths of topsoil to preclude increased infiltration of water into waste. Adequate moisture storage capacity and plant cover are essential to maximize losses of incident precipitation to evapotranspiration.

Although cost of a layered rock intrusion barrier is relatively high compared to the chemical barrier the cost relative to operation, closeout and long-term management of the site would be minimal. A commercial operation, charging $165/m^3$ ($5/ft^3$) to bury waste, would expend roughly $0.67/m^3$ isolate to apply a 1 meter thick cobbel-gravel barrier, based on cost estimates of appling this barrier at Los Alamos.

Questions relative to effectiveness of layered rock intrusion barrier over long periods of time, under various degrees of subsidence and under full scale conditions are being addressed in on-going studies. Although we expect that cobble-gravel will adequately satisfy all the requirements of a good barrier material, present data are not sufficient to say so with a high degree of confidence.

Chemical toxins is such as Trifluralin, that prevent plant root intrusion appear to satisy most of the requirements of a good barrier material for plant roots. However, supporting data are not yet available to determine long-term effectiveness under field conditions and the effects of animal burrowing and subsidence on the physical integrity of the barrier layer. Further evaluation of the toxic properties of trifluralin need to be determined for other native plant species, particularly trees and shrubs.

A methodology which may be worthy of consideration is to combine the rock and chemical barrier systems. The chemical toxin, when placed beneath the rock barrier, could serve as the plant root intrusion barrier, while a reduced thickness cobble-gravel (or cobble) layer could serve in preventing animal intrusion. Overall cost of such a methodology would be reduced because of the reduced need for a thick cobble-gravel layer.

Table 5. Cost of applying layer rock and chemical bio-intrusion barriers in waste site covers.

Barrier Type	Configuration	$/ha
Cobble-gravel	75 cm cobble	75k
	25 cm gravel	25k
Trifluralin beads	9mm X 9mm with 25% trifluralin (3.7×10^6 beads/ha)	13k

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TABLE 1. CUMULATIVE NUMBER OF ROOT PENETRATION THROUGH BIOBARRIER AS A FUNCTION OF VEGETATION TYPE, BIOBARRIER TYPE, AND ELAPSED TIME SINCE SEEDING. SAMPLE SIZE FOR EACH COLUMN IS 4. (from ref. 25).

	Elapsed Time (days)					Never
	72	101	119	143	172	Penetrated
Crushed Tuff						
Alfalfa	14	23	23	23	23	1
Barley	24	24	24	24	24	0
Clover	17	22	23	23	23	1
Clay						
Alfalfa	4	8	10	11	15	9
Barley	13	14	14	14	14	10
Clover	7	10	11	11	11	13
Cobble						
Alfalfa	1	4	5	8	8	16
Barley	12	18	18	18	18	6
Clover	0	2	4	4	4	20
Cobble-Gravel						
Alfalfa	0	0	3	3	4	20
Barley	15	18	20	20	20	4
Clover	0	1	2	4	5	19

TABLE 2. CUMULATIVE NUMBER OF ROOT PENETRATIONS THROUGH CRUSHED TUFF BIOBARRIERS AS A FUNCTION OF SOIL THICKNESS, BIOBARRIER THICKNESS, AND ELAPSED TIME SINCE SEEDING. SAMPLE SIZE FOR EACH COLUMN IS 12, WITH PERCENTAGE OF PENETRATION IN PARENTHESES (from ref. 25).

Elapsed Time (days)	Soil-Barrier Thickness Combinations (cm)					
	30-30	60-30	30-60	60-60	30-90	60-90
53	12 (100)	5 (42)	6 (50)	a	a	a
72	12 (100)	12 (100)	12 (100)	8 (67)	7 (58)	4 (33)
77	12 (100)	12 (100)	12 (100)	a	a	a
101	12 (100)	12 (100)	12 (100)	12 (100)	12 (100)	9 (75)
119	12 (100)	12 (100)	12 (100)	12 (100)	12 (100)	10 (83)
148	12 (100)	12 (100)	12 (100)	12 (100)	12 (100)	10 (83)
172	12 (100)	12 (100)	12 (100)	12 (100)	12 (100)	10 (83)
Never Penetrated	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	2 (17)

[a]Samples not taken.

TABLE 3. CUMULATIVE NUMBER OF ROOT PENETRATIONS THROUGH COBBLF-GRAVEL BIOBARRIERS AS A FUNCTION OF SOIL THICKNESS, BIOBARRIER THICKNESS, AND ELAPSED TIME SINCE SEEDING. SAMPLE SIZE FOR EACH COLUMN IS 12, WITH PERCENTAGE OF PENETRATIONS IN PARENTHESES (from ref. 25).

Elapsed Time (days)	Soil-Barrier Thickness Combinations (cm)					
	30-30	60-30	30-60	60-60	30-90	60-90
53	4(33)	0(0)	1(8)	a	a	a
72	4(33)	2(17)	4(33)	4(33)	1(8)	0(0)
77	5(42)	3(25)	4(33)	a	a	a
101	5(42)	3(25)	4(33)	4(33)	2(17)	1(8)
119	7(58)	4(33)	4(33)	4(33)	3(25)	3(25)
146	8(67)	5(42)	4(33)	4(33)	3(25)	3(25)
172	9(75)	6(50)	4(33)	4(33)	3(25)	3(25)
Never Penetrated	3(25)	6(50)	8(67)	8(67)	9(75)	9(75)

a Samples not taken.

TABLE 4. MINIMUM EFFECTIVE LEVELS OF TRIFLURALIN REQUIRED TO INHIBIT LONGITUDINAL ROOT GROWTH, AND EFFECTS ON SHOOT AND ROOT DRY WEIGHT (from ref. 29).

Plant	Time for Root to Reach Treated Zone[a] (days)	Duration of Study (days)	Minimal Effective Concentration[b] (ppm)	Effect on Shoot/Root Dry Weight[c] (% of Control)
Russian Thistle	17	31	0.3	92/82
Tansy Mustard	21	45	4.7	90/85
Fourwing Saltbush	15	45	4.0	72/77
Gardner Saltbush	16	45	3.1	115/94
Winter Fat	18	55	1.9	57/50
Crown Vetch	14	45	6.4	94/115
Rocky Mtn. Penstemon	24	45	0.9	99/101
Palmer Penstemon	20	45	1.5	102/97
Whitmar Wheatgrass	13	45	0.8	97/85
Thickspike Wheatgrass	21	59	0.7	71/67
Russian Wildrye	14	56	0.5	86/82
Lewis Blue Flax	13	56	2.5	83/101
Bitterbush	14	54	1.2	95/96

[a]Roots grew from 18 to 24 cm below surface; 2-cm treated zone located 25 cm from surface

[b]Plugs for analysis removed from soil just below root zone

[c]Mean of three replicates

Table 5. Trifluralin in Soil Samples Taken (April 1982) from the Soil Profile at Grand Junction.

Distance Above Pellets (cm)	μg Trifluralin/g Soil Pellets Placed at 5 cm intervals[1]	Pellets Placed at 2.5 cm intervals
0-1.3	41.3 ± 20.2	81.6
1.3-2.5	19.1 ± 14.6	15.4
2.5-5	4.5 ± 2.2	3.8
5-7.6	3.8 ± 3.8	0.6
7.6-10	0.2 ± 0.2	0
10-12.7	0.1 ± 0.1	0
12.7-15.2	0.1 ± 0.1	0
15.2-76	0	0

[1]3 replicates

Table 6. Cost of applying layer rock and chemical bio-intrusion barriers in waste site covers.

Barrier Type	Configuration	$/ha
Cobble-gravel	75 cm cobble 25 cm gravel	75k 25k
Trifluralin beads	9mm X 9mm with 25% trifluralin (3.7×10^6 beads/ha)	13k

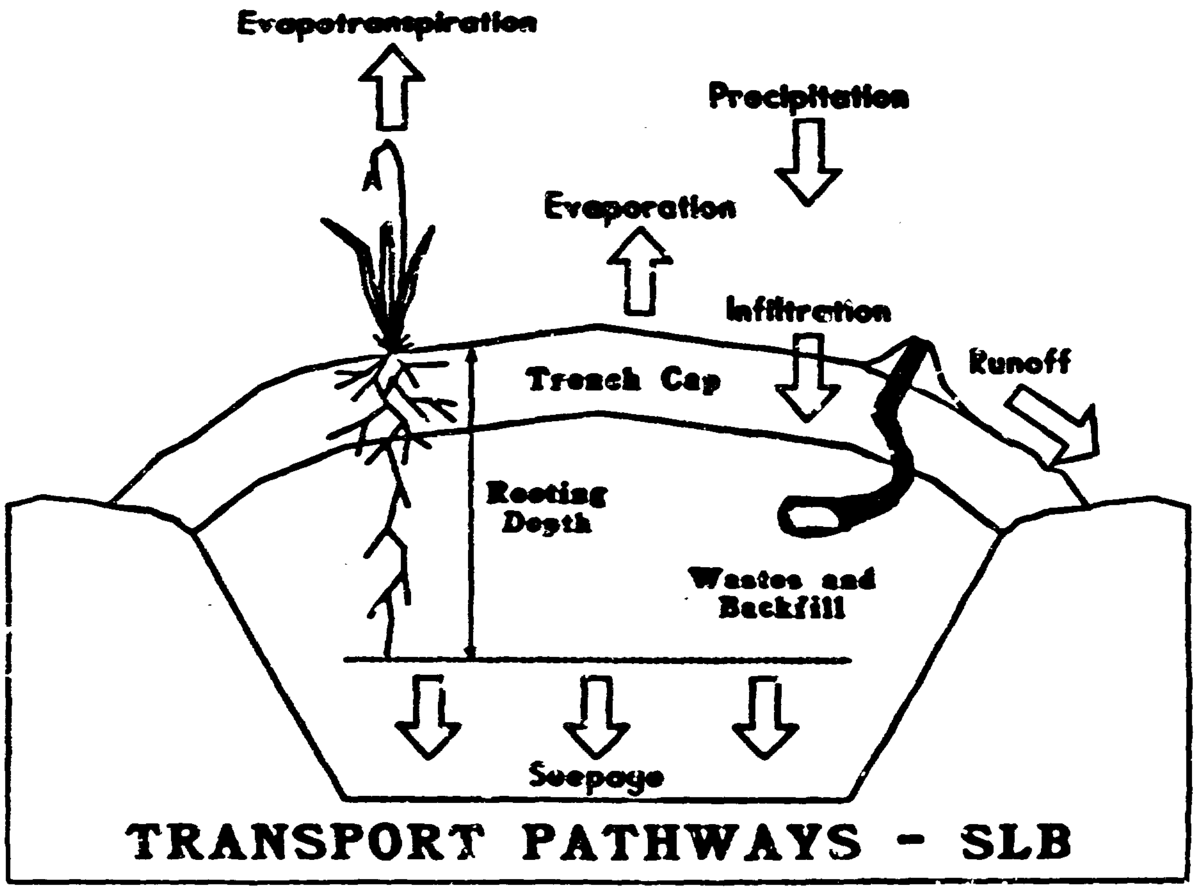

Evapotranspiration
Precipitation
Evaporation
Infiltration
Runoff
Trench Cap
Rooting
Depth
Wastes and
Backfill
Seepage
TRANSPORT PATHWAYS - SLB

FIGURE 1

FIGURE 2

PLUTONIUM TRANSPORT PATHWAYS

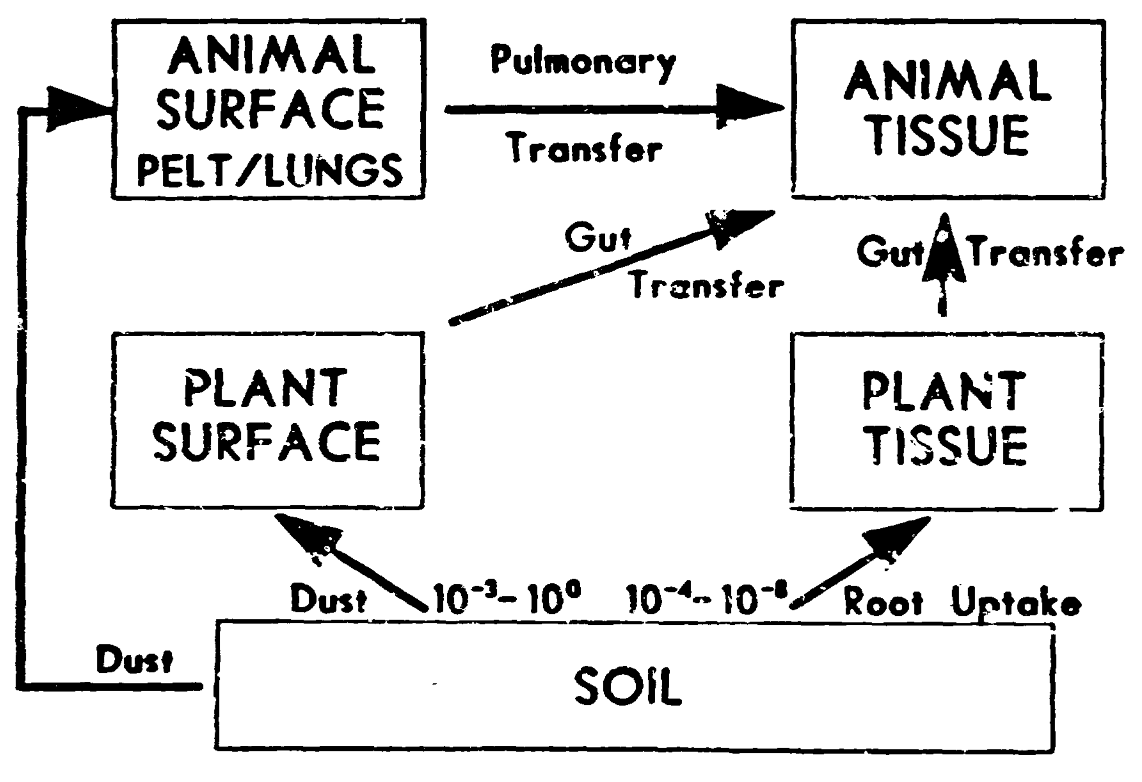
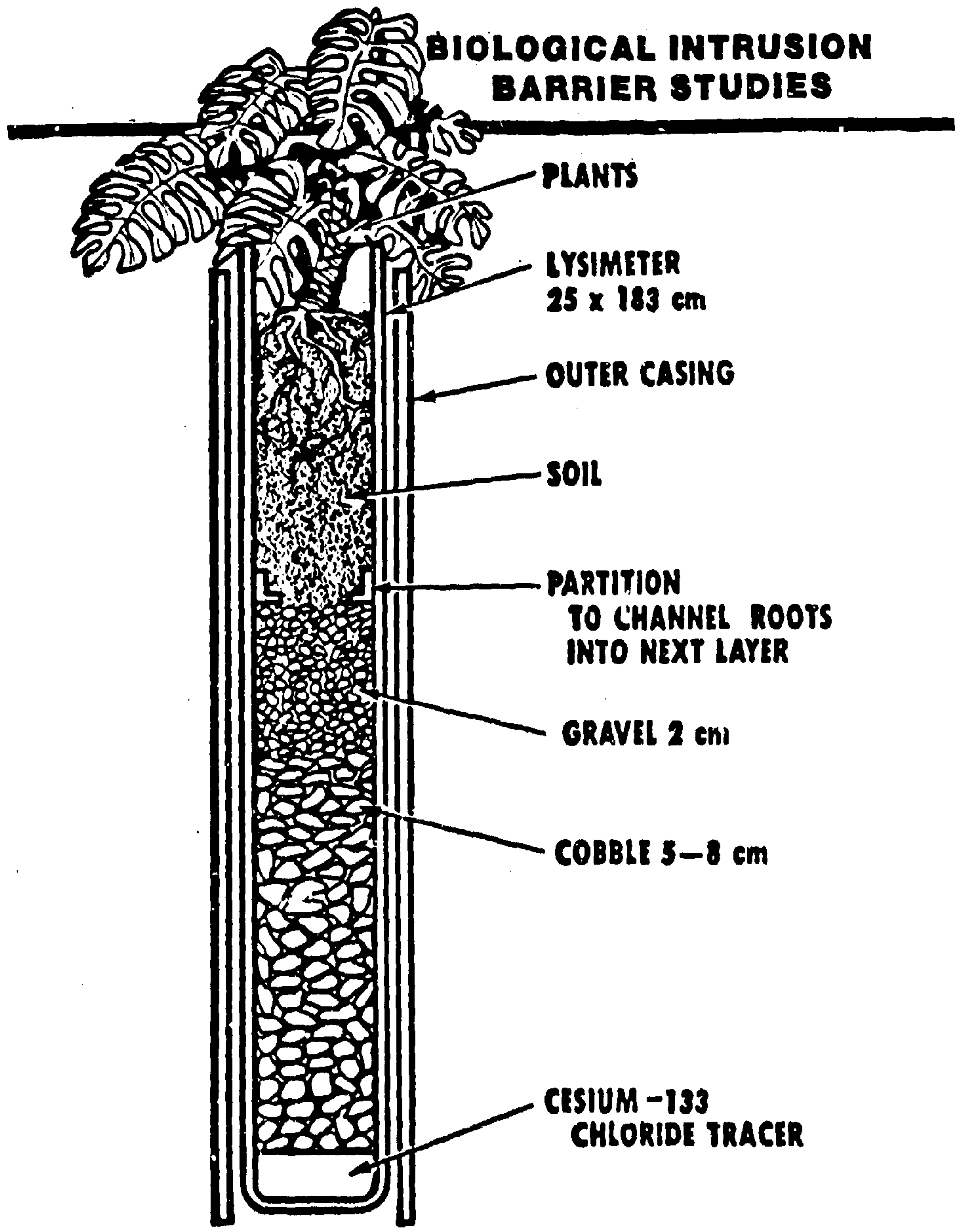


FIGURE 3


BIOLOGICAL INTRUSION
BARRIER STUDIES
PLANTS
LYSIMETER
25 x 183 cm
OUTER CASING
SOIL
PARTITION
TO CHANNEL ROOTS
INTO NEXT LAYER
GRAVEL 2 cm
COBBLE 5—8 cm
CESIUM -133
CHLORIDE TRACER