Appendix C

Biointrusion Data

C-1.0 BURROWING ANIMAL AND INSECT INTRUSION

Excessive burrowing animals and insects can have a detrimental effect on a landfill cover system. Burrowing animals can produce preferential flow (Hakonson 1986, Bowerman and Redente 1998, Cadwell et al. 1989, Pratt 2000). Dwyer (2003) revealed that preferential flow can provide flux through a cover system under unsaturated conditions, but this flow generally does not occur until the soil moisture approaches saturation where the matric potential is reduced to about 1000 cm. Burrowing organisms have the potential to redistribute contaminants within the soil profile, to transport them to the ground surface, and to become contaminated in the process. The importance of animal burrowing at a given LANL site will depend on the vertical location of waste in the landfill, cover system design (soil type, soil depth, type, and longevity of intrusion barrier), nature of the waste in the near surface environment, plant cover (species composition, quantity, and changes with time), fauna and/or insects that occupy the site (species composition, changes with time), and the stability of the cover over the long term (disturbances from fire, drought, etc.). Figure C-1.0-1 shows typical small mammal burrow holes.

Figure C-1.0-1. Small burrow holes found on mixed waste landfill at Sandia National Laboratories

Some species of kangaroo rats are known to burrow to depths of 25–175+ cm below the ground surface (Coulombe 1971). The activities of pocket gophers can account for the transport of large quantities of buried waste to the ground surface and have been shown to have a wide range of both positive and negative effects on the integrity of ET covers (Cox 1990, Ellison 1946, Ellison and Aldous 1952). Studies of pocket gophers on low-level radioactive waste sites at LANL brought 11,255 kg of material to the ground surface over a 14-month period. This resulted in large areas of void space in the landfill (Gonzales et al. 1995, Hakonson et al. 1982b). Macropores (e.g., void spaces left over by decaying roots and animal passages) also provide direct conduits for water movement into the soil profile (Hakonson et al. 1994).

Insects also have the ability to tunnel deep into a landfill cover (Figure C-1.0-2). Biointrusion into a landfill cover profile by ants (Johnson and Blom 1997, Gaglio et al. 1998), earthworms (Edwards et al. 1988, Lee 1985, MacKay and Kladivko 1985, Waugh et al. 1999), or roots (Waugh et al. 1999, Reynolds 1990) is a contributing factor to preferential flow. Harvester ants (Figure C-1.0-2) can develop tunnel systems to depths of 6 m and have been responsible for significant increases in contaminant levels found on the surfaces of landfills (Cole 1968).

Studies in Idaho showed that infiltration of water into areas disturbed by ants is higher than in non-disturbed areas (Blom et al. 1994) but that ant mound soil moisture dries out quicker than non-mound soil.

Figure C-1.0-2. Anthill on landfill cover

Some field studies (O'Farrell and Gilbert 1975, Winsor and Whicker 1980, Arthur and Markham 1983, Hakonson et al. 1982b) showed that burrowing animals may alter the vertical distribution of soil radionuclides present near the ground surface and in the process the animals themselves can become contaminated, thus further spreading the radionuclides. Other studies show that animal burrowing can influence water balance, erosion, and vegetation species composition and biomass on landfill caps by changing the physical and hydrologic characteristic of cap soil (Sejkora 1989), Gonzales et al. 1995, Hakonson 1998). Burrowing activity loosens the soil, creates surface roughness, increases infiltration, and increases soil moisture at least temporarily (Hakonson 1998). Controlled studies of this potential problem show that increased soil moisture does not necessarily lead to increased percolation of moisture into the waste when a vegetation cover is present on the cap (Sejkora 1989, Hakonson 1998, Gonzales et al. 1993). The increased soil moisture resulting from burrowing effects on infiltration can actually stimulate increased plant growth, leading to an increase in plant transpiration (Hakonson 2000, Gonzales et al. 1993) with a resulting net decrease in flux.

C-2.0 BURROW DEPTHS

Fossorial animals spend much of their life underground in tunnel systems created for resting, breeding, feeding, and excreting of waste products. Assumptions for ecological risk assessments usually use tunnel depths of about 60 cm. However, there is ample evidence in the literature that fossorial mammals can excavate burrows to greater depths. For example, pocket gophers develop very extensive tunnel systems in the soil although most of the tunnel system is concentrated in the upper rhizosphere. Gopher tunnel systems can extend to depths of 2 m (Miller 1957). Prairie dogs excavate tunnels to over 4 m while ground squirrels, depending on species, can burrow to depths of 30-120 cm (Reynolds and Wakkinen 1987, Linsdale 1946). Larger species such as the badger (Figure C-2.0-1) may create burrows to at least 150 cm deep and 15–20 cm in diameter. Estimates of burrowing depths for various species are given in Table C-2.0-1.

Figure C-2.0-1. Badger hole found adjacent to a radioactive waste landfill in Hanford, WA

Table C-2.0-1

Burrowing Depths of Some Representative Burrowing Animals (from Cline et al. 1982)

Species Recorded	Tunneling Depth (cm)
Marmota monax (marmot)	40–50
Cynomys ludovicianus (black tailed prairie dog)	91–427
Spermophilus townsendi (ground squirrel)	50–80
Thomomys talpoides (pocket gopher)	10–30
Perognathus longimembris (pocket mouse)	52–62
Dipodomys spectabilis (kangaroo rat)	40–50
Dipodomys merriami (Merriam's kangaroo rat)	26–175+
Spermophilus townsendi (ground squirrel)	50–80
Thomomys talpoides (pocket gopher)	10–30
Perognathus longimembris (pocket mouse)	52–62
Dipodomys spectabilis (kangaroo rat)	40–50
Dipodomys merriami (Merriam's kangaroo rat)	26–175+
Spermophilus townsendi (ground squirrel)	50–80

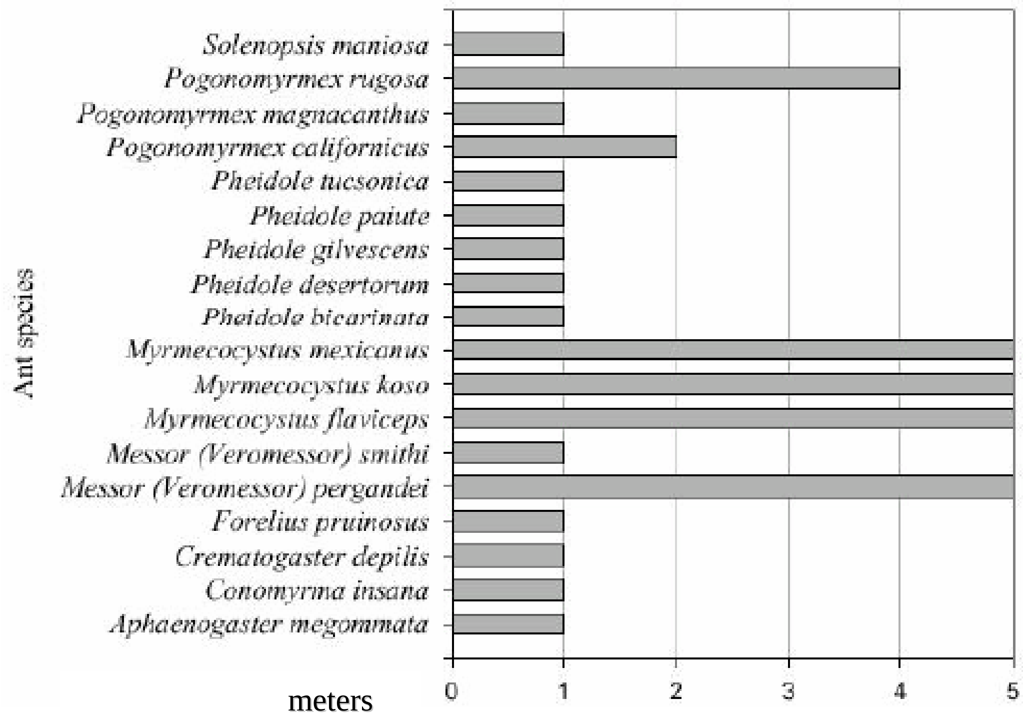

Figure C-2.0-2. Burrowing depths of some representative ant species (Jensen 2000)

C-3.0 RATES OF SOIL TURNOVER

Pocket gophers, and other burrowing mammals, have the potential to displace large amounts of soil as a consequence of burrowing. Maximum pocket gopher densities have been reported to range from 54 to 120 animals per ha (Hansen 1965). Actual amounts of soil moved to the surface by pocket gophers have ranged from 16 to 103 ton/ha/yr (Mielke 1977, Spencer et al. 1985). Estimates of 12–20 ton/acre/yr have been reported for pocket gopher densities on the order of 10 per acre (Grinnell 1923, Ellison 1946). However, much of the displaced soil is not pushed to the surface, but is re-deposited within the burrow system. For example, Andersen (1987) found that 41–87% of excavated soil was deposited as backfill within the tunnel systems below ground.

Hakonson et al. (1982b) conducted a study of soil excavation rates by pocket gopher on a LLW site at LANL. They found that over a 401-day study period on a study area (total area was 0.95 ha), pocket gophers produced about 5 mounds per day per ha. The total mass of the soil in these mounds over the 401-day study period was 11 ton per ha per year, for an average excavation rate of about 30 kg per ha per day. Mound-building activity was greatest in the late summer and fall, when a total of about 60 kg per ha of soil was brought to the surface of the landfill each day.

Hakonson et al. (1982b) also found that the digging activity of pocket gophers on the LLW site at LANL turned over less than 1/10% of the cap soil during the 401-day observation period. However, the 11,255 kg of material brought to the soil surface over the 14-month period represented a volume of about 8.3 m^3—so, presumably, about 8.3 m^3 of void space was created within the cover profile. Based on an average tunnel cross-sectional area of 30 cm^2, based on filed measurements, 8.3 m^3 of void space within the cover profile represents about 2800 m of pocket gopher tunnel system per ha.

C-4.0 LANL STUDY ON GOPHERS

Gophers are the primary burrowing mammal of concern for cover systems at LANL. A study at Los Alamos (Hakonson 1998) on ET cover plots showed that pocket gopher burrowing in the presence of vegetation resulted in large decreases in runoff, erosion, and contaminant loss (tracer cesium [Cs]-133) via erosion but increased migration of the surface applied tracer into the subsurface soil due to increased infiltration. Vegetation slightly decreased runoff but greatly decreased erosion and contaminant loss by erosion. As with gophers, vegetation enhanced movement of contaminant into the soil. Gophers alone had an effect similar to vegetation alone in that they decreased runoff and erosion and only slightly decreased contaminant losses due to erosion. The study concluded that the effects of pocket gopher burrowing in degrading ET cover plots were minimal when vegetation was a component of the cover. Burrowing decreased erosion of the cover but did so at the expense of increasing water and surface contaminant migration into the soil. Those effects, however, were mitigated by soil moisture removal by the vegetation.

C-5.0 ADDITIONAL GOPHER EFFECTS ON EROSION/INFILTRATION

Gophers can have a positive impact on soil covers if their burrowing activity is not excessive. Their burrowing can enhance infiltration (Marshall and Holmes 1979), Lysikov 1982, Aubertin 1971, and Grant et al. 1980) that leads to a more robust stand of vegetation. The burrowing activity can mix soil nutrients vertically within the soil profile (Culver and Beattie 1983, Czerwinski et al. 1971, Levan and Stone 1983, Lockaby and Adams 1985). The combination of increased infiltration and soil nutrient mixing can lead to a healthier diversity of vegetation cover (Mielke 1977, Tilman 1983, Grant et al. 1980, Ellison and Aldous 1952, Laycock and Richardson 1975).

A study by Sejkora (1989) is relevant to LANL covers because it was designed specifically to evaluate the effects of pocket gopher burrowing and vegetation cover on water balance, erosion, and contaminant transport on an ET cover. Sejkora used a 50-foot diameter rotating boom rainfall simulator to apply several storm events over a two-year period, applied at 60 mm/hr over one hour, to measure erosion from 8 - 3 × 11-m plots with a 5% surface slope. The plots were either vegetated or devoid of vegetation and designed with or without pocket gopher burrowing. Compared to plots without pocket gopher burrowing, Sejkora found that burrowing activities of pocket gophers reduced surface runoff by an average of 21%, decreased soil erosion by 42%, and reduced erosional transport of tracer Cs applied to the surface of the plots by 33%. Sediment yields from the plots containing gophers were reduced due to an average decrease of 30% in flow velocity and a decrease of 10–75% in calculated erosion. Conversely, Sejkora found that total water infiltration increased by an average of 95% on plots disturbed by gophers and, due to reduced runoff velocity brought about by the increased surface roughness, a 27% enrichment in the silt and clay fraction in eroded soil leaving the plots. Although enriched in fines, the total mass of material eroded from the plots with gophers and vegetation averaged just 28% of that eroded from vegetated plots without gophers. Of the dependent variables investigated in Sejkora's study, total soil loss was most affected by surface treatment. Soil loss for the non-vegetated, no gopher treatment remained relatively uniform over the two-year duration of the study, while soil loss associated with the other three treatments (i.e., non-vegetated with gophers, vegetated, and vegetated with gophers) showed a general decline through time. For example, at the end of the two-year study, sediment yields from these three treatments averaged from 5–25% of that measured on these same plots at the beginning of the study. Averaged over the two-year period, vegetated plots had 72% less soil loss than plots without plant cover, while plots that were both vegetated and contained pocket gophers had about 4% of the soil loss measured on the bare plot treatments without gophers.

This burrowing by gophers and other mammals and insects can have significant negative impacts, however. The burrowing can create a pathway for release of hazardous waste. Cover designs that rely on vegetation for water extraction and erosion control also create habitat for animals that may contribute to the degradation of the cover. Burrowing animals can mobilize contaminants by vertical displacement or by altering erosion, water balance, and gas release processes (Hakonson and Lane 1992, Suter et al. 1993, Bowerman and Redente 1998). Vertical displacement results as animals excavate burrows, and can be followed by ingestion or external contamination on skin and fur (Hakonson et al. 1982b), McKenzie et al. 1982). Once in the surface environment, contaminants may then be transferred through higher trophic levels and carried offsite (e.g., O'Farrell and Gilbert 1975, Arthur and Markham 1983). Loose soil cast to the surface by burrowing animals is vulnerable to wind and water erosion (Winsor and Whicker 1980, Cadwell et al. 1989). Burrowing influences soil-water balance and gas releases by decreasing runoff, increasing rates of water infiltration and gas diffusion, but also increasing evaporation due to natural drafts (Cadwell et al. 1989, Sejkora 1989, Landeen 1994). The cover thickness can be the primary biointrusion deterrent. Water retention in the soil creates habitat for relatively shallow-rooted plants, and the thickness of a cover soil profile can exceed the depth of most burrowing vertebrates in the area. Periodic inspection is the most efficient means for monitoring encroachment and intrusion of covers by animals. Inspectors shall look for and document evidence of animal traffic on the cover such as tracks, trails, and droppings. If evidence of animals that could damage the cover is observed, such as fecal material from large ungulates that could overgraze or trample vegetation, then institutional controls such as fencing shall be considered to prevent animal access. Inspectors should also look for animal burrows and holes large enough to cause channeling of water or displacement of loose soil to the surface where it is vulnerable to erosion.

C-6.0 TRANSPORT OF RADIOACTIVE WASTE VIA FAUNA

As with vegetation, the resuspension of soil particles can be a major source of contaminants to animals living in arid ecosystems. Soil particles can be transported to animals in association with exterior surfaces of food and by direct transfer of soil to the animal via inhalation, ingestion, and contamination of the pelt (Hakonson and Lane 1992).

Plutonium is the best example of a radionuclide whose transport to animals in arid ecosystems is dominated by physical processes. Data from many field sites and source conditions show that gut availability of plutonium and other contaminants bound to soil in a variety of animals including rodents, deer, and cattle is very low (gut to blood transfer $<10^{-5}$), leading to very low concentrations of contaminant in internal tissues and organs (Smith 1977, Moore et al. 1977, Hakonson and Nyhan 1980, Arthur et al. 1987). Highest concentrations of most soil contaminants in dry, dusty environments are usually found in tissues exposed to the external environment. Those tissues include the pelt, gastrointestinal tract, and lungs. At Los Alamos, about 96% of the plutonium body burden in rodents from the canyon liquid waste disposal areas was in the pelt and gastrointestinal tract (Hakonson and Nyhan 1980).

Because soil passes through the gastrointestinal tract of free-ranging animals on a daily basis, there is a potential to redistribute soil radionuclides across the landscape. Studies at the Nevada Test Site with cattle (Moore et al. 1977), at Rocky Flats Plant with mule deer and small mammals (Little et al. 1980, Arthur and Alldredge 1979), and at Idaho National Engineering Laboratory with small mammals and coyotes (Arthur and Markham 1983,) demonstrate that horizontal (and vertical in the case of burrowing animals) redistribution of soil plutonium does occur as animals move within and outside contaminated areas. However, the magnitude of this transport was shown to be very small over the short term (Arthur 1979, Arthur and Markham 1983, Arthur et al. 1987).

There are circumstances where animal transport of soil contaminants can assume more importance. For example, fission product sludge containing strontium (Sr)-90 and Cs-137 in a salt form was released to unlined cribs at Hanford and the cribs were backfilled with clean soil. A large animal, probably a coyote or badger, then burrowed down to the sludge and created direct access for other animals seeking the salts, including jackrabbits (O'Farrell and Gilbert 1975). Jackrabbits ingested the radioactive salts, became contaminated, and then excreted Sr-90 on the ground surface. Levels of Sr-90 in excreta were found over a 15 km^2 surface area (O'Farrell and Gilbert 1975). This incident with Sr-90 and jackrabbits was a special case that involved liquid waste sludge disposal trenches that were not adequately covered.

Potentially more soluble Sr and Cs transport to animals in arid ecosystems involves a combination of physical and physiological processes. The more tightly bound these radionuclides are to soil (related to clay content of soil and local climate), the more their transport will be governed by soil particle transport. Data on Sr-90 and Cs-137 in small mammals from Nevada Test Site (Romney et al. 1987) and at a burial ground at Idaho National Engineering Laboratory (Arthur et al. 1987) show relatively high concentrations of these radionuclides in lung, pelt, and gastrointestinal tract similar to plutonium. This suggests that physical transport of these more "soluble" radionuclides is also important as with plutonium. The bioavailability of radionuclides such as Cs and Sr will depend on chemical form, local environmental conditions, and the structure and function of the relevant food webs.

Tritium would be one of the few exceptions to the general observation that physical transport mechanisms dominate in the transport of soil surface contaminants to biota. Uptake by roots or sorption through the leaf surface would dominate in tritium transport to vegetation. Levels of tritium in animals would reflect levels in the source (i.e., concentration ratios are 1 or less) since tritium is not concentrated as it moves through abiotic and biotic pathways. Furthermore, tritium in vegetation is available to nectivorous organisms such as honeybees as well as herbivores. While tritium is readily transported through ecosystems, it is rapidly turned over in biological systems at rates corresponding to water turnover in these systems. In humans, body water turnover is about three days (Radiological Health Handbook 1970).

C-7.0 FLORA INTRUSION

Many lessons have been learned from the UMTRA program. The UMTRA program began by designing each layer of the final cover system individually to address a specific issue rather than designing the cover to act as a system within a dynamic ecosystem. An example involves the use of rock riprap as a surface cover to prevent biointrusion (Figure C-7.0-1). The effects of this layer actually changed the cover system by introducing a nonconductive surface layer, thus significantly reducing evaporation and creating a saturated soil layer beneath that, in turn, attracted deep woody rooted plant species that were not intended.

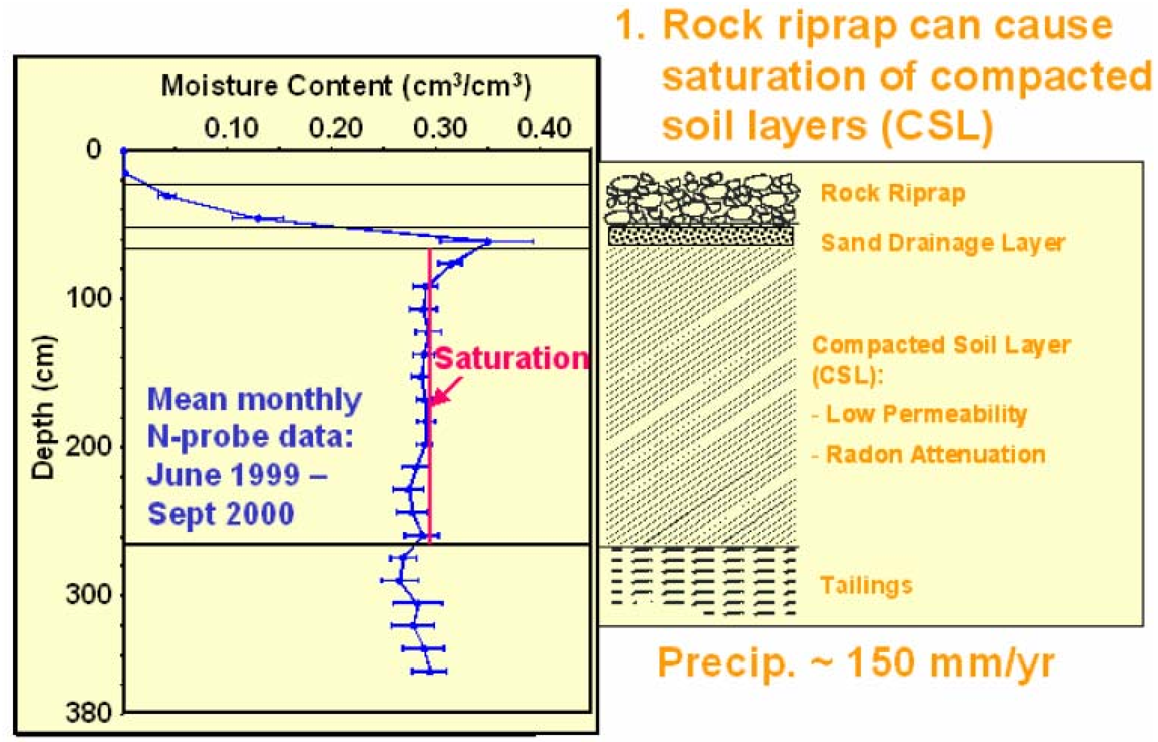

Figure C-7.0-1. Cover profile from UMTRA cover (Waugh 2004)

The larger woody roots from trees and shrubs can provide significant preferential pathways for moisture to move through the cover. However, they can also pull moisture out from much deeper in the profile. The variance in matric potential is much stronger from soil to plant to atmosphere than directly from soil to atmosphere. Often the deep penetration of roots into the waste is a problem to be avoided, however. It has been noted these roots have provided preferential pathways, but have also extracted waste to the surface in the plants themselves (Adriano et al. 1980, Arthur 1982, Foxx et al. 1984, Tierney and Foxx 1987). There are many examples of waste brought to the surface unintentionally through the plant. An example from the Hanford site is the infamous radioactive tumbleweeds (Dabrowski 1973) where roots penetrated subsurface radioactive waste. The weeds ingested some of the radioactive material. After the weeds died, the waste was transported by winds blowing the weeds across the site. There are ongoing research efforts and studies that have looked at using plants to remediate sites by allowing the selected vegetation to extract the unwanted subsurface wastes. Nitrates have been remediated in this manner. However, this is generally termed phytoremediation, whereas landfills by definition generally warrant the isolation of the underlying waste.

The plant community on a cover system is often reflective of the cover profile and the soils in that profile. A research effort demonstrating various alternative landfill cover system performed in Albuquerque, New Mexico (Dwyer 2003) produced an altered plant covering. The soils used were obtained from the same borrow source. The covers were installed side-by-side; therefore, the climatic conditions were identical for all (Figure C-7.0-2). Cover 1 shown is a simple prescriptive municipal waste type landfill that is 60 cm thick and heavily compacted to meet minimum saturated hydraulic conductivity requirements. It produced a relatively average yield of grasses and shrubs representative of the surrounding environment. Cover 2 also had a 60-cm-thick surface soil layer, but this layer was not compacted. This soil was found to have greater than 10% by weight $CaCO_3$ content that negatively influenced the vegetation establishment. Cover 3 was similar to cover 2 except the $CaCO_3$ was less than 10%, thus producing a better stand of vegetation. Cover 4 only had a 30-cm-thick surface soil layer that was too thin to maintain a vegetation layer. The thin (30 cm) topsoil layer did not have adequate water storage capacity to maintain native vegetation, especially during dry periods. Cover 5 had an adequate soil thickness that also had gravel mixed into the surface soil (25% by weight) to minimize erosion. This gravel admixture served as mulch and produced the best stand of native grasses of the six covers. Cover 6 was similar to cover 5, except that the surface treatment used was a gravel veneer (2–4 cm thick) on the surface. This was also deployed to reduce surface erosion. The gravel veneer reduced the evaporation from the underlying soil (not as much as a thick riprap layer) that in turn allowed for moisture retention just below this gravel layer that allowed for a higher percentage of surface vegetation. This thin gravel layer on the surface also served to hold seed in place until germination. The added vegetation covering increased the available transpiration capacity. A higher percentage of shrubs and weeds were present on this cover than the others, thus resulting in a higher LAI.

1. 2-ft thick compacted topsoil layer

2. 2-ft thick uncompacted, high calcium carbonate

3. 2-ft thick uncompacted. low calcium carbonate

4. 1-ft thick uncompacted, low calcium carbonate

5. Gravel/Soil admixture surface treatment

6. Gravel veneer surface treatment

Figure C-7.0-2. Surface treatment effects on vegetation establishment (Dwyer 2003)

C-8.0 TRANSPORT OF RADIOACTIVE WASTE VIA FLORA

Although vegetation is very important in controlling erosion and percolation in landfill covers (Nyhan et al. 1984), deeply penetrating plant roots have the potential to access buried waste and bring plant available constituents, including landfill contaminants, to the surface of the site (Klepper et al. 1979, Foxx et al. 1984, Tierney and Foxx 1987). Contaminants such as tritium can be incorporated within plant tissue and enter the food web of herbivorous or nectivorous organisms. For example, at LANL tritium transport away from a controlled LLW site occurred via the soil moisture/plant nectar/honeybee/honey pathway (Hakonson and Bostick 1976). As another example, deep-rooted Russian thistle (Salsola kali) growing over the waste burial cribs at Hanford penetrated into the waste, mobilized Sr-90, and then transferred it to the ground surface. The contaminated surface foliage was transferred away from the cribs when the matured thistle (tumbleweeds) blew away from the site (Klepper et al. 1979). Two mechanisms for soil contaminant transport to terrestrial plants are absorption by roots and deposition of contaminated soil particles on foliage surfaces. Field studies suggest that deposition of soil particles on foliage surfaces is a major transport mechanism for soil-associated contaminants under many arid site and contaminant source conditions (Romney and Wallace 1976, Romney et al. 1987, White et al. 1981, Arthur and Alldredge 1982).

C-9.0 SOIL PROPERTY CHANGES

Figure C-9.0-1 reveals the intrusion of roots that led to an increase in the saturated hydraulic conductivity of the cover soil. Thinner roots like these can be beneficial by increasing transpiration even though they can increase the saturated hydraulic conductivity of the soils from their as-built status.

Figure C-9.0-1. Root intrusion into landfill cover soil

Preferential flow through soil profiles is a phenomenon that exists (Beven and Germann 1982), yet is generally unaccounted for in cover designs or the design tools (computer programs) used in the designs (Dwyer 2003). Flury et al. (1994) believe the occurrence of preferential flow is the rule rather than the exception. Hornberger et al. (1990) determined that the most significant amount of flow through a soil profile in Orono, Maine was through preferential flow channels. Watson and Luxmore (1986) determined that approximately 96% of water was transmitted through only 0.32% of the soil volume. They concluded that the larger the water flux, the larger the macropore contribution to total water flux. Many other studies (Rawls et al. 1993, Edwards et al. 1988) have concluded that preferential flow is the largest contributor to water flux through soil profiles. Aubertin (1971) in a study of macropores in forest soils attributed increases in hydraulic conductivity to void spaces left by decomposing roots and animal passages. These macropores provided direct conduits for water movement into the soil profile. Lysikov (1982) reported hydraulic conductivities of 6.7 mm/min on non-mound soil in an area disturbed by moles (Talpa europaea) compared to 96.4 mm/min on mounds less than one year old. Grant et al. (1980) reported a twofold increase in hydraulic conductivity on pocket gopher (Thomomys talpoides) mounds compared to that of adjacent, undisturbed prairie soil.

Dwyer (2003) showed that as barrier soil layers reached a volumetric moisture content of about 20%, preferential flow occurred. This 20% moisture content corresponded to a matric potential for the given soil conditions of about 1000 cm. Preferential flow can easily take place at a suction of 1000 cm (Stormont 1999).

Dwyer (2003) used a simple set of calculations to illustrate that preferential flow occurred through a soil cover. The hydraulic conductivity for the cover was calculated using the van Genuchten (1980) formula at the peak barrier soil moisture content of 20% that produced the largest measured percolation event (Equations C-1 and C-2).

$\theta = [1+(\alpha h)^n]^{-m}$ **Equation C-1**

where: θ = normalized water content,

h = suction head,

α, n = fitting parameters,

$m = 1 - 1/n$,

$K(\theta) = K_s * \theta^{0.5} [1 - (1- \theta^{1/m})^m]^2$ **Equation C-2**

where: K_s = saturated hydraulic conductivity.

Given: K_s = 1.23E-6 cm/sec, α = 0.033, n = 1.36, m = 0.26;

θ = 0.50,

Thus $K(\theta)$ = <u>3.26E-10 cm/sec</u>

Using the Darcy Buckingham (Jury et al. 1991) formula (Equation C-3) to calculate the hydraulic conductivity from the measured flux rate (J_w), assuming a unit gradient flow (constant matric potential):

$J_w = K(h)\ \partial H/\partial z$, **Equation C-3**

where: $\partial H/\partial z = 1$ (unit gradient),

H = total potential,

z = depth,

and h = 100 cm (for measured moisture content = 20%).

$J_w = K(h)$ = 2.5 mm/month = <u>9.3E-8 cm/sec</u>

Thus the expected hydraulic conductivity of the soil is two orders of magnitude lower than that estimated from the measured flux. The assumption governing here is that this difference is due to flow occurring preferentially through regions with a substantially greater hydraulic conductivity than that expected for the bulk of the soil, that is, preferential flow. Preferential flow increased with time even though the overall flux decreased with time (Dwyer 2003). This relative increase in preferential flow corresponded with ongoing ecological changes observed on the cover profiles (i.e., desiccation cracking, root intrusion, earthworm activity, and animal intrusion) as well as soil pedogenic processes that led to changed soil properties, as measured with a field tension infiltrometer (Dwyer 2003). The decease in flux was attributed to the maturation of the surface vegetation.

Figure C-9.0-2 shows a cross-section of the barrier layer in a landfill cover with an earthworm hole.

Figure C-9.0-2. Earthworm hole in barrier soil layer

Given a wormhole the size of that shown above (about 1 mm in diameter), the following calculations illustrate just how much preferential flow a single wormhole can produce. Using Poiseulle's Law (Equation C-4) (Jury et al. 1991):

$Q = \pi R^4 \rho_w g(L+d)/(8L\nu)$, **Equation C-4**

where:

Q = water volume flow rate;

R = radius of wormhole = 0.5mm;

ρ_w = water density = 1 g/cm^3;

L = depth of cover profile = 60 cm;

d = diameter of soil column (assume 1 wormhole per diameter of 10 cm);

ν= water viscosity = 0.01 g/cm*sec

$Q = 0.3\ \text{cm}^3/\text{sec}$.

Assuming one wormhole per square meter of surface area for a given landfill cover:

$Q = \{(0.3\ \text{cm}^3/\text{sec})/(1\ \text{m}^2)\}/(100\ \text{cm})^2 = 3 \times 10^{-5}\ \text{cm/sec}$

It is understood that wormholes do not run vertically from top to bottom of a soil profile, but meander through it. Nonetheless, it is clear that structural voids such as those created by fauna intrusion can have a dominant effect on water movement through a cover.

Ants have been found to loosen the dry bulk density of soil in the immediate area of the anthills. Salem and Hole (1968) reported 20% of the volume of ant (*Formica exsectoides*) mounds being occupied by voids 2–23 mm in diameter. By applying Darcy's Law describing movement of fluid through a porous medium, the intrinsic permeability of the soil is proportional to the squared radius of the soil pores (Marshall and Holmes 1979). The range of void dimensions in the above case would result in a 100-fold difference in hydraulic conductivity. Lockaby and Adams (1985) found a significant reduction in bulk density on non-mound and mound soils, respectively, in the vicinity of fire ant (*Solenopsis invicta*) activity in a forest soil. Similar findings were reported by Baxter and Hole (1967) on ant (*F. cinerea*) mounds in a prairie soil. Decreases in bulk density imply a higher fraction of pore space in the soil.

Lower bulk densities on mound vs. non-mound soils have also been reported for pocket gopher mounds (Laycock and Richardson 1975, Ross et al. 1968). This increase in pore space has an influence on hydraulic conductivity of the soil. Mielke (1977) found that soil moisture content increased from 2.6–7.7% on non-mound vs. mound soils in an area disturbed by pocket gophers. Although not statistically significant, the findings of Grant et al. (1980) indicated a tendency for higher moisture content on gopher mounds. Conversely, Skoczen et al. (1976) documented the drying effect brought about by mole tunnels. This drying effect was attributed to airflow through the open tunnels.

Ross et al. (1968) found that other animals more frequently disturb the soil present on and near mima-type mounds. Ground squirrels (Citellus spp.), badgers (Taxidae taxus), and toads (Bufo hemiophzts) were among the species found at these sites. The increase in animal activity in the vicinity of these mounds is thought to perpetuate the effects of the mound in modifying bulk density, soil chemistry, and vegetation distribution. Movement of soil material by animal activity can influence the distribution of primary particles (sand, silt, and clay) in the soil. Baxter and Hole (1967), Salem and Hole (1968), Alvarado et al. (1981), and Levan and Stone (1983) reported that soil material in ant mounds has a higher proportion of clay than adjacent non-mound soil. The findings of Laycock and Richardson (1975) also indicate a tendency for enrichment of soil fines in mounds resulting from pocket gopher burrowing.

In addition to affecting the compaction, porosity, and particle size distribution of the soil, animal activity has been shown to influence the amount and distribution of chemicals in the soil. Many of the studies on the influence of ant activity have indicated significant increases in levels of K, P, Ca, Mg, and iron in mound vs. non-mound soils (Baxter and Hole 1967, Culver and Beattie 1983, Czerwinski et al. 1971, Levan and Stone 1983, Lockaby and Adams 1985, Salem and Hole 1968).

Increases in plant nutrients have also been shown to occur in mounds created by burrowing mammals (Abaturov 1968, Mielke 1977). Laycock and Richardson (1975) also showed a slight increase in nitrogen on gopher mounds. However, Spencer et al. (1985) reported lower levels of some nutrients in mound soils.

These discrepancies may be due to specific site characteristics and time since disturbance (Turner et al. 1973). Since clay content of soil has a direct influence on the CEC, the differences in clay content of mound vs. non-mound soils noted earlier may contribute to the observed differences in soil chemistry. Clay also is important to soil structure and the stability of aggregates, factors which affect the detachment of soil by rainfall and runoff (Alberts et al. 1980).