Review of Sandia National Laboratories/New Mexico
Evapotranspiration Cap Closure Plans for the Mixed Waste Landfill
by Tom Hakonson, Ph.D., Environmental Evaluation Services, LLC

The following report was made possible with a grant from the Monitoring and Technical Assessment Fund (MTA) to assist in performing independent technical studies of the Mixed Waste Landfill (MWL), a hazardous legacy waste site located at Sandia National Laboratories (SNL). The funding, established as a part of a $6.25 million court settlement between the U.S. Department of Energy (DOE) and 39 nonprofit and environmental groups, assists tribes and other non-governmental organizations in conducting their own independent technical studies of sites at DOE facilities.

Citizen Action commissioned Dr. Tom Hakonson, a former environmental scientist with Los Alamos National Laboratory, to perform an independent peer review of the cap closure plans proposed for the MWL. A copy of Dr. Hakonson's curriculum vitae and a list of his published papers are included with this report.

"I am willing to state, unequivocally, that most of the environmental processes discussed in this report will, without doubt, affect the long-term distribution and transport of contaminants in the Mixed Waste Landfill."

- T.E. Hakonson

REVIEW OF SANDIA NATIONAL LABORATORIES/NEW MEXICO EVAPOTRANSPIRATION CAP CLOSURE PLANS FOR THE MIXED WASTE LANDFILL

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2/15/02

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Disclaimer

The portions of this report relating to the SNL/NM ET cap are based on a review of documents provided to me by Citizen Action as listed in Appendix A of this report. As such, my recommendations in this report are also based upon that review of Appendix A documents. If other SNL/NM documents are available that would relate to my review and recommendations, I was unaware of such documents during completion of this report. This means that my recommendations in this report stand until such time as additional documents, should they exist, are identified and reviewed.

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Executive Summary

This report presents the results of my technical review of the vegetated soil cap (ET cap) that SNL/NM has proposed for closing the Mixed Waste Landfill (MWL). Conceptually, an ET cap consists of a vegetated soil layer that represents an optimum of soil type, soil depth, vegetation cover, surface slope, and surface management practice in order to control erosion and minimize percolation of soil moisture into the waste. Given that the outcome of the forthcoming Corrective Measures Study and revised risk assessment for the MWL may lead to the use of other remediation alternatives, it is still certain that a final cap will be required as a part of any closure plan selected for the landfill. Furthermore, that final cap will contain all of the functional elements of the proposed ET cap, including soil for moisture storage and vegetation to remove soil moisture via transpiration and to control erosion.

This report presents discussion on 3 topics: 1) a literature review of general concepts concerning landfill closures, capping design alternatives, failure modes, and long term performance, 2) a review of the two evapotranspiration cap design reports offered by SNL/NM for closure of the MWL, and 3) some recommendations concerning the proposed ET cap closure and post-closure monitoring period.

Depending on the reader, there may be concern or delight in the fact that I did not attempt to relate the information I derived from the literature review to specific conditions at the MWL. I have purposely not attempted to link results from the literature review to the MWL because it would require me to speculate about conditions at the MWL that cannot be verified with existing data. For example, there is nothing published on the MWL that quantifies or characterizes the kinds of fauna and flora present or the amount and consequences of biological intrusion, subsidence, or soil erosion on contaminant distribution and transport.

Despite my unwillingness to be specific about the degree to which physical and biological processes will impact the MWL, I am willing to state unequivocally that most of the environmental processes discussed in this report will, without doubt, affect the long term distribution and transport of contaminants in the MWL I would assume that the NMED, EPA, and the owners of the landfill would have a vested interest in documenting just how important these processes are in assuring the long term safety of workers and the public. While SNL/NM may believe that the MWL site has been characterized sufficiently to answer all of the important questions about present and future transport of MWL contaminants, I can assure the reader that important questions remain unanswered

It is clear that applicable EPA regulations permit the use of vegetated soil covers for closure of radioactive and hazardous waste landfills. Criteria permitting their use include the outcome of the health and environmental risk assessments, the climate at the burial site, and demonstration that the alternative cover design provides protection of the waste equivalent to traditional engineered barrier designs that are recommended by EPA. In the absence of site specific performance data, this evaluation of equivalency relies heavily on the use of water balance modeling and relevant site characterization data. Based strictly on this hydrologic analysis, it would appear that the use of an ET cover for closure of the MWL is justified. However, this analysis ignores the potential effects of biological processes in mobilizing buried contaminants and the consequences of this transport on future changes in contaminant concentrations in surface soil. Because SNL/NM proposed to only monitor tritium in the vadose zone for a few years post-closure, changes in contaminant concentrations in surface soils and biota would go undetected.

A modeling study conducted by Pacific Northwest Laboratory addresses the issue of long term consequences of biointrusion into arid site low level waste landfills on dose to man. Results show that estimated dose to man resulting from biological transport of radionuclides at two reference low level waste sites was of the same order (i. e., about 50% less) as dose calculated from a human intrusion scenario.

The potential importance of processes that contribute to contaminant transport by physical and biological processes operating near and on the ground surface stems from the fact that only a couple of meters of cover soil (i. e., about 1 meter of existing soil, 0.5 meters of subgrade, and 1-1.5 meters of ET cap soil) will separate the MWL waste from the ground surface when the ET cap is installed. In contrast, several hundred meters of unsaturated soil in the vadose zone separates the waste from ground water. In arid environments such as the MWL, transport of most if not all of the MWL contaminants through this extensive, dry vadose zone is certain to be low and slow even for tritium which exhibits 2 phase transport. The fact that tritium currently emanates from the surface of the MWL is most certainly related to a large degree to the presence of burrowing animals and vegetation present on the landfill surface and the effects of these organisms have on soil moisture status and soil porosity.

Both plants and animals have the potential to transport buried waste to the ground surface. Plants do so via roots that can penetrate several meters into the landfill. Furthermore, most plant species have the capability to penetrate the relatively thin cover soil layer proposed for the MWL. This means that the term, "shallow rooted" as used by the SNL/NM ET cap designers is inappropriate given that the grass species that they propose to use to revegetate the ET cover all have the capability to send roots several meters into the soil. If soil moisture penetrates beyond the existing rhizosphere, plant root distribution will extend downward to capture moisture at the deeper depths.

Roots in contact with waste can incorporate soluble constituents and transport them to the ground surface. This uptake process is analogous to a one-way valve in that contaminants are pumped upward to above ground vegetation that eventually senesces and deposits associated contaminants on the ground surface. Burrowing by animals and insects also has the potential to access buried waste several meters below the ground surface. This can lead not only to chemical and radiation exposures to the organisms but also to physical transport of the waste upward in the soil profile and to the ground surface.

Should contaminants be transported to the ground surface, several complex but coupled processes involving enrichment of soil fines and associated contaminants begin to operate to transport soil contaminants to biota, across the landfill surface, and to offsite areas. These processes include erosion by wind and water, transport by contaminated animals moving on and off the landfill, deposition of soil particles on biological surfaces from rainsplash and wind resuspension, and wind transport of senescent vegetation to offsite areas.

The importance of erosion of cover soil over long time frames needs to be carefully evaluated in light of potential disturbances by burrowing animals in combination with loss of vegetation cover resulting from catastrophic disturbances such as fire, disease, and drought. Based on recent field studies, fire disturbances can change hydrologic (and presumably wind) erosion rates by as much as a factor of 25 over undisturbed conditions. This means that modeling results based on average erosion rates may under-represent the actual long-term rates of deflation of the cover soils.

The persistence of effects caused by disturbances is not well known. Some studies show that the effects of fire on soil erosion may persist for several years while other studies suggest that these effects are short lived and depend on the rate of recovery (e.g., reseeding) of the disturbed area. The relative importance of these processes in mobilizing MWL contaminants will depend on several factors including vertical distribution of waste contaminants in the landfill trenches and pits, soil type and depth, type of vegetation cover, changes in the vegetation cover, animal and insect species composition, and changes in faunal species composition.

Burrowing by animals also creates extensive disturbances of the soil profile. While it could be assumed that these disturbances would lead to accelerated erosion and percolation of water to the buried waste, the small amount of available research data suggest that burrowing and soil casting to the ground surface has relatively small effects on erosion and percolation as long as a good vegetation cover is present on the soil surface. Increased infiltration of water into the soil from animal and insect burrowing is often followed by an increase in vegetation cover biomass and ET, which combined, reduces the potential for erosion and deep percolation. However, erosion and percolation increase dramatically when the vegetation cover is absent in the presence of burrowing.

The magnitude of subsurface transport is intimately related to processes that operate on or near the landfill surface. Aqueous phase transport of contaminants is dependent on the ability of the cover to control the amount of moisture that penetrates into the waste. Key among those processes is evapotranspiration, which has the potential under most arid site conditions to remove virtually 100% of the moisture that infiltrates into the soil.

However, it is ironic that a cover that is effective in minimizing soil moisture in the landfill can also contribute to an increase in vapor phase transport of volatiles such as tritium. The relative importance of aqueous versus vapor phase transport of tritium at the MWL will be difficult to determine but will depend on a host of physical, chemical, and biological processes that are complex and coupled. The fact that tritium moves in more than one phase ensures that it will be relatively widely dispersed from the initial burial location. Therefore, I am certain that monitoring data from the MWL will show that tritium is currently present in fauna and flora.

A further complication is that if moisture does penetrate through the landfill cover, plants have the ability to send roots downward in pursuit of that moisture. This means that the concept of shallow rooted plants versus deep rooted plants is misleading in that most "shallow rooted" plant species have the capability to send roots much deeper than the couple of meters of cover proposed for the MWL. The good news is that this plasticity of plant roots to penetrate downward in search of moisture helps ensure that very little moisture will escape into the vadose zone. The bad news is that deeper penetrating roots can also contact buried waste and transport plant available contaminants to the ground surface.

Because burrowing organisms can come into much closer contact with buried waste, it is also possible that they can be exposed to relatively high chemical and radiation doses. Radiation doses to free ranging burrowing animals that live on the MWL would be relatively easy to measure. A technique that was developed in the 1970's uses thermoluminescent dosimeters (TLD) that can be implanted or attached to free ranging animals. When retrieved, the TLD's provide a good measure of radiation exposures to the organisms over time.

Data on the concentrations of contaminants in plants, animals, and cast soil at the MWL apparently are not available but would be instructive about the potential of biological intrusion for mobilizing MWL waste. Because the site was opened in 1959 and closed in 1988, there may be some portions of the landfill site that have been undisturbed for several decades. Directed sampling in those areas would provide a measure of the importance of biological transport.

I recognize that SNL/NM conducted grid sampling of soils for the Phase 2 RCRA Facility Investigation of the MWL in 1990. However, the RFI soil sampling was coarse in resolution, non-random in space, involved at least some sampling areas that were recently disturbed (e. g., Trench F backfilled just prior to soil sampling), and did not purposely include disturbances created by burrowing animals.

Concerning human intrusion, a conservative approach would be to assume that institutional control is lost and that humans come to occupy the landfill surface for a home site, growing crops, industrial activities, or other uses that are intimately associated with the landfill. There would seem to be no easy answers on how to prevent this intrusion, but I would start by considering the use of marker systems placed judiciously at the site during closure activities. For example, ceramic or glass tiles, ala Anasazi clay pottery with embossed warning messages, could be scattered beneath the cover as it is constructed so that any future excavation on the landfill would encounter the warning tiles. Surface markers could also be constructed but one would have to assume that such tiles or surface markers do not become an attractive nuisance, i. e., become collector's items.

The argument could be made that the use of a marker system in the early phases of the closure increases the possibility that the landfill owners will forget about the landfill. Consequently, it is prudent to get a binding administrative and financial commitment from the landfill owners and appropriate regulatory authorities to fulfill all obligations during the period of institutional control. I am not sure how this would be accomplished from a legal view but I would presume it might involve an escrow account that would cover any reasonable projections of future problems.

Specific to the SNL/NM ET cover designs for the MWL, my review led me to three conclusions. First, both reports do a credible job of analyzing the ET cover for the MWL given the guidance provided by EPA. They also adequately discussed the regulatory and technical basis for the ET cap and used the results from several modeling studies to evaluate design variables. Construction details in both reports were sufficient to convince me that the ET cap could be built to specifications.

One could quibble about technical details relative to the respective designs. However, in my opinion deficiencies in the areas described below far outweigh the relatively minor problems with cap design. Let me say that I believe that an ET cap closure for the MWL, as described in both SNL/NM reports, will provide adequate protection against percolation of site contaminants to ground water. However, this assumes that the site is diligently monitored and maintained throughout the post closure period. It also assumes that the surface pathway involving biota proves to be unimportant in contributing dose to man.

This leads to what I believe is one of the more important deficiencies in the proposed MWL closure, namely the assumption that vertical and horizontal transport of site contaminants resulting from biological processes is not an important contributor to exposure pathways. My review suggests that relevant data from the MWL on contaminants in vegetation, animals, and soil cast to the surface by burrowing animals apparently do not exist. The reason biointrusion may be important is that it represents the major mechanism leading to vertical transport of contaminants to the ground surface and through the drying effect of plant transpiration on cover soils, plays a major role in the evolution of volatile contaminants from the ground surface. While vertical transport by biota may be small on a short time scale, over many decades these processes may become dominant in mobilizing buried waste.

It is my opinion that the soil sampling done by SNL/NM in 1990 as a part of the Phase 2 RFI provides little information that can be used to answer questions about the effects of biointrusion in transporting MWL contaminants to the soil surface. The RFI soil sampling grid resulted in evenly spaced samples (i. e., that were non-randomly distributed), that provided coarse spatial resolution of contaminant concentrations, and that involved sampling locations that were recently disturbed such as Trench F where backfill was added just months before the soil samples were taken. Furthermore, those samples that were taken in 1990 represent a single snap shot in time and depending on the degree of past mechanical disturbances that occurred within the MWL boundaries, they may represent a snap shot with little elapsed time between soil surface disturbance and when the soil samples were taken.

Technical evaluation of biointrusion at the MWL would involve a careful survey of contaminants in surface soils and biota and identification of species presently occupying the site. This could be done now on trench/es closed early in the landfill operation and assuming that the ground surface has not been disturbed since the trench/es were closed. If repeated mechanical disturbances of the ground surface have occurred at the MWL throughout it's use history, then the alternative method for evaluating the importance of biointrusion would be to initiate a long term sampling program after the site is closed.

I would add that the addition of less than two meters of clean soil during ET cap construction does not assure that problems with biointrusion go away. Most plants and many animals have the potential to penetrate deeper than the proposed thickness of the ET cover.

The third conclusion I drew from the review is that little or no planning has been done on the post-closure phase of the MWL closure. It is possible that the prevailing philosophy behind this lack of planning and guidance is to address problems as they are recognized. Obviously the ability to recognize problems with the containment system is dependent on diligent monitoring of all relevant pathways.

Long-term data are not available to demonstrate how well vegetated soil covers will work in preventing transport of buried contaminants over extended time frames. Furthermore, it is likely certain that the proposed ET cover will not be 100% effective in isolating MWL contaminants from the biosphere over long periods of time. Therefore, a comprehensive monitoring program during the period of institutional control will be important for verifying the validity of initial closure assumptions and calculations and for identifying potential problems.

The general consensus of the scientific community is that some problems with the containment of waste in the landfill will occur over the time frames involved. This places a special burden on the owner of the MWL to identify and resolve problems in real time. Without careful monitoring of the site during the post-closure phase, little problems can become bigger problems that may be defy remedy and will certainly elevate costs for solutions. This aspect of the MWL closure would appear to be especially important since statements are made that the ET cap closure is intended to lead the way for other DOE landfill closures using alternative caps.

In my opinion, the post closure monitoring plan should provide for measurements on all possible migration pathways including movement through the vadose zone, surface contamination, and biological transport. Those measurements will be invaluable for validating or invalidating some of the assumptions and data used in the risk modeling. While some or all of these pathways may eventually prove to be unimportant from a risk perspective, the lack of consideration of plant and animal intrusion into the MWL and the consequences relative to effects on concentration in surface soil, soil erosion and other means of contaminant transport detract from the proposed closure.

A further problem is the lack of a well-defined plan of action should the cap not perform as predicted. This means that there are no decision criteria or action plans for mitigating the various failure modes should one or more occur. The ET cap reports do not discuss these issues and in my opinion, they are vital to the credibility of the proposed closure.

Whether the MWL requires removal or not is not for me to judge. I do believe that a well designed cap, a financially secured, quality post-closure monitoring plan, and plan of action in the event of a containment problem/s, will likely work for the MWL, at least until re-evaluation of the site is made at some point in the future. However, based on documents I reviewed, SNL/NM has done little or nothing of substance on evaluating the long term effect of biointrusion on the surface pathway, developing a post-closure monitoring plan, or establishing decision criteria for possible corrective actions for the MWL closure.

I recognize that the costs of any additional sampling before and after MWL site closure and including possible future corrective actions will fall directly on the taxpayers of this country, not the State of New Mexico, not DOE, nor SNL/NM. Setting aside large amounts of public funding for some unspecified corrective action to remedy problem/s with a low probability of occurring would not seem to be the best use of financial resources for protecting public health given that the taxpayer will be expected to shoulder the financial burden of any needed future fix for the site. Latest cost estimates for excavation, transport and disposal of mixed waste, based on the Area P clean closure at Los Alamos, are about $10,000/ yd^3$.

In my opinion, I believe secure funding would be better spent on the post-closure monitoring phase for the MWL because a well designed monitoring program with assured continuity will provide early identification of potential problems with the MWL containment system. I believe that early identification of problems with the closure will greatly reduce potential costs of corrective actions that might be required to fix unspecified future problems. Furthermore, it will provide a defensible basis for recommending for or against further closures using the same technology.

A. Objectives Of This Review

This report to Citizen Action represents my attempt to evaluate the technical merits of Sandia National Laboratories, New Mexico (SNL/NM) plan to use a vegetated soil cap for closure of the Mixed Waste Landfill (MWL). The MWL, located on Kirtland Air Force Base in Albuquerque New Mexico, is about 2.6 acres in size and was used for disposal of radioactive and hazardous waste. Details concerning what are known about the use history of the MWL including the kinds and amounts of waste are presented in several existing documents and will not be repeated here (see documents reviewed in Appendix A). Suffice it to say that the MWL use history began pre-1976 (pre-RCRA). This means that the landfill is unlined, used a tip and dump disposal method, contains a variety of radioactive and non-radioactive contaminants in various waste forms, and that precise inventories of all of the radionuclides, metals, and chemicals that went into the landfill are not known.

The MWL has been the subject of several special studies to characterize waste contaminant concentrations, inventories, distribution, transport, and associated risks. The SNL/NM closure of the MWL proposes to use an evapotranspiration (ET) cap and to implement a post-closure monitoring and maintenance program based on the ground water pathway. I think their intent is to reassess the need for additional closure measures a few decades into the future, when relatively short-lived radionuclides have decayed. Details concerning if and when this reassessment will occur are vague at best.

My review is primarily focused on the technical aspects of the proposed evapotranspiration cover closure of the MWL to include some post-closure monitoring issues. I do not intend to address topics concerning accuracy or completeness of the waste inventory, methodology and estimates of risks, the accuracy and representativeness of the monitoring data, or accuracy and completeness of published information by the various stakeholders.

I refer repeatedly in this report to the SNL/NM risk assessment as described in the SNL/NM Phase 2, RCRA Facility Investigation report published in 1990. It has been pointed out that this risk assessment may no longer be valid just as the proposed ET cap closure may no longer be valid depending on the outcome of the proposed Corrective Measures Study being imposed upon SNL/NM. Because my charge was to evaluate the ET cap proposed for the MWL, it seems logical to use the Phase2 risk assessment that was used in part to justify the selection of the ET cap. Furthermore, since my goal was to evaluate the ET cap, I believe it is appropriate to refer to this risk assessment with the caveat that it (and the proposed ET cap) may no longer apply to what eventually happens with the MWL.

It is obvious from reading the various documents supplied to me as a part of my assigned task, that some issues related to the MWL are contentious, including the choice of closure alternatives. I do not intend to become embroiled in those issues in this report. Whether the ET cap is the right choice or not for the MWL closure is not for me to judge given that the final decision must weigh non-technical (i. e., social and political), regulatory, as well as technical issues.

The task at hand in this review is whether a cover closure plan proposed by SNL/NM for the MWL is technically defensible. My approach will be to review what is known and not known about environmental processes that will likely affect the long-term ability of the cover to isolate the underlying waste.

A recent decision by the State of New Mexico Environment Department directs SNL/NM to conduct a Corrective Measures Study (CMS) to reconsider several alternatives, in addition to the ET cap, for closure of the MWL. This means that the final closure plan for the MWL may or may not involve the use of an evapotranspiration cover as proposed by SNL/NM. I expect, however, that SNL/NM will continue to favor the use of a cover as the primary means of closure for the MWL because their monitoring data and risk assessments to this point in time indicate that the potential for migration to ground water and exposure of receptors is low. However, this may change if new monitoring data, risk assessments, and corrective measures studies do not support the use of a cover closure as the sole remedy for the landfill.

Even if the ET cap is not selected as the central feature of the MWL closure, I am certain that under almost any cleanup scenario chosen for the site, including waste removal, that a final cap of some kind will be required. Furthermore, the waste removal option is certain to be less than 100% efficient in removing MWL waste contaminants such as tritium. Depending on the amount and kinds of residual contamination, post-closure maintenance and monitoring may be required for the removal option.

There may be concern or delight, depending on the reader, that I did not attempt to relate the information I derived from the literature review to specific conditions at the MWL. I have purposely not attempted to link results from the literature review to the MWL because, first of all, I do not have any certain answers about linkages, and secondly, it would require me to speculate about conditions at the MWL that cannot be verified with existing data. For example, there is nothing published that quantifies or characterizes the kinds of fauna and flora at the MWL or the amount and consequences of biological intrusion, subsidence, or soil erosion on contaminant distribution and transport.

Despite my unwillingness to be speculate about how physical and biological processes relate specifically to the MWL, I am willing to state unequivocally that all of the processes discussed in this report will, without question, effect the long term distribution and transport of MWL contaminants. I would assume that the NMED, EPA, and/or the owners of the landfill would have a vested interest in discovering how important these processes are in assuring the long term safety of workers and the public.

B. Hakonson's Technical Background And Expertise Relevant To This Review

Before proceeding, the reader should know something about my technical background and experience in order to place my review comments in context. I have 3 graduate degrees with science emphasis in Wildlife Biology (MS, 1964), Radiation Health Physics (MS, 1967) and Radioecology (PhD, 1972) from Colorado State University. Most of my professional life was spent as a research scientist and Group Leader in the Environmental Science Group at Los Alamos National Laboratory (1972-1993). My research at Los Alamos focused on two areas including the distribution and transport of plutonium and other radionuclides in liquid waste disposal areas at Los Alamos, in the fallout zone from the Trinity Site atomic bomb test in south-central New Mexico, and in nuclear safety shot areas in Plutonium Valley at Nevada Test Site. My radionuclide transport studies focused on hydrologic processes and especially the role of runoff and erosion in mobilizing Pu and other soil radionuclides in these arid/semiarid ecosystems.

My second area of expertise is on landfill cover alternatives. Beginning in 1980, my colleagues and I used fully instrumented field plots to measure hydrologic processes (i.e. water balance relationships, erosion, and contaminant transport) in RCRA and alternative cover profiles including evapotranspiration cap designs. We designed, constructed, monitored, and published results on landfill cover field demonstrations at Los Alamos, NM; Hill Air Force Base, Utah; and Marine Corp Base Hawaii, at Kaneohe, HI. These studies were predecessors to SNL/NM's current Alternative Landfill Cover Demonstration. I was nominated as a Laboratory Fellow in 1981 and received Los Alamos National Laboratory's Distinguished Performance Award for my work on landfill covers in 1982. Most of my publications since 1980 are on landfill cover research.

I retired from Los Alamos in 1993 and was appointed to the faculty at Colorado State University to develop an academic, training and research program for the University's Center for Ecological Risk Assessment and Management. I served as Director of the ERAM program from 1993-1996 and participated in a variety of human health and ecological risk assessments for industry, citizen groups, and DOE. From 1997-2001, I was an Associate Professor in the Radiological Health Sciences Department where I continued my research on landfill covers and actinide transport.

I served as a technical expert on various aspects of plutonium distribution and transport as a part of downwinder litigation at Hanford and to the International Atomic Energy Agency on closure of low and intermediate level radioactive waste sites. My most recent research investigated runoff and erosion as Pu transport mechanisms at the Waste Isolation Pilot Plant, Rocky Flats Environmental Technology Site, and Hanford as a component of a comprehensive, multi-organization study of the various modes of actinide transport in the environment. I am currently retired but consult with various government and public groups on a range of problems in radioecology, hydrology, ecology, and environmental restoration. I have over 120 publications on my research activities

C. Specific Topics Addressed In This Report

Citizen Action, a citizen activist group located in Albuquerque NM, commissioned me to perform a technical review of the proposed MWL evapotranspiration cap closure that addressed the following topics:

1. Potential migration of contaminants via abiotic/biotic pathways that may occur under context of an evapotranspiration soil cap combined with long-term stewardship to include:

   a. Potential modes of contaminant transport from radiological/ non-radiological waste items buried in the landfill (physical, aqueous, vapor phase), and

   b. Evaluation of plant, animal and human "intrusion potential" for long-term isolation of waste, which will consider the following: contaminant pathways via vegetation;
      - Location of landfill to city and future development of area;
      - Current and future intrusion by burrowing animals; and
      - Potential for risk associated with abiotic/biotic means of transport.

2. Review of the evapotranspiration soil cap design submitted for approval by the NMED for final closure of the Mixed Waste Landfill (Environmental Restoration Project), and of a second cap design (Dwyer, Stormont, and Anderson, 1999) not selected by the NMED.

- Selection of type and depth of cover materials.
- Surface slope, runoff, and erosion control.
- Vegetation component planned for evapotranspiration cover and potential for future intrusion by other plant species.
- Post closure monitoring systems designed to detect air, soil, water, moisture content, and vadose zone contamination.
- Financial assurance plan for supporting post closure activities.
- Uncertainties associated with projected performance of an experimental cap.
- Engineering QA/QC to demonstrate cover is constructed as specified.

3. The study will also give the following recommendations regarding long-term performance:

- Soil cap design, sediment mix, implementation of a biointrusion barrier, back up systems in case of failure;
- Establishment of an air monitoring program at the MWL;
- Sampling program to detect contaminants in vegetation;
- Erosion control.

This report provides discussion in three areas as follows:

(1) A section reviewing general concepts concerning landfill closures, capping design alternatives, failure modes, and long term performance (topic A items listed above). I want to focus heavily on this first section of the report to present the results of published research on landfill caps. My intent is to identify what is known and unknown about abiotic and biotic processes that effect cap design and function and to provide a basis for judging the merits of the SNL/NM proposed ET cap closure and post closure monitoring plan,

(2) A review of the two evapotranspiration cap design reports offered by SNL/NM for closure of the MWL (item B above), recognizing that the ER group closure plan has been selected by SNL/NM and has undergone scrutiny by NMED, and

(3) Recommendations as listed in item C above.

D. Technical Concepts And Issues

D1. General Considerations

Selecting a cleanup action for the MWL that adequately protects human health and the environment requires risk managers to synthesize and evaluate a large amount of technical, regulatory, and socio-economic information to arrive at an optimum, or best decision for closing the site. Applicable regulations require an assessment of the human health and environmental risks of candidate management alternatives prior to any corrective action (EPA, 1989a; Harwell, 1989; Bartell et al. 1992; Suter 1993). These risk assessments provide the fulcrum between science and policy. They are the interface at which predictive capability about ecological processes and contaminant kinetics can be applied to aid in resolving environmental problems and managing risk at sites such as the MWL.

While I am not going to discuss the MWL risk assessments conducted by SNL/NM and the various critiques of that assessment, I will say that, in my opinion, the risk assessments are the most important part of the decision process for selecting a closure option for the MWL as they are the only means for estimating future ability of the site to contain waste. These risk assessments must be based on reliable, quality data for conducting the assessment and for evaluating risk model output.

Depending on the level of risk to both humans and ecosystems from MWL contaminants, the alternatives for remediating the landfill can range from a no further action, in-situ / ex-situ soil treatment processes to remove selected contaminants, or removal of most of the contaminant inventory by excavation of the landfill. It is possible that all of these options could be candidates for the forthcoming Corrective Measures Study of the MWL.

The option finally selected for remediating the MWL should have a strong technical basis as derived from the health and environmental risk assessments. Properly done, the risk assessments should represent the best science available on the distribution and transport of the contaminants at the landfill under different closure alternatives in both the near and long term.

Whatever the eventual choice for closure of the MWL, it seems reasonable to demand that any use of public funds for remediation of the MWL landfill must be tied closely to the level of current and potential future risk. Cost will always be important criteria for selecting options for remediating sites such as the MWL. In general, the objective is to reduce costs to a minimum while convincing decision-makers that the potential risks from the site are acceptable under the assumed land use scenario. A comparison of unit costs for construction (i.e., O&M costs not included) of several capping alternatives at Los Alamos is compared to the cost of excavating the waste in Table 1. The message in Table 1 is that cost of remediation can vary by orders of magnitude depending on the alternative chosen and that none of the options are inexpensive.

The cost of the excavation alternative is estimated for a low level radioactive waste landfill at Los Alamos and for mixed waste based on the recently completed clean closure of the Area P landfill at Los Alamos (Bostick, pers. comm.). Cost for excavation and disposal of mixed waste is estimated to be about a factor of 20 higher ($10,000/yd^3$ vs. $500/yd^3$) than for low-level waste. Costs for in-situ and ex-situ soil treatment alternatives, which are not shown in Table 1, are also of the same order as the excavation options. Actual costs of any of these options will depend on local conditions, waste types and amounts, and re-disposal options.

Arguments about O&M costs of one closure option versus another are problematic in my opinion since even the excavation option will very likely require some long term inspection, maintenance, and/or monitoring. As mentioned, attempts to remove the waste from the MWL will not be 100% efficient (e. g., H^3). The O & M costs for a particular closure option will depend on several factors including the type of waste in the landfill, landfill location and climate, and required measurement frequency for inspections and monitoring.

None of the options in Table 1 are risk free including actions to remove the waste from the landfill. Consequently, risk managers must decide whether near term risks associated with waste removal are more or less acceptable than potential future risks resulting from other closure options. Further complicating the issue is that near term risks likely have less uncertainty associated with them compared to more uncertain predicted future risks.

D 2. Regulatory Requirements

Cover closures of sanitary (there are about 226,000 in the U.S.), and radioactive and hazardous waste landfills (there are a few thousand) are pervasive in the U.S. for a variety of reasons, including some that are valid and some not so valid. There are cases where old (pre-RCRA) sanitary and radioactive waste landfills have leaked for a variety of reasons including poor siting of the landfill, high local precipitation, and/or inadequate attention to cover design (Duguid, 1977; Jacobs et al., 1980; EPA, 1988). EPA (1988) details some of the containment problems in a survey of 163 randomly chosen sanitary landfills. Containment problems of various degrees had cropped up at most of these sites and about 25% of those required near term corrective actions.

Many of these old pre-RCRA landfills used similar disposal methods in that a trench or pit was dug into the soil, waste was placed into the excavation w/ or w/o backfill, and when full, the landfill was covered with soil (Duguid, 1977; Jacobs et al., 1980). Sometimes the landfill was reseeded and sometimes it was not. This general approach to waste disposal dates back thousands of years (Langer, 1968). Requirements of current regulations such as RCRA and CERCLA now stipulate methods for remediating old landfills in considerable detail and for constructing, operating, and closing new landfills.

Table 1. Estimated costs of remediation alternatives for landfills.

Alternative[1]	Cost/Unit[2]
Excavate LLW Landfill	$80M/Ha
Excavate MW Landfill	$ 1,600M/Ha
RCRA Cap	$4.9M/Ha
Soil/Capillary Barrier Cover	$1.5-3.7M/Ha
Infiltration Control w/ Vegetation	$0.24-0.5 M/Ha
ET Cap with Erosion Control	$0.12-0.8M/Ha

[1]Technical basis for selecting remediation alternatives should be based on human and ecological risk assessments.

[2]Costs for the LLW excavation option (assume excavation to depth of 8 m) adapted from DOE's Environmental Restoration program 5-year plan. Costs of excavation of mixed waste based on actual costs for recently completed Area P clean closure at Los Alamos. The RCRA cap costs are from the Maxey Flats Kentucky Corrective Measures Study. Costs for the remaining capping options estimated by author based on installation costs of field demonstrations including SNL/NM Advanced Landfill Cover Demonstration (Dwyer, 1998). Exact costs for a particular option will be site specific.

Based on many years of research and observations on landfill operations and closures, I am of the opinion that most of the “problems” that crop up at old landfills resulted from the period when active waste disposal was occurring. During this period, disposal trenches were open and lacked any kind of mechanism for removing precipitation that fell on the landfill. Because these old landfills were usually active for many years, the potential existed for very large amounts of precipitation to enter the landfill, move downward through the waste, and, depending on the permeability of the surrounding soil, to move out of the bottom of the landfill. Furthermore, the amount of precipitation entering the disposal units each year of operation could approach the annual precipitation. I further believe that observed problems with contaminant migration from landfills in arid sites occurred prior to closure of the landfill with a vegetated cover. Failure to vegetate soil covers after landfill closures was an especially bad practice because this major soil moisture removal mechanism, (i. e. transpiration) was lacking.

The regulatory requirements for closure of landfills with caps are detailed in several EPA guidance documents (EPA, 1979; 1982, 1985, 1989b and c, 2002). The regulations basically require the owner/operator of a landfill to perform landfill closures. The primary closure requirement is that the owner/operator must design and construct a low-permeability cover over the landfill to minimize migration of liquids into the waste and to provide for post-closure monitoring and maintenance in order to prevent unacceptable future waste migration into the environment.

EPA guidance to permit applicants also recommends that an analysis of the final cover design be presented in the closure plan. The analysis of the final cover design must describe how the design meets the following performance criteria:

1. Minimizes liquid migration,
2. Promotes drainage while controlling erosion,
3. Minimizes maintenance,
4. Has a permeability equal to or less than the permeability of natural subsoil,
5. Accounts for freeze/thaw effects, and
6. Accommodates settling and subsidence so that the covers integrity is maintained.

It should be emphasized that these general performance standards allow flexibility in the cover design proposed for the site (EPA, 1989b, c). This flexibility has now being formalized in a new guidance document soon to be released by EPA (EPA, 2002).

In order to demonstrate that a proposed final cover design complies with the regulatory performance standards, EPA states that it is necessary to model water balance and erosion on the proposed cover. EPA also suggests that the water balance model, HELP, be used for the water balance calculations (User's Guide for the Hydrologic Evaluation of Landfill Performance (HELP), version 3, model (EPA, 1994).

The numbers of landfill cover designs that can be evaluated with HELP are limited to a couple of versions of the RCRA cap design and monolithic soil cap designs. The HELP model does not give accurate predictions of water balance in a particular cap design (EPA, 1994). It is intended as a screening tool to provide comparative response between design alternatives rather than realistic numbers.

Because the HELP model cannot handle unsaturated soil moisture conditions, cap designers sometimes use other models to supplement the HELP modeling results. Both SNL/NM ET cover design groups did this. The use of alternative models is an exercise in futility in my opinion because seldom is there enough data to initialize these models and nor is there enough relevant data to compare with model predictions. Consequently, without such data, it is a far stretch to say that one of the "better" models predicts water balance any better than HELP.

EPA also recommends the use of an empirical formula called the Universal Soil Loss Equation (USLE) to calculate annual average soil loss from the proposed cover design (EPA, 1989b,and c). The average annual soil loss is predicted based upon a number of factors including the geographical location, the length and steepness of slopes, the texture of the cover soil, and the vegetation cover.

More recent erosion prediction models on erosion developed by the U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS) are sometimes used to evaluate erosion on landfill caps. These models, which were not used by SNL/NM, include the Revised Universal Soil Loss Equation (RUSLE) (Renard, 1985) and Chemicals, Runoff, and Erosion in Agricultural Management Systems (CREAMS) (Knisel, 1980). Predictions with erosion models suffer from the same problems as water balance models. Good quality data are needed to initialize the models and validate predictions. All of these models come with default parameters and default databases for use in setting up the model runs. EPA (1994) states that site-specific data for initializing the model are much preferred.

As long as these models are used as screening tools, they will be useful in comparing cap designs. However, if the model output is used to specify exact numbers (and they are believed), then there must be an independent means of confirming model predictions. Very seldom do such data exist for a site like the MWL.

D 3. Regulatory Basis for Alternative Cap Designs

A range of cover designs representing various complexities and costs have been proposed for landfill closures (Hakonson, 1997a). Those designs range from multi-layered engineered barriers, such as EPA's clay cap designs (EPA, 1989b, c), to simple vegetated soil caps that rely primarily on evapotranspiration to manage site water balance (Anderson et al. 1997, Hauser, 1994; Hakonson et. al., 1997a, b, Dwyer et. al., 2001).

An alternative cap design is acceptable for radioactive and hazardous waste landfill closure (EPA 1989a, b, 2002) as long as it's performance can be demonstrated to be equivalent to the RCRA clay cap designs EPA (1989a, b). Because experimental data demonstrating equivalency are generally unavailable, site operators and regulators in the past have been reluctant to use or approve alternative designs. However, based upon the results of field demonstrations over the last few years, EPA now recognizes that alternative cap designs are sometimes preferable to RCRA clay barrier designs especially in arid sites where clay barriers are subject to desiccation cracking (EPA, 1989 a, b).

As a consequence of this now formalized latitude in selecting cover designs for landfills, there has been renewed interest in vegetated soil caps as an alternative for landfill closures. Modeling studies (Hauser et. al., 1994; Khire et al, 1995) and limited experimental data (Anderson, 1993, Dwyer, 1997, Dwyer et. al., 2001) suggest that vegetated soil covers, or ET caps, can be effective in controlling site water balance, particularly in arid and semiarid locations.

There are several possible cover designs that could be considered for the MWL besides the ET cap and it is possible that one of these options may eventually be agreed upon for closure of the site. Designs options include those that incorporate engineered barriers such as EPA's RCRA C cap with it's clay barrier or RCRA-GCL (geosynthetic clay liner) designs (EPA, 1989). Other barrier design possibilities include capillary barriers (Nyhan et. al., 1990b Nyhan et. al., 1997a, b; Stormont and Morris, 1998) and combinations of several barrier technologies (UMTRA-DOE. 1989; Buckmaster 1993).

EPA's technical guidance for final covers describes what has been called the RCRA C cover that they believe will meet the final cover performance standards for hazardous and mixed waste sites. The RCRA C cover design is composed of three layers which can be configured for soil water management:

1. An uppermost-vegetated layer to prevent erosion and promote evapotranspiration,
2. Underlying drainage layer/s to convey percolation out of the cover, and
3. A moisture barrier/s to prevent percolation through the cover.

The functional requirements of the topsoil layer are to promote runoff from major storms but restrict erosion rates to acceptable limits. While runoff can promote erosion and degradation of the cover system, vegetation and/or other surface treatments impede erosion and support the long-term integrity of the cover. The topsoil must also be thick enough to provide storage capacity for soil moisture for removal by evapotranspiration and to protect the hydraulic barrier layer from freezing and desiccation. EPA states that typically, a thickness of 60 to 90 cm (2 to 3 ft) is sufficient, but the actual requirement is climate, soil, and design specific.

EPA also states that drainage layers are not necessary at all sites since some sites may not have sufficient rainfall and infiltration to produce a standing head of water on the hydraulic barrier for long periods. If used, the drainage layer should be designed to reduce leakage through the hydraulic barrier layer by lowering the hydraulic head.

Capillary barriers have been investigated extensively as components of landfill cap designs since 1980 (Nyhan et al. 1990). Conceptually, they consist of two layers with widely differing hydraulic conductivities. Generally they are comprised of a fine-grained soil or sand overlying a coarse-grained gravel or rock.

Capillary barriers function as a moisture barrier by impeding flow at the interface between the two layers. Water moving downward through the soil encounters the coarse gravel layer, where capillary forces in the overlying soil prevent breakthrough of the water into the gravel at soil moisture conditions less than saturation. When saturation of the soil occurs, water breaks through the capillary barrier. By placing an angle on the interface between the soil and gravel layers, lateral flow can occur, reducing the potential for saturation and barrier failure by preventing build up of hydraulic head. Selection of materials for the capillary barrier system is critical in that rapid lateral flow is essential to prevent the buildup of water as it drains laterally downslope.

D 4. Relationship of Water Balance to Cap Design

The fate of meteoric water falling on the surface of a landfill is often referred to as the water balance of the site. A simplified representation of water balance describes surface runoff and one-dimensional movement of water in the soil profile to the plant rooting depth. For net rates and amounts, the water balance equation is:

$$dS/dt = (P - Q - ET - L)/dt \qquad \text{(Equation 1)}$$

Where dS/dt is the time rate of change in soil moisture, P is the precipitation per unit area, Q is the runoff per unit area, ET is the evapotranspiration per unit area, L is the percolation below the root zone per unit area, and t is the unit of time used in solving the equation.

Application of the concept of water balance to design of landfill caps, including the ET cap design, takes advantage of the fact that there are strong interactions between the various components of water balance (Hakonson et. al., 1982a). For example, a reduction or elimination of the runoff term (Q) must be accompanied by increased infiltration of water into the soil. Increased infiltration results in increased soil moisture storage, which is then followed, by an increase in ET and/or percolation. Conversely, reducing percolation necessitates that more of the precipitation be partitioned between soil moisture storage, ET, and/or runoff.

The coupled nature of the processes comprising the water balance can be used to advantage in designing a caps that minimize or eliminate hydrologic processes that contribute to contaminant migration (i.e. percolation (L) in Equation 1) while enhancing other terms (i.e. ET) that reduce the potential for aqueous phase contaminant transport (Nyhan et al., 1990b; Hakonson, 1997a, b; Hakonson et al., 1993; Lane, 1984a; Lane and Nyhan, 1984b; Dwyer, 1997, 2001; Anderson et. al., 1993).

D 5. ET Cap Design

A common misconception about ET caps is that they are unique and different from other cap designs. In fact, virtually any cap design that contains a vegetated soil layer functions primarily as an ET cap regardless of the number, type, and placement of engineered barriers within it. This means that most of the precipitation that infiltrates in the cap soil is removed by the vegetation cover via evapotranspiration.

For example, from about 90-100% of the precipitation that infiltrates into the vegetated top soil in environments receiving <50 cm, is removed by evapotranspiration (Anderson et. al., 1993; Hakonson, 1998; Hakonson et. al., 1990; Lane, 1984a,b; Nyhan et. al., 1990b, Nyhan et. al., 1997b; Dwyer, 2001). This also applies to the RCRA cap where most of the function in controlling percolation downward into the soil is due to the ET component of the design and not to the clay barrier (Dwyer, 2001; Warren et al, 1996 a, b).

In the absence of engineered barriers, a well-designed ET cap consists of a single, vegetated soil layer constructed to represent an optimum combination of soil hydraulic properties, soil thickness, surface slope, and vegetation cover (Hakonson, 1997a; Figure 1). The conceptual framework for the ET landfill cap design was developed from several short-term studies (i. e. studies of a few years duration) in the 1980's (Hakonson et. al., 1982a; Hakonson et. al., 1986a; Nyhan and Lane, 1986, 1987; Nyhan et. al., 1990b). Those studies, which used instrumented field plots in arid and semiarid environments, demonstrated that simple but well designed soil covers were very effective (i.e. as effective as EPA's RCRA designs) in preventing excessive runoff, erosion, and percolation of water through the cover. Those studies also demonstrated that the vegetation component of the cover served as the principal mechanism inhibiting soil moisture movement through the cover and into the waste.

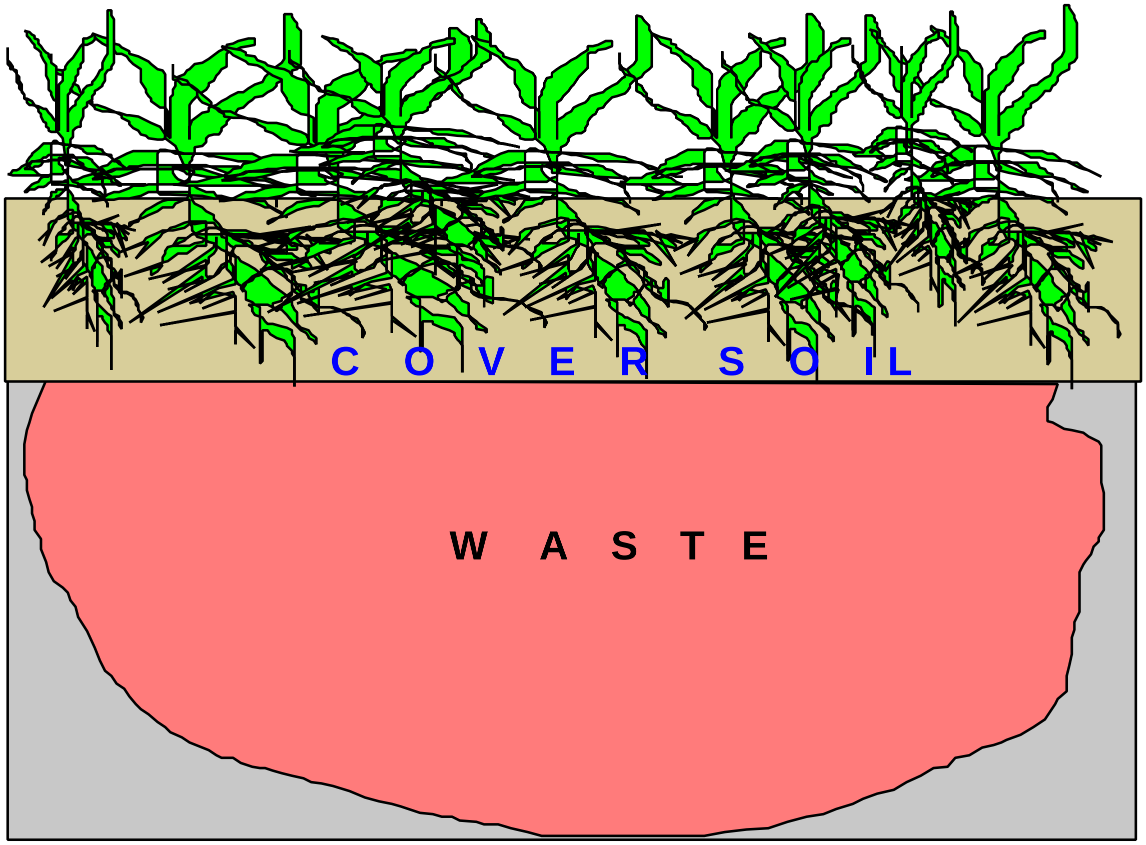

Figure 1. Conceptual ET cap representing optimal combination of soil type, soil depth, surface slope, vegetation type and density, and surface management practices such as gravel mulching to control erosion.

Ideally, the vegetation cover should consist of an optimum mixture of native species that represent late successional stages, including cool and warm season grasses and possibly species with different growth forms (such as grasses, shrubs, or trees). The intent of the vegetation cover is to provide long-term protection against soil erosion, resistance to catastrophic events such as fire and drought, and to fully utilize precipitation that falls on the site by spreading ET over as much of the year as possible.

For a site such as the MWL, the vegetation growing on undisturbed Upper Sonoran rangelands in the Albuquerque area would best represent a species mix that would be stable over the long-term. Shrubs should not be discounted in the species mix selected for the MWL. As will be discussed later, concerns about shrub root penetration into the MWL miss the point in that any species or mix of species planted on the MWL has the potential to penetrate into the waste environment. Conceptually, the goal is to capture all of the moisture before it gets to the waste. If that can be achieved under actual precipitation rates at the MWL then plant roots will remain in the cover soil.

Successional processes will most likely occur when the vegetation consists of early successional species or non-native species. Therefore, the optimal cover for maximizing

ET over the long term is likely to be the one maximizing both Leaf Area Index (LAI) and diversity among life-forms, and species that have evolved in the area.

D 6. Causes Of ET Cap Failure

D 6.1 Physical Transport Processes

D 6.1.1 Landfill Surface- Under ideal conditions, the primary functions of any cap design are to isolate the buried waste from the surface and ground water environment by controlling abiotic and biotic processes that can contribute to contaminant migration from the site (Hakonson et al., 1992a). Hydrologic and erosion processes account for most of the performance-related problems at LLW and sanitary landfills (Duguid, 1977; Jacobs et al., 1980; EPA, 1988).

For example, erosion associated with runoff can breach the cap and expose waste to the biosphere (Nyhan and Lane, 1982; Nyhan et al., 1984). Erosion rates must be within tolerances to leave the cap intact over the mandated lifetime of the facility. EPA recommends a soil Tolerance Level (TL) of 2 t/ac/yr (4.4T/ha/yr) in order not to deflate the cover surface over the lifetime of the site. Tolerance Level is an arbitrary amount of erosion (i. e., specific to site conditions) that is about equal to the rate of soil formation. The goal is to ensure that erosion rates are at or below the level where the soil surface begins to deflate with time.

Changes in erosion rates on a landfill cover can occur and may be associated with changes in vegetation biomass, animal species, plant and animal species composition, and disturbances such as fire or drought. Cover design features that are used to prevent erosion include the establishment of vegetation, the use of mulching techniques, synthetic mats, control of the slope and slope length, and the construction of terraces or benches.

Preventing buried waste from reaching the ground surface is important because once contamination on the soil surface, it is subject to transport by wind and water erosion processes (Hakonson et. al., 1981, Hakonson and Lane, 1992b; Lane and Hakonson, 1982). Erosion of contaminated soil can lead to transport of contaminants off the landfill by both physical and biological processes.

The importance of wind and water in transporting soil contaminants results from the fact that many contaminants are nearly quantitatively deposited in soil and are tightly bound to soil particles (Hanson, 1975; Ritchie and McHenry, 1990; Whicker and Schultz, 1982). Furthermore, concentrations of most contaminants in soils are a strong function of soil particle size. Generally, the silt and clay size fractions (< 50µm diameter) contain up to a factor of 10 higher concentrations than the bulk soil. This is especially true of most radionuclides such as cesium, plutonium and strontium (Watters et. al., 1980). Consequently, processes which transport soil also transport soil-associated contaminants.

In many cases, both wind and water preferentially detach and transport the finer size fractions that often contain the highest concentration of radionuclides and other contaminants. Moreover, the finer soil fractions are carried farther (and deposited later) than coarser fractions of eroding soil (Lane and Hakonson, 1986).

Recent studies were conducted at the Waste Isolation Pilot Plant, Rocky Flats Environmental Technology Site, and Los Alamos National Laboratory to evaluate the effects of fire on transport of fallout Cs-137 by wind and water erosion (Johansen, et. al., 2001a; Johansen et. al., 2001b). Those studies, which used a large rainfall simulator to generate runoff and applied controlled or natural fires as study treatments, found that soil erosion and soil associated fallout cesium-137 transport on burned plots increased by a factor of 4-25 over unburned plots depending on the study area.
Results demonstrated that erosion and soil radionuclide transport rates determined under undisturbed conditions do not reflect possible changes in rates due to a catastrophic disturbance such as fire. Without intense post fire management, such as reseeding, the effects of fire on water erosion can persist for years (Simanton and Emmerich, 1994).

The combined phases of runoff, soil erosion, sediment transport, and deposition of sediment on upland areas and in stream channels usually result in enrichment of smaller soil particles and organic matter in transported sediment (Graf, 1971) including concentrations of sediment associated contaminants (Massey and Jackson, 1952; Menzel, 1980; Lane and Hakonson, 1982). This enrichment is often expressed as an enrichment ratio, defined as the concentration of contaminant in the transported sediment divided by its concentration in the un-eroded soil.

Enrichment ratios have been related to sediment concentration, sediment discharge rate, and sediment yield (Massey and Jackson, 1952; Menzel, 1980). Lane and Hakonson (1982) analyzed sediment transport rates by particle size classes in alluvial channels and derived the following expression:

$$ER = \frac{\sum[Cs\ (di) \times Qs\ (di)]}{Cs \sum[Qs\ (di)]} \qquad (1)$$

Where:

- ER = alluvial channel enrichment ratio,
- Cs (di) = Concentration of contaminant in sediment particles of size class i, with representative diameter, di, in millimeters.
- Qs (di) = Sediment transport (mass/time) for particles in size class i, with representative diameter, di, in millimeters.
- Cs = Mean concentration of contaminant in soil over all particle size classes.

Equation 1 supports the empirical observation that enrichment ratio increases with decreasing sediment discharge rates. For example, at very low sediment discharge rates (those associated with low runoff velocities) the bed load discharge rate for coarse sediment particles is low and most of the transported sediment is in the smaller particle size classes. Under such conditions, ER would approach the ratio of concentrations in the finest size classes (Cs (di)) to the mean concentration over all size classes (Cs).

At high sediment discharge rates (those associated with high runoff velocities) more of the bed sediments are in transport. At the extreme, if all of the bed sediments were in transport in the same proportion, as they exist in the bed material, ER in Equation 1 would be unity.

Field measurements of enrichment ratios for nutrients and plutonium at several locations in the United States are listed in Table 2. The first four entries are for soil nutrients in runoff from small agricultural areas; mean values vary from 2.6 to 7.1. The next three entries represent enrichment of fallout plutonium in runoff from agricultural watersheds; mean values range from about 1.6 - 2.5. The last entry represents enrichment of plutonium in runoff in ephemeral stream channels at Los Alamos, New Mexico.

Enrichment ratios based on measurements in runoff in canyons at Los Alamos ranged from 1.4 to 13.3 with a mean of 5.5. Predicted enrichment ratios for Los Alamos stream channels [Eq. (1)] ranged from 2.9 to 7.0 with a mean of 5.2 (Lane and Hakonson, 1982). The close agreement between observed and predicted enrichment ratios suggests that particle sorting alone can account for ratios observed at Los Alamos.

In spite of wide differences in watershed size, hydrologic regime and chemical characteristics, the enrichment ratios resulting from sediment transport given in Table 2 are quite similar for several sediment-associated chemicals. Particle sorting is clearly one of the important factors involved in transport of soil and sediment associated contaminants.

Enrichment processes can lead to higher concentrations of radionuclides in sediment deposition areas. For example, fallout cesium and plutonium concentrations in reservoir sediments have been shown to be higher than concentrations in soils from upland areas that contributed the sediments to the reservoirs (Sprugel and Bartelt, 1978; Muller et. al., 1978). This is because the small soil particle sizes that usually contain highest concentrations of radionuclides are easily detached and transported to downstream areas and they are last to settle out of the water column as flow velocities decrease.

Soil resuspension by wind, rain splash, and mechanical processes also undergoes particle sorting. For example, rain splash and/or wind resuspends soil particles and deposits them on vegetation surfaces (Dreicer et al., 1984; Foster et al., 1985), and animals (Romney and Wallace, 1977; Hakonson and Nyhan, 1980).

Table 2. Approximate Enrichment Ratios for Nutrients and Plutonium Associated with Locations in the United States.

Land use and location	Approximate enrichment ratios	Comments

	Mean	Range	
Cropland, USA[a]	4.5	2.5 - 7.4	Nitrogen
	3.6	2.6 - 6.0	Phosphorus
Rangeland, USA[a]	2.6	1.1 - 6.7	Nitrogen
	7.1	2.7 - 17	Phosphorus
Cropland, USA[b]	1.6	1.1 - 2.5	Fallout Plutonium
Pasture, USA[b]	2.3	0.8 - 4.0	Fallout Plutonium
Mixed Cropland, USA[c]	2.5	1.2 - 4.0	Fallout Plutonium, Transport in Perennial River
Semiarid, USA[d]	5.5	1.4 - 13.3	Waste Effluent Plutonium Transport in Ephemeral Streams

[a]Small agricultural watersheds (5.2 - 18 ha) at Chickasha, Oklahoma.

[b]Small agricultural watersheds (2.6 - 2.9 ha) near Lebanon, Ohio.

[c]Great Miami River (Drainage area = 1401 km^2) at Sidney, Ohio.

[d]Los Alamos Watersheds (176 - 15,000 ha) near Los Alamos, New Mexico.

Field studies with plutonium (Nyhan, 1980; Watters et al., 1980; Romney and Wallace, 1977) show that physical deposition of contaminated soil particles on vegetation surfaces is 100-1000 times more important than root uptake as a means of contaminating vegetation with this radionuclide.
Likewise, most of the body burdens of plutonium are associated with the GI tract and pelt of small mammals living in contaminated areas. The association of plutonium with those tissues implies that soil ingestion and grooming activities are important mechanisms for contaminating animals.

The importance of physical transport of MWL contaminants will ultimately depend on the effectiveness of the ET cap in preventing transport of buried contaminants to the ground surface. Should transport of buried waste to the landfill surface occur, then transport by wind and water erosion will also occur. Ultimately, the fate of soil contaminants once they are present on the ground surface will depend on the fate of the soils and sediments themselves.

In an attempt to predict the amounts of soil lost under different regimes of climate, soil, topography, and land management, a number of approaches have been taken. Wischmeier and Smith (1960) developed the Universal Soil Loss Equation (USLE), a tool for predicting soil loss. The USLE combines known factor values for rainfall erosivity, soil erodibility, slope length and steepness, cover/management, and supporting practices to estimate soil loss values for use in environmental planning and assessment. Others have gone a step further by combining equations for fundamental hydrologic and erosion processes into models to predict soil losses and losses of pollutants including agricultural chemicals. One of these efforts includes that of the U.S. Department of Agriculture's development of CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems), a model capable of evaluating runoff, erosion, and chemical transport from field-sized areas (Knisel, 1980).

D 6.1.2 Subsurface Processes- Depending on climate, geology and soil conditions, water that infiltrates into and through the cap on old landfills can accumulate in the trench (bathtub effect) and/or percolate with solutes into groundwater. Percolation can also increase subsidence of the cap as a result of enhanced decomposition of bulky waste in the trench. Subsidence may occur some variable time after closure of the land disposal unit and after final placement of the cover. Although subsidence has the potential to seriously damage a landfill cover, predicting subsidence and subsidence effects is very difficult because of the heterogeneous nature of the waste forms, backfill materials, and variation in local climatic conditions.

In landfills that contain volatile contaminants, movement might also involve both aqueous and vapor phase transport such as has been observed for tritium at the MWL. Controlling aqueous transport of volatile contaminants does not necessarily control vapor phase transport. In fact, maintaining low soil moisture content of cover and backfill soils to reduce aqueous phase transport may be associated with increases in vapor phase transport of volatile contaminants (Jury, 1987). This is likely what occurs at the MWL regarding tritium. Vapor phase transport may also be more pronounced near the ground surface where changes in soil barometric pressure, rapid wetting and drying of soil, and plant root biomass and animal burrowing leading to macropore formation are greatest.

In climates that experience freezing temperatures or drought, the cover, including the soil layer and man-made construction materials, may be effected by the freezing or drying of the soil. Frost heaving and desiccation cracking is common in soils with high clay content. However, these soil surface disturbances are reduced when vegetation cover is present.

Freezing temperatures and drought can disrupt the integrity of barrier layers and freezing can also increase the amount of runoff when frozen ground limits infiltration of moisture into the soil. Desiccation of clay soils, such as hydraulic barriers, is a potentially important problem in arid sites (Suter et al., 1993). Because of potential problems with desiccation, EPA (1989) notes that alternatives to clay hydraulic barriers should be considered for sites with a high risk of barrier desiccation.

D 6.2 Biological Processes

Biological processes associated with the cap include plant root and burrowing animal intrusion into cover soil and potentially into the underlying waste. Penetration of plant roots and animals to the waste may contribute to migration of contaminants from the burial environment by both biological and physical/mechanical processes (Klepper et al., 1979; O'Farrell and Gilbert, 1975; Winsor and Whicker, 1980; and Arthur and Markham, 1983; Arthur and Markham, 1982, 1987; Arthur and Janke, 1986). Both plants and animals also affect physical processes such as water balance and erosion. Plant and animal related processes in landfill covers are closely coupled so that a response in one elicits a response in the other.

D 6.2.1 Plant Related Processes- 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 et al., 1987).

Contaminants such as tritium can be incorporated within plant tissue and enter the food web of herbivorous or nectivorous organisms. For example, at Los Alamos National Laboratory tritium transport away from a controlled low-level waste site occurred via the soil moisture/plant nectar/honey bee/ 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 ^{90}Sr, 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).

Table 3. Comparison of plutonium concentration ratios for field and glasshouse conditions (Romney and Wallace, 1976).

Soil Source	Field	Glasshouse
NTS Area 11B[a]	1.3×10^{-2} to 1.6×10^{-1}	1.5×10^{-4}
	-2 -1	-4

NTS Area 11C	4.5 x 10 to 3.4 x 10	1.8 x 10
NTS Area 13	7.8×10^{-2} to 4.4×10^{-1}	1.1×10^{-4}

[a]NTS (Nevada Test Site)

Comparative studies of plant uptake of plutonium under both field and laboratory conditions generally yield results of the type shown in Table 3. The results of laboratory studies represent root uptake of plutonium from soils and yield concentration ratios that are at least one order of magnitude (and often 2-3 orders of magnitude) lower than ratios observed under comparable conditions at field sites.

The differences in concentration ratios between laboratory and field studies implies that a mechanisms exists in arid environments for delivering at least 10 times more plutonium to vegetation than would be predicted based upon root uptake as measured in greenhouse studies.

The higher ratios observed at field sites have been attributed to the presence of surficial contamination on vegetation (Romney et al., 1987; Hakonson and Nyhan, 1980; Little et al., 1980). That conclusion is supported by the obvious presence of soil on foliage surfaces in the field and by the ability to remove up to 90% of the plutonium contamination from vegetation by washing (White et al., 1981; Arthur and Alldredge, 1982).

Studies at Los Alamos demonstrated that rain-splash of soil particles with subsequent deposition on foliage surfaces can easily contribute all of the plutonium measured in field-site vegetation (Dreicer et al., 1984). More importantly, those studies, which employed a labeled-soil particle technique and the scanning electron microscope, have shown that relationships that govern lateral movement of plutonium by soil erosion processes also govern transport of plutonium to foliage surfaces.

For example, the energy of impacting raindrops caused an enrichment of the smaller soil particles on foliage surfaces. The amount of soil deposited on the plants was also related to height from the ground surface and characteristics of the rainstorms. Calculations based on the mass and plutonium content of soil measured on the plants demonstrated that the rainsplash mechanism could easily account for the high concentration ratios observed in field samples (White et al., 1981; Foster et al., 1985).

While absorption of soluble forms of plutonium through leaf surfaces has been demonstrated (Cataldo and Vaughn, 1980) it is likely to be of limited importance in arid field sites because environmental plutonium exists as an oxide and is very tightly bound to soil. Studies on the uptake of plutonium by vegetable crops grown in field sites at Los Alamos show that as much as 50% of the plutonium in edible crop samples was surficial contamination that could be removed by washing (White et al., 1981) or peeling.

The remainder that could not be removed was associated with very fine soil particles adhered to the vegetable surfaces as determined by the electron microscope. Cataldo and Vaughn (1980) and White et al. (1981) showed that submicron particles on foliage surfaces are difficult to remove by simulated wind, rain, or household food washing procedures. While a large number of the published studies on environmental fate and effects deal with plutonium, physical processes will also control the environmental behavior of many other radionuclides.

D 6.2.2 Root Distribution in Soil- Root distribution in the soil profile is strongly related to the depth of water penetration into the soil (Canadell et al, 1996; Jackson et al. 1996). Although average and maximal reported rooting depths vary with species and life form, there is a great deal of plasticity within most species to respond to variation in soil water availability. Hence, if water is available at deeper depths, roots of a species viewed as "shallow rooted" may occur there. For example, in a semiarid ecosystem in New Mexico, plant roots of a number of species have been observed to depths of at least a few meters in the pursuit of soil moisture (Foxx et al., 1984; Tierney et al., 1987). Alfalfa roots have been found over 40 m below the ground surface (Foxx et al., 1984).

If the root structure of certain species is confined to the upper few centimeters of the soil profile, it is largely because that is where most of the soil moisture is captured by the plants and removed from the soil. If moisture becomes available at deeper depths, most species have the potential to exploit this moisture by sending roots downward to capture available moisture, often to depths greater than previously recognized (Canadell et al. 1996). In normal situations where multiple species co-exist on a site,one species may exploit moisture near the ground surface while another exploits moisture deeper in the soil profile (Evans and Ehleringer, 1994, Golluscio et al. 1998, Breshears and Barnes, 1999).

Canadell et al. (1996) summarized what was known about the maximum rooting depth of species belonging to the major terrestrial biomes. They found 290 observations of maximum rooting depth in the literature that covered 253 woody and herbaceous species. Maximum rooting depth ranged from 0.3 m for some tundra species to 68 m for Boscia albitrunca in the central Kalahari; 194 species had roots at least 2 m deep, 50 species had roots at a depth of 5 m or more, and 22 species had roots as deep as 10 m or more. The average for the globe was 4.6+/-0.5 m.

Maximum rooting depth by biome was 2.0+/-0.3 m for boreal forest, 2.1+/-0.2 m for cropland, 9.5+/-2.4 m for desert, 5.2+/-0.8 m for sclerophyllous shrubland and forest, 3.9+/-0.4 m for temperate coniferous forest, 2.9+/-0.2 m for temperate deciduous forest, 2.6+/-0.2 m for temperate grassland, 3.7+/-0.5 m for tropical deciduous forest, 7.3+/-2.8 m for tropical evergreen forest, 15.0+/-5.4 m for tropical grassland/savanna, and 0.5+/-0.1 m for tundra.

Grouping all the species across biomes (except croplands) by three basic functional groups: trees, shrubs, and herbaceous plants, the maximum rooting depth was 7.0+/-1.2 m for trees, 5.1+/-0.8 m for shrubs, and 2.6+/-0.1 m for herbaceous plants. The mixture of grasses that SNL/NM intends to use in reseeding the MWL is lumped within the herbaceous plant category.

These data show that deep root habits are quite common in woody and herbaceous species across most of the terrestrial biomes, far deeper than the traditional view has held up to now. The implications for the MWL are that no matter what vegetation is planted on the landfill, if moisture penetrates beneath the ET cover, roots can be expected to follow.

D 6.2.3 Animal Related Processes

D 6.2.3.1 Uptake- 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, 1992b).

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; Romney et al., 1970).

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, gastro-intestinal 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 gastro-intestinal tract (Hakonson and Nyhan, 1980).

Because soil passes through the gastro-intestinal tract of free-ranging animals on a daily basis, there is a potential to redistribute soil radionuclides across the landscape. Studies at Nevada Test Site with cattle (Moore et al., 1977), at Rocky Flats Plant with mule deer and small mammals (Little, 1980; Arthur, 1979), and at Idaho National Engineering Laboratory with small mammals and coyotes (Arthur and Markham, 1983; Arthur et al., 1980) 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., 1980).

There are circumstances where animal transport of soil contaminants can assume more importance. For example, fission product sludge containing Sr^{90} and Cs^{137} in 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 ^{90}Sr on the ground surface. Levels of ^{90}Sr in excreta were found over 15 km^2 (O'Farrell and Gilbert, 1975). I would emphasize that this incident with ^{90}Sr and jackrabbits was a special case that involved liquid waste sludge disposal trenches that were not adequately covered.

Potentially more soluble strontium and cesium 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., 1983) 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 gastro-intestinal 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 cesium and strontium 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.

As mentioned, 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 3 days (RHH, 1970).

D 6.2.3.2 Burrowing- The subject of animal intrusion into landfills is seldom explored in any detail. The Dwyer et. al. ET cap proposal includes the use of an animal intrusion barrier. Their basic assumption in proposing the use of the barrier is that animal burrowing is bad for landfills. This is an assumption that by no means has been demonstrated conclusively. Therefore, I want to explore the subject of animal burrowing effects in more detail in this section.

The role of burrowing animals in mobilizing buried waste is not well known because very few relevant studies have ever been conducted. Some field studies deal specifically with animal burrowing in contaminated sites (O'Farrell and Gilbert, 1975; Winsor and Whicker, 1980; and Arthur and Markham, 1983; Hakonson et. al., 1982) and those studies show that burrowing animals may, in some cases, alter the vertical distribution of soil radionuclides that are present near the ground surface and in the process can become contaminated themselves.

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; Hakonson et. al., 1982b; Gonzales et. al., 1993; Hakonson, 1998). Burrowing activity loosens the soil, creates surface roughness, increases infiltration, and increases soil moisture at least temporarily (Hakonson, 1998).

It could be assumed that increased soil moisture could lead to increased moisture movement into the waste. However, controlled studies on this potential problem show that increased soil moisture does not lead to increased percolation of moisture into the waste when a vegetation cover is present on the cap (Sejkora, 1981, Hakonson, 1998, Gonzales et. al., 1993).

The increased soil moisture resulting from burrowing effects on infiltration stimulates plant growth and plant transpiration (Hakonson, 2000; Gonzales et. al., 1993). Consequently, these studies show that the net effect of the animal burrowing is lower, not higher potential for percolation of water into the waste as long as avegetation cover is present (Gee and Ward, 1997; Hakonson, 2000).

The small number of studies actually conducted on contaminated sites all suggest that the effects of animal burrowing on erosion, infiltration of water into the cap, and contaminant redistribution are second order in importance or that they actually promote isolation of buried contaminants via feedback between soil moisture status and the vegetation cover. However, these studies were conducted on sites that were vegetated. Results may be altogether different if the soil surface is highly disturbed such as from overgrazing, fire, or mechanical actions such as mowing of the vegetation cover.

While the numbers of studies that are specific to waste sites are limited, there are substantially more ecological studies of animal burrowing effects on soil, vegetation, and water balance on forests and rangelands. The vast majority of published information on the effects of animal burrowing is specific to pocket gophers (*Geomyidae*). Furthermore, much of the research was carried out between 1930 and 1960 and appears to have been initiated primarily in response to potential impacts of gopher burrowing and herbivory on the health of rangelands and forests.

Animal burrowing into the soil on the MWL has been conclusively documented (see Dwyer et al ET cap proposal) although I could not find any publications that document the species of animal involved, their numbers, or the consequences relative to waste transport to the ground surface or contamination of the animals. Kangaroo rats, a communal animal that creates an extensive den, are probably present on the landfill. In the absence of monitoring data or special studies on the effects of burrowing by Kangaroo rats or any other species on the MWL, little can be said about the consequences of this burrowing.

D 6.2.3.3 Burrow Depths- Fossorial animals spend a major part 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 much greater depths.

For example, pocketgophers 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 meters (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 may create burrows to at least 150 cm and 15-20 cm in diameter (Table 4). Estimates of burrowing depths for other species are given in Table 4.

Insects also have the ability to tunnel deeply into a landfill cap. For example, some ant species develop tunnel systems to 6 m (Table 5) below the ground surface (Cole, 1966; Cowan, et. al., 1985; Cline et. al., 1976) although most species tunnel to depths of 1-4 m (Hölldobler and Wilson, 1990). Studies in Idaho show that infiltration of water in 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.

D 6.2.3.4 Rates of soil turnover- There is little question that pocket gophers, and likely other small 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 54-120 animals ha^{-1} (Hansen 1965). Actual amounts of soil moved to the surface by pocket gophers have ranged from 16-103 T ha^{-1} yr^{-1} (Mielke 1977, Spencer et al. 1985).

Estimates of 12-20 T $acre^{-1}$ yr^{-1} have been reported for pocket gopher densities on the order of 10 per acre (Grinnell, 1923; Grinnell and Storer, 1924; Ingles, 1952; Shelford, 1929; Ellison, 1946). However, much of the displaced soil is not pushed to the surface, but is re-deposited in other parts of the burrow system. For example, Andersen (1987) found that 41-87% of excavated soil was deposited as backfill in tunnels below ground.

Hakonson et. al. (1982) conducted a study of soil excavation rates by pocket gopher on a low level waste site at Los Alamos. They found that over a 401-day period, pocket gophers on the 0.95 created 1998 separate mounds ha study area for an average mound production of about 5 day^{-1} ha^{-1}. The total mass of the soil in these mounds over the 401 day study period was 11 T ha-1 yr-1, for an average excavation rate of about 30 kg $ha^{-1}day^{-1}$. Mound building activity was greatest in late summer and fall when a total of about 60 kg ha^{-1} of soil was brought to the surface of the landfill each day.

Hakonson et. al., (1982) also found that the digging activity of pocket gophers on the LLW site at Los Alamos 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, as measured in the field, 8.3 m^3 of void space within the cover profile represents about 2800 m of pocket gopher tunnel system per hectare.

D 6.2.3.5 Effects on Soil Characteristics- Aubertin (1971) in a study of macropores in forest soils attributed differences 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^{-1} on non-mound soil in an area disturbed by moles *(Talpa europaea)* compared to 96.4 mm min^{-1} on mounds less than 1 year old. Grant et al. (1980) reported a 2-fold increase in hydraulic conductivity on pocket gopher *(Thomomys talpoides)* mounds compared to that of adjacent, undisturbed prairie soil.

Table 4. 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 bottae (Botts pocket gopher)	5-35
Thomomys talpoides (pocket gopher)	10-30
Geomys bursarius (Plains pocket gopher)	23
Perognathus longimembris (pocket mouse)	52-62
Perognathus parvus (Great Basin pocket mouse)	35-193
Dipodomys spectabilis (kangaroo rat)	40-50
Dipodomys microps (Banner-tailed kangaroo rat)	25-45
Dipodomys merriami (Merriam's kangaroo rat)	26-175+
Taxidea taxus (badger)	150+

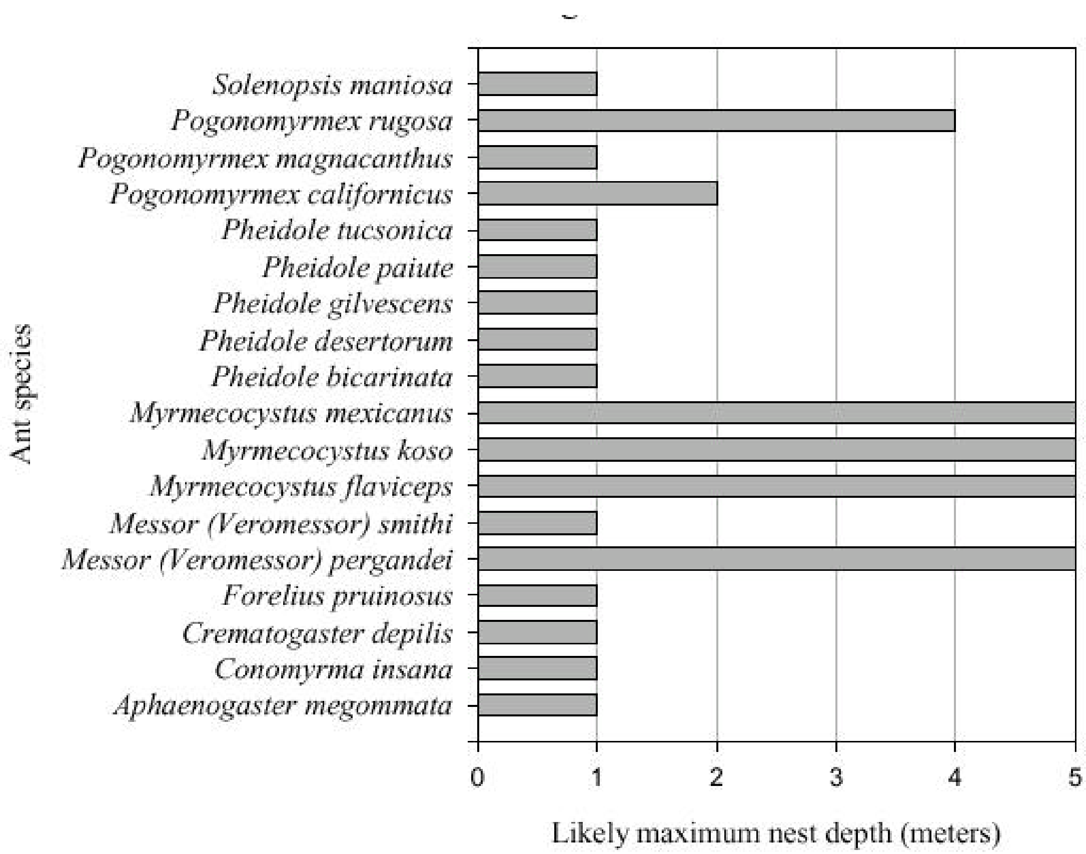

Figure 2. Burrowing depths of some representative ant species (Jensen, 2000).

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 (P<0.0001) reduction in bulk density from 1.07 Mg m^{-3} to 40.85 Mg m^{-3} 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 undoubtedly has a large influence on hydraulic conductivity of the soil.

Mielke (1977) found that soil moisture content increased from 2.6 to 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, 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 P, K, Ca, Mg, and Fe 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 1972, Grant and McBrayer 1981, Mielke 1977). Laycock and Richardson (1975) also showed a slight increase in nitrogen on gopher mounds. However, Hirsch et al. (1984) and 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 cation exchange capacity, 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).

D 6.2.3.6 Effects on vegetation cover- Large differences in the abundance and type of vegetation on and near areas disturbed by animal activity have been reported. Ward and Keith (1962), Luce et al. (1980), and Bandoli (1981) related differences in plant species composition to the food preference of pocket gophers. Ellison and Aldous (1952) suggested that pocket gopher foraging was responsible for a decline in dandelion *(Taraxacum officinale)* and other annual plant species. Ross et al. (1968) reported that mima mounds had a much higher abundance of shrubs than adjacent non-mound soils. Similar results regarding vegetation abundance and species diversity have been shown for areas disturbed by ants (Culver and Beattie 1983).

Ellison and Aldous (1952) reported increases in rhizomatous species, grasses, and sedges in central Utah. Laycock and Richardson (1975) also measured increases in total standing crops of grasses and rhizomatous forbs where gophers were present. Grant et al. (1980) found that gopher mounds resulted in a net increase of about 5-6% in overall primary productivity in shortgrass prairie.

Presumably, these increases were due to increased aeration from turnover of the soil and increased infiltration of surface water resulting from increased infiltration rates and increased surface roughness (due to soil mounding) leading to reduced runoff velocities. Mielke (1977) reported enhanced plant growth in a semi-arid environment and attributed this to gopher activity and consequent alteration of soil texture, humus content, mineral availability, and change in surface roughness.

Foster and Stubbendieck (1980), Hirsch et al. (1984), and Spencer et al. (1985) found higher proportions of bare ground in areas disturbed by gophers when compared to exclosures free of gopher activity. There was also less organic matter in the soils from the disturbed areas.

In contrast, Turner et al. (1973) and Mielke (1977) found greater aboveground biomass production near mounds. Laycock (1958), Bookman (1983), and Tilman (1983) related such differences to the environmental gradients established by animal activity. Differences in moisture and chemical content, soil compaction, and species selection by animals were listed as possible explanations for these changes in vegetation abundance, biomass, and diversity.

A study at Los Alamos (Hakonson, 1998; Gonzalez, et. al., 1997) 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 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 an 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.

D 6.2.3.7 General Effects on Erosion- There is some disagreement as to the role of pocket gophers as causative agents of soil erosion. However, a preponderance of the information in the literature indicates that their role in soil erosion processes is rather small and that they may actually be beneficial in soil retention. There seems to be little or no evidence to suggest that rodents or other animals, under natural conditions, promote soil erosion (Taylor, 1935). The few authors who do state that pocket gophers contribute significantly to soil erosion (Day, 1931 and Gabrielson, 1938) provide anecdotal observations and no data specific to the question.

Gopher burrowing impact on soil structure includes increased porosity as a result of mechanical loosening, which aids in water infiltration and prevents heavy surface runoff (Grinnel, 1933; Ellison, 1946; Ingles, 1952; Ursic and Esher, 1988; Laundre, 1993). Ellison (1946) and Buechner, (1942) studied different species of pocket gophers in Utah and Texas and concluded that they had little appreciable effect on soil erosion. Numerous other studies also concluded that animals in a natural environment do little to promote erosion and may even help prevent soil loss (Taylor, 1935; Lowdermilk, 1934; Hansen and Morris, 1968).

Lowdermilk (1934) points out that the primary cause of accelerated erosion in rangelands is destruction of the native mantle of vegetation and that gophers, in the absence of heavy grazing by other herbivores, are generally thought to promote plant growth and reduce erosion. The principal causes of extensive vegetation destruction include heavy grazing, fire, destructive lumbering, railroad and highway cuts, and clearing and cultivation for agricultural crops. Based on information in the literature, pocket gophers and other small burrowing mammals do not appear to be responsible for accelerated erosion in natural areas. They may, however, compound the problem of erosion in heavily grazed and cultivated lands.

D 6.2.3.7.1 Effects on Wind Erosion- Several authors speculate that wind erosion of mound soil is possible but none of them offer quantitative data to support such statements (Murray, 1967; Smallwood, 1996). The few credible published anecdotal statements that infer a wind erosion mechanism for destruction of soil mounds (Murray, 1967; Foster and Stubbendieck, 1980; Litaor et al., 1996) are generally linked to studies of animal burrowing activities on steep slopes, alpine and subalpine areas with high snowfall and precipitation rates, or to highly disturbed sites such as those that were heavily overgrazed. In no case do these authors provide measurement data supporting their suggestions of a wind erosion pathway for soil mounds.

Despite the lack of specific studies and the anecdotal observations, it seems probable that under the right environmental conditions, some wind erosion of mound soil does occur, particularly if the site conditions are conducive to accelerated erosion (mechanically disturbed, over grazed, steep slopes, etc.). However, the amount of soil eroded and the distance that eroded soil and associated contaminants would be transported are strongly related to characteristics of the wind storm events, the type and density of the surrounding vegetation, and the texture and moisture content of the mound soil. These are factors that are known to be important based on general studies of wind erosion (Bagnold, 1942; Graf, 1971; Marshall, 1973; Gallegos, 1978; Sehmel, 1980; and Anspaugh et al., 1974). Resuspension of soil generally increases as a power function of wind speed and decreases with increasing plant height and cover and with increasing coarseness of the soil and increasing soil moisture content.

A major determinant of the importance of wind erosion in the transport mound soil from the MWL will be the height and density of the vegetation cover on the landfill and along the upwind and downwind pathway. Sehmel (1980) observed a 5 order of magnitude decrease in resuspension rates of tracer particles at the Hanford Reservation as surface roughness height increased from 0.005 cm to 6 cm. The greater the density and height of the vegetation cover, the lower the wind velocities at the soil surface and the associated soil resuspension rates (Bagnold, 1942; Graf, 1971; Marshall, 1973; Gallegos, 1978; Sehmel, 1980; and Anspaugh et al., 1974). Sehmel (1980), again at Hanford, stated that non-respirable particle sizes are carried only a short distance while respirable fractions can be carried to greater distances.

D 6.2.3.7.2 Effects on Water Erosion- As mentioned above, the only quantitative data on the effects of burrowing and soil mounding by fossorial organisms is in reference to hydrologic processes. It is instructive to review these data as they provide some insight on the importance of these organisms in relation to erosion on landfill caps.

Studies that have quantitatively measured hydrologic erosion in areas infested with pocket gophers include those by Burns (1979) and Thorn (1978, 1982). These authors both studied the northern pocket gopher on south facing slopes in the alpine tundra of Colorado at elevations above 3000 m.

Burns calculated that about 35% of mound soil deposits were eroded from the mounds each year, amounting to a soil surface deflation of 0.0037 cm/yr over the study area. He also noted that erosion rates caused by immobile, long lived snow patches (a process called nivation) deflated the soil surface by 0.009 cm/yr while "normal wind and water erosion on the alpine tundra" resulted in a soil loss of 0.0001 cm/yr.

Thorn (1978) calculated a deflation rate of 0.03 cm/yr, which at his study area was 10 times that due to nivation processes and 1000 times that of "normal wind and water erosion on the tundra". Based on these two studies, we calculated the worst-case erosion rate at less than 3 metric tons/ha/yr, which is below the Tolerance value of 4.4 metric tons/ha/yr.

Numerous authors have found that soil mounding by fossorial organisms actually contributes to site stability by:

- enhancing infiltration of precipitation into the soil (Marshall and Holmes, 1979; Lysikov, 1982; Aubertin, 1971; and Grant et al., 1980);

- mixing soil nutrients vertically in the soil profile (Baxter and Hole, 1967; Culver and Beattie, 1983; Czerwinski et al., 1971; Levan and Stone, 1983; Lockaby and Adams, 1985; Salem and Hole, 1968);

- increasing plant nutrients in the mounds (Abaturov, 1972; Grant and McBrayer, 1981; Mielke, 1977); and

- enhancing the diversity and amount of vegetation cover on and adjacent to the mounds (Turner et al., 1973; Mielke, 1977; Laycock, 1958; Bookman, 1983; and Tilman, 1983; Grant et al., 1980; Ellison and Aldous, 1952; Laycock and Richardson, 1975) and decreasing soil erosion (Sejkora, 1989).

A study by Sejkora (1989) is particularly relevant to the MWL situation in that it is to our knowledge the only comprehensive study that 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 2-year period, applied at 60 mm/hr over 1 hr, to measure erosion from 8 - 3 x 11m 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 cesium 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 erosivity.

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 2-year duration of the study, while soil loss associated with the other 3 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 2-year study, sediment yields from these 3 treatments averaged from 5-25% of that measured on these same plots at the beginning of the study. Averaged over the 2-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.

D 6.2.3.8 Long term Biological Intrusion- Predicting the long term consequences of biological intrusion at the MWL is not possible given the current lack of data on the transport of site contaminants to the ground surface by plants and animals. Additionally, there are many post-closure variables that will affect future potential for biological intrusion at the site, including final depth of "clean" soil place over the waste, physical and chemical form of the contaminants, species of animal and insects that come to occupy the site, and bioavailability of the contaminants.

There is very little information that addresses the long-term impact of biological intrusion on the mobility of waste site contaminants. To my knowledge, only one modeling study (McKenzie et. al. 1982) looked specifically at the potential importance of long-term biological intrusion on dose to man under arid site conditions. They compared 100 year dose to man resulting from animal intrusion of two reference low level radioactive waste sites with the estimated dose based on the human intrusion scenario developed in 10 CFR 61.

McKenzie et. al. concluded that dose to man resulting from plant and animal intrusion over a 100 year period was of the same order (about 50% less) as that resulting from the human intrusion scenario. Their conclusion was based on modeling that used published data and assumptions about species of plants and animals present on the LLW sites, penetration depths on roots and burrows, cover thickness, depth to waste, and waste types and forms.

Actual radiation doses to free ranging animals at nuclear facilities have been measured using small dosimeters implanted or attached to individual animals. The first such study was conducted in the 1960's at Oak Ridge National Laboratory and involved attaching dosimeters to free ranging rodents living in contaminated sites (Kaye, 1965). Follow up studies with implanted dosimeters was conducted at Nevada Test Site with jackrabbits (French et. al., 1974) and Los Alamos with several species of rodents (Miera and Hakonson, 1978). The Los Alamos studies, which used thermoluminescent dosimeters implanted into rodents living in treated liquid waste outfalls, demonstrated that doses in the rads/year range were possible for small, burrowing ground dwelling animals living in contaminated areas (Miera and Hakonson, 1978). Several other similar studies have also been conducted with animals such as free ranging rodents, coyotes and ungulates (Arthur et. al., 1986; Groves et. al., 1986; Halford et. al., 1982; Halford and Markham, 1978).

Given the presence of contaminants within the plant rooting and burrowing depths of biota, transport of contaminants to the ground surface and outside the boundaries of the waste site could be expected to occur as concluded by the McKenzie et al (1982) modeling study. The only way to confirm whether biological intrusion has occurred at the MWL is to conduct a well-designed study that provides unambiguous data on biological transport of site contaminants. This will entail careful consideration of the spatial and temporal distribution of soil, plant, and animal samples. While biological transport may not be important on a short time scale, over decades it could assume more importance relative to the ground water pathway in contributing dose to man.

The limited numbers of soil sample results from the 1980's described in the Phase I RFI for the MWL are not useful in such an evaluation. Furthermore, the documents I reviewed for this report are silent on biological sampling so it either has not been done in the past or has been evaluated and deemed unimportant. In either case, the subject should be adequately addressed in the closure plans for the MWL.

A final point is that if the ET cover and subgrade thickness is 1.5-2m as planned by SNL/NM, that thickness will not necessarily preclude burrowing animals from accessing the waste. Kangaroo rats, which occur on the MWL, can easily penetrate to those depths as can other burrowing animals (see Table 4 and Fig. 2). Even in the presence of a wire mesh intrusion barrier, as proposed by Dwyer et. al., burrowing insects such as ants and termites have the potential to deeply penetrate into the landfill waste.

It is worth noting that the physical separation of MWL waste from the ground surface is at most a couple of meters compared to over 100 meters separating the waste from groundwater. This means that processes that operate on or near the ground surface deserve adequate, credible attention to not only evaluate whether transport of waste contaminants has occurred prior to the planned closure (i. e., pre-closure conditions should represent the "natural analog" of post-closure conditions), but to the potential consequences of long term physical and biological processes for transporting waste constituents to the ground surface. I would repeat again that it is certain that tritium is now present in vegetation and animals that occupy the MWL.

D 6.2.3.9 Conclusions About Plant and Animal Intrusion- The literature on the effects of animal burrowing on physical, chemical, and biological characteristics of the soil can be summarized as follows:

1) The vegetation that is seeded into the MWL ET cover and it's successional counterparts creates a multiple paradox in that the purpose of vegetation is to remove soil moisture to prevent percolation of water into the waste. However, if the plant cover is effective in maintaining dry conditions in the cover, vapor phase transport of volatile constituents such as tritium may be increased (Jury, 1987).

It is also a paradox that roots penetrating to deeper sources of soil moisture not only can retrieve the soil moisture, but also any plant available contaminants. The technical concept behind the ET cover is to maximize root distribution in cover soil to maximize soil moisture removal and thereby limit percolation of moisture into the waste. In the event that moisture does escape beneath the root zone, it is certain that plants roots will follow this moisture given the absence of barriers to root penetration. This is because the concept of "shallow rooted" plants as used by many cap designers ignores the fact that the rooting depth for most individual plant species encompasses a broad range. Consequently, if moisture is available at deeper depths, most plant species have the capability to send roots after that moisture. As with animals, it is certain that vegetation on the MWL will reflect tritium levels in the soil.

2) 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 site such as the MWL will depend on the vertical location of waste in the landfill, cap design (soil type, soil depth, type and longevity of intrusion barrier), plant cover (species composition and changes with time), and fauna that occupy the site (species composition, changes with time).

Some organisms such as ants and termites have the potential to penetrate deeply (6 m) into the soil. The importance of the burrowing by animal and insects in transporting buried waste to the surface of the SNL/NM ET cap will depend on the thickness of the cover, nature of the waste in the near surface environment, the kind, amount, and changes in the vegetation cover, and the stability of the cover over the long term (disturbances from fire, drought, etc.). It is certain that animals will take up tritium from the MWL from burrowing and feeding activities.

3) Burrowing animals such as the pocket gopher have the ability to create extensive tunnel systems in a landfill cover. This results in the production of void space, an increase in hydraulic conductivity, and an increase in macropores that can channel water to deeper depths. While these factors may seem to create a long-term problem for percolation of water into the waste, a small amount of research data suggests that the consequences of this burrowing are minimal or actually beneficial as long as vegetation is present on the cover. The primary factor limiting the negative impacts of animal burrowing on percolation of soil moisture downward into the soil is the close linkage between plant available soil moisture and plant growth. Studies show that increased soil moisture elicits an increase in plant growth and transpiration rates. Consequently, the net effect appears to be that soil moisture regimes in vegetated soils disturbed by animal burrowing are dryer on average than soil not subjected to the burrowing.

Research data also show that mounding of soil on the ground surface as a result of animal burrowing, does not increase the potential for erosion of cap soil when vegetation is present on the site. However, very little research has been done on the effects of animal burrowing on soil erosion. Additionally, disturbances of the vegetation cover due to mowing, fires, and drought would increase rates of erosion of the cover with or without animal burrowing.

Extensive infestations of the ET cover with animals such as pocket gophers can influence the species composition of the vegetation cover. Studies in rangelands show that pocket gophers prefer weedy species as food leading to increases in the abundance of non-forb species.

4. Information on the concentrations of contaminants in biota and surface soils at the MWL would be instructive about the potential of biological intrusion for mobilizing waste. Because the site was opened in 1959 and closed in 1988, there has conceivably been several decades during which processes involving plant and animals could have brought subsurface contamination to the ground surface. I am certain that tritium from the MWL will be present in site biota.

D 6.2.4 Human Intrusion- SNL/NM states that they intend to re-evaluate the MWL at some point in the future to determine if the ET cap closure will be adequate for isolating waste into the distant future. SNL/NM is vague as to when this reevaluation will occur, what it would consist of, and the possible alternative actions that might be triggered if the ET cap proves less than effective in isolating the waste. If my impressions are correct, SNL/NM proposes to maintain institutional control of the MWL for some time after closure, but it seems prudent to assume, as does the National Research Council (NRC, 2000), that vigilance at the MWL will wane and that institutional memory and control will degrade or be lost.

Therefore, let's assume that it is possible that humans at some point in the future could occupy the landfill surface for a home site, growing crops, industrial activities, or other uses that are intimately associated with the landfill. Given that potential, the question then becomes one of what can be done now to prevent future human intrusion should control of the site be lost.

Presuming that future generations are still literate, a simplistic but effective approach might involve the use of marker systems placed judiciously at the site. For example, ceramic or glass tiles, ala Anasazi clay pottery, with embossed warning messages could be scattered beneath the cover as it is constructed so that any future excavation on the landfill would encounter the warning tiles. Surface markers could also be constructed but one would have to assume that such tiles or surface markers do not become an attractive nuisance, i. e., become collectors' items.

I suppose the argument could be made that the use of a marker system in the early phases of the closure increases the possibility that the landfill owners will forget about the landfill. Consequently, it is prudent to get a binding administrative and financial commitment from the landfill owners to fulfill all obligations during the period of institutional control. I am not sure how this would be accomplished from a legal view but I would presume it might involve an escrow account that would cover any conceivable future costs.

SNL/NM argues that tritium is the primary concern at the MWL (see p. 8-1, MWL Phase 2 RCRA Facility Investigation, 1966) and correctly infers that most of the potential problem with tritium mostly goes away in 5 half lives of the radionuclide. This assumption presumes that there are no future surprises with other MWL contaminants. Current monitoring data offered by SNL/NM and NMED suggest that over the intervening period following construction of the landfill in 1959, that migration of contaminants other than tritium has been rather minor.

E. Review Of SNL/NM Proposed ET Caps And Recommendations

E 1. General Comments- My review of the reports from SNL/NM proposing the two candidate ET cover designs for MWL closure was conducted within the context of the literature review presented above. One of the SNL/NM ET cap proposals was authored by the SNL/NM Environmental Restoration Project (ER) and the other by Dwyer et al (see Appendix A). Both reports described construction-engineering methods in enough detail to convince me that the cover would be built as specified.

The selection of the ET cap was based upon a risk assessment conducted by SNL/NM in the Phase 2 RFI, which showed that migration of waste contaminants by surface and subsurface processes was not predicted to significantly impact receptors. Ancillary geologic and pedologic analyses were used to demonstrate the lack of percolation of precipitation to ground water over the last several thousand years.

In general, both groups did a credible job of analyzing the ET cover. In general, both proposals appeared to follow EPA guidance and conformed to the general guidance requirements. It is also clear that EPA regulations permit the use of this alternative closure method under HSWA and DOE Orders given that the risks can be shown to be acceptable. Key to their analysis was the use of several models to evaluate design variables.

E 2. SNL/NM ET Cap Designs The ET cap designs proposed in both reports are very similar in terms of layering. Construction involves the placement and compaction of a subgrade to level the site, an earthen layer for moisture storage and root development, and final topsoil later for vegetation establishment and moisture storage. Both propose similar surface slopes of about 3-5% and reseeding the cover with native grasses. The results of their respective modeling efforts show that moisture penetration through the proposed ET covers will be very low.

I conducted a HELP 3 analysis of an ET cover for SNL/NM several years ago to assist in the design of the Advanced Landfill Cover Demonstration (ALCD; Hakonson, 1993). The simulations were done using the average, 2x average, and 3x average annual precipitation for Albuquerque, NM and several soil types and soil depths for the cover. I concluded the following:

"Both soil depth and soil type have an effect on percolation of water through a vegetated soil profile. However, based on an average annual precipitation of 8.12 inches for Albuquerque, NM, the maximum amount of percolation predicted from the thinnest layer and most conductive of the 3 soils examined (i.e. 24 inches of soil #22 with a Ks of $1.9x10^{-5}$) averaged only 0.007 in/yr or less than 0.1% of the annual precipitation. A similarly small amount of percolation (about 1.5% of the precipitation) was predicted for a 24-inch layer of soil #22 when 2x annual average precipitation was used in the model. As soil depth increased, percolation also decreased under all 3 precipitation regimes. For average precipitation rates, from 1-2 feet of soil appears to be adequate to keep average annual percolation rates to less than 0.01 inches.

Under the normal precipitation pattern of 8.12"/yr, the relationship between percolation and soil type was not clearly evident. For example, there did not appear to be any benefit to using the less conductive soil type 24 over the more conductive types 22 and 23, when 38-48 inches of soil were used. (Authors note: when the cover was 38-48" thick, ET was able to remove all of the precipitation regardless of soil type). In contrast, at 2X and 3X annual precipitation, percolation was positively related to the hydraulic conductivity of the soil at all soil depths.

Given that the native soil at the ALCD has shown textural and hydrologic properties similar to HELP3 soil type 23 (personal communication with Steve Dwyer), it is recommended that these native soils be used, unamended, in constructing the ET cap.

Furthermore, since half of the ET cap, when installed at the ALCD, will receive supplemental irrigation (to establish vegetation) to augment natural precipitation, it is recommended that about 36 inches of the native soil be used to construct the ET cap. Based on the analysis presented above, this depth is more than adequate for the normal amount of precipitation received in Albuquerque, NM, and should be sufficient to limit the annual average percolation to less than 0.01 inches, assuming that supplemental irrigation brings the total applied to the cover plot to twice normal amounts."

The basic difference between the two SNL/NM ET cap designs is that the Dwyer et. al. design recommends 4' (120 cm) of cover thickness while the ER design recommends 3' (90 cm). This difference appears to be due to differences the two groups made in the initial assumption about saturated hydraulic conductivity (Ks) of the cover soil. The ER group used Ks of about 2 x 10^{-5} cm sec^{-1} while the Dwyer group used about 2 x 10^{-4} cm sec^{-1}

This difference in initial Ks of an order of magnitude would account for the differences in soil thickness needed to store precipitation that infiltrated into the cap. If anything can be said to favor of one design versus the other, it is that more cover thickness is better than less in terms of controlling percolation of water and preventing biointrusion through the cover. Both groups could probably take some credit for the subgrade level, which will add some unspecified thickness of clean soil to the total cover thickness.

Both groups made assumptions that the plant root distribution will be confined to the cover soil when conducting the water balance modeling. I would caution that the depth of available soil moisture, not the thickness of the cover profile, would govern the distribution of plant roots in the ET cap. The distribution of plant roots may or may not be confined to the thickness of the cover depending on the relationship between water flux and soil depth. The most vulnerable period for potential percolation of water through the cover will be when moisture inputs are relatively high and ET is relatively low. At the MWL, this will be from late winter through early spring.

The Dwyer et. al. design includes a biointrusion barrier, which is lacking in the ER design. Dwyer et. al. states that the barrier is intended to prevent small mammals from burrowing to the waste. Whether animals will burrow down to the waste is problematic given that no information exists on species that occupy the site.

All of the reports given to me for review (Appendix A) are silent regarding biological sampling of the MWL including the RCRA RFI Phase 2 report. I take this to mean that no sampling of biota has been done at the MWL.

It seems certain to me that tritium must be measurable in both plant and animals from the site. In the case of vegetation, concentrations of tritium in vegetation will reflect the concentrations in pore gas or soil moisture in contact with the roots. This means that tritium levels in vegetation whose roots have penetrated into the waste could be relatively high compared to tritium levels in surface air or soil pore gas near the ground surface.

It is also certain that the wire intrusion barrier proposed by Dwyer et al will not impede insect tunneling to the waste if such were to occur. Both ants and termites are present in the area and develop tunnel systems that can extend several meters into the soil (see Table 4 and Fig. 2). Whether this becomes an important transport pathway or not is irrelevant given the intent of using the barrier was to prevent animal intrusion.

If a biointrusion barrier is to be installed into the ET cover, I favor the wire mesh design proposed by Dwyer over the rock intrusion barriers that have been studied in the past (Hakonson, 1986c, Cline et. al., 1976). While rock intrusion barriers have been demonstrated to prevent plant root and burrowing animal intrusion through landfill covers, no one knows how long they will work in preventing biointrusion. The problem is that the void spaces between the rocks in the barrier may eventually fill with soil. Rock barriers work over the short term for the following reasons:

- they provide a capillary break that inhibits downward percolating water flow,
- they confine roots to the soil above the rock barrier, and
- they prevent animal burrowing because of the large size of the rocks.

Both SNL/NM ET proposals state that the design cover depth will be greater than the expected rooting depth of the vegetation cover. By chance, this statement may be correct but, if so, it is not correct because the plants don't have the potential to send roots downward through the cover. If the statement is correct, it is because the soil moisture will be captured by evapotranspiration before it reaches the bottom of the cover, not because plant roots can't penetrate to those depths. Plant root distribution in the soil profile is controlled by moisture distribution. If moisture percolates through the ET cover as designed, roots will also penetrate the cover.

Relative to the MWL, the SNL/ER version of the ET cap conducted an evaluation of erosion using a modified version of the USLE (MUSLE) for hydrologic erosion and a wind erosion counterpart, the Wind Erosion Equation (WEQ). Results suggested that erosion by both mechanisms was below the EPA guidance of 2 t/ac/yr (EPA, 1989). The ER proposal correctly notes that many factors can affect erosion rates over the long term so that the estimated long term average erosion rate may will not reflect year to year erosion rates. The Dwyer et al analysis of the ET cap assumed that the subsurface pathway was the only one of importance and did not conduct an erosion analysis. However, both SNL/NM versions of the ET cap include erosion control measures under the assumption that erosion needs to be controlled over the long term.

Both groups propose to use a gravel-soil mixture to control erosion. Their recommendation is based on studies in arid and semi-arid sites that have shown that the use of soil-gravel mixes or a thin gravel cover applied to the ground surface, very effectively controls erosion and has a positive effect on plant establishment and production of biomass (Nyhan et. al., 1986; Hakonson et. al., 1990; Lavin et. al., 1981; Berg and Sims, 1984; Waugh, 1994).

Gravel sized stones inhibit runoff, enhance infiltration of precipitation, and at least temporarily increase soil moisture over non-mulched surfaces. While enhanced infiltration might seem to increase the potential for deep percolation, the resulting increase in the biomass of the vegetation cover (and ET) is more than sufficient to prevent an increase in percolation. Therefore, the SNL/NM recommendation to use gravel in the cover to control erosion is technically sound.

As an aside, the natural analog of gravel covers for erosion control on landfill caps was developed from studies at the Nevada Test Site and southern Arizona (Simanton et. al., 1988; Nyhan et. al., 1990; Hakonson, 1990). Much of the ground surface in the Northern Mojave and Chihuahuan deserts are covered by erosion pavement (i. e. desert pavement), a natural layering of stones that has developed over thousands of years in many of the worlds deserts. This natural stone covering has a very profound effect on water balance in these arid ecosystems by decoupling runoff from erosion and by greatly enhancing infiltration and plant available moisture. The enhanced soil moisture results in increased plant biomass (Lane et. al., 1986).

E 3. Post-closure Monitoring Issues- I believe the lack of or poorly described post closure monitoring plan and, more importantly, criteria that will be used to trigger a response action to increased potential for contaminant migration is the Achilles heel in the proposed ET cap closure. Furthermore, the lack of serious thought and development of this plan detracts from the credibility of the proposed ET cover closure. If such planning has been done, then it needs to be included in the ET cap closure plan.

It is a stretch to assume that the cover will perform flawlessly and that there is no need for an effort to confirm that the assumptions of the risk assessment were valid and that some dismissed pathways such as the surface pathways at the MWL continues to be unimportant. This aspect of the MWL closure is especially important since it is intended to lead the way for DOE landfill closures using alternative caps.

Monitoring systems (e. g., air, soil, biota, soil moisture) should be placed in the near field environment so that corrective actions can be taken before a potential waste isolation problem becomes impractical to remedy. SNL/NM states that the ET cover system must function for at least a few decades at which time (as yet unspecified) further consideration will be given to other closure options. Until such time, the monitoring systems are the only link between what was promised of the ET cap and what will actually be delivered.

The post closure monitoring system should provide measurements on all possible migration pathways to justify some of the assumptions used in the risk modeling, including assumptions about those pathways that were omitted from the risk assessment. While several pathways may eventually prove to be unimportant from a risk perspective, I believe that the potential for plant and animal intrusion into the MWL should be carefully examined because of the negative consequences relative to transport of waste to the ground surface.

I am also concerned about the lack of a well-defined plan of action should the cap not perform as predicted. This means that there are no decision criteria or action plans for mitigating the various failure modes should one or more occur. The ET cap reports do not discuss these issues and in my opinion, they are vital to the credibility of the proposed closure.

Monitoring systems for the ground surface of the MWL might include soil sampling, radiation surveys, and collection of vegetation and animals. While an animal or vegetation pathway to key receptors was not part of the risk assessment, it would seem prudent to include them in any post closure monitoring plan given that tritium from the MWL has undoubtedly appeared in biota. Actual radiation doses to free ranging animals could also be measured periodically using small dosimeters implanted or attached to individual animals as mentioned previously.

I also mentioned a honey bee- honey pathway for tritium and would add that honeybees can forage miles from their hives in search of nectar, pollen, and water (Hakonson et. al., 1984). House pets also often "hunt" large distances from their home residence and birds of various kinds and food habits undoubtedly spend some time on the landfill. It would seem prudent to have post closure monitoring data for the MWL that establishes whether or not contaminants are present in soils and biota.

Air sampling is a more difficult problem in that it is very difficult to determine the source of collected materials (i.e., dust, chemicals) when the source area of interest is small, such as the MWL, and is surrounded by other potential sources (i.e., a fetch problem). I do not know enough of the details concerning chemical or radiological source areas at SNL/NM other than the MWL, but seriously doubt that the MWL is the only source of some of these contaminants at SNL/NM. Regardless, those details need to be resolved before implementing any kind of post closure air monitoring program for the MWL that could provide ambiguous data with little worth for monitoring the MWL.

SNL/NM must have an operational air monitoring program and an extensive historical database that should be looked at before committing to a localized air monitoring program at the MWL. If an air sampling program for the MWL seems prudent, then I believe it should be installed on top of the landfill and close to the ground surface to reduce some of the fetch problems and unidentified upwind contributing sources.

A post-closure monitoring plan for the ground water pathway is offered by the ER group for the MWL ET cap closure while Dwyer et. al. lists EPA requirements for post closure monitoring and assumes that an appropriate monitoring program would be developed from those requirements. Both imply or describe a monitoring plan based upon the groundwater pathway. EPA requirements for post-closure monitoring as listed in the Dwyer et. al. report on p.14 would seem to indicate that this focus is all that might be required after closure of the MWL given the outcome of the risk assessment.

Without looking at surveillance data on the biological components of the MWL, I would be very uneasy assuming that the ground water pathway is the only one of concern. If monitoring data suggest that biointrusion and the effects on physical and chemical factors are not an important pathway, then a monitoring program involving biota and soil is still called for, even if at a low level. Future questions about the MWL as a source of surface contamination will be unanswerable without monitoring data.

The ER ET cap proposal describes a methodology for detecting water in the cover and in soils to 145' beneath the cover. Their methodology uses the neutron moisture gage (NMG) and fiber optic technology to indicate percolation of water into and through the ET cover and in the vadose zone beneath the landfill. The method description does not describe how the monitoring data would be used to conclude that percolation was or was not occurring. In my opinion, the lack of a description of how the data will be interpreted and used illustrates major deficiencies of the NMG approach, in that the data are very difficult to interpret relative to moisture flux.

I am unfamiliar with the fiber optic technology but have many years of experience with the NMG. The NMG is very reliable (i. e., it works under field conditions) but it is labor intensive in that an operator is required to make the measurements and to download and manage the data. Some sort of long-term administrative and financial commitment to these measurements must be convincingly put forth by SNL/NM.

The NMG must also be calibrated to the soil in which it is being used to measure soil moisture. That can be difficult when layered soils are involved (i.e. sub-grade soil, earthen material, topsoil) and when variation in texture, compaction, and rock content exist. Reliable measurements with the NMG are also limited to volumetric water contents above 5%.

A further problem with the NMG is that it provides instantaneous estimates of soil moisture so that time of measurement following input of precipitation is critical. Measurements must be keyed to the drainage cycle in order to "catch" any possible percolation event at critical measurement locations in the soil profile. This means that it is possible to make a measurement with the NMG that shows no increase in moisture from a previous measurement. However, the water front from a percolation event could have already passed the measuring point in the time interval between measurements. The point is this; this instrument does not measure moisture flux.

Another problem with the NMG is that it integrates moisture content over a relatively large interrogation area that changes as soil moisture changes. Thus it is difficult to know just what depth zone is being interrogated during any one measurement. The interrogation area can be 10's of centimeters surrounding the probe or it can be a couple of centimeters. The interrogation area is large in dry soils and progressively smaller as soils wet.

Despite all these concerns, the NMG is probably ok for use under the landfill (i. e., to depths of 145'). However, it will not be very useful as an early warning system in the cover. Additionally, an established protocol should be developed to interpret what NMG measurements at 145' mean, what constitutes and unacceptable reading or series of readings, and the response actions that might be taken to remedy perceived problems.

As an alternative to the NMG, I recommend consideration of a few judiciously placed pan lysimeters placed beneath the cover to get an absolute measurement of water flux through the cover and into the waste environment. A pan lysimeter consists of a collecting pan and a drain or monitoring port for measuring and emptying accumulated water. I think Warren Air Force Base, Cheyenne, Wyoming used pan lysimeters on the Landfill 2 closure to directly measure percolation of moisture into the waste as required by the Wyoming Environment Department.

E 4. Summary Remarks- In general, I do not have a conceptual problem with the intended ET cap closure from a technical perspective. It was developed based upon a risk assessment using data that were collected specifically for that purpose. Furthermore, the risk assessment and closure plan apparently withstood scrutiny by the state NMED until just recently when NMED called for a Corrective Measures Study. I recognize that the risk assessment and proposal to use and ET cap may or may not withstand further analysis and evaluation.

Finally, the effectiveness of this closure is supposed to be evaluated at some point in the future by SNL/NM to decide if the status quo is ok into the distant future or whether some other closure action is required. If the ET cap continues to be the method of choice for closure of the MWL and supported by the revised risk assessment, then the key to the success of closure will be vigilance and commitment by the landfill owners and regulators over the post closure period. This commitment should be reflected by a well-defined plan of action for any contingency that might develop including criteria used for judging the effectiveness of the cover closure at some point in the future.

Given that, there are some basic assumptions regarding biological components of the MWL that were dismissed without a proper evaluation as to potential for contributing to risk. At a bare minimum, monitoring data for plants and animals prior to the closure must document the presence or absence of MWL contaminants.

Furthermore, some level of monitoring of the surface soil and biological components should continue into the post-closure monitoring period to confirm assumptions made by SNL/NM that these pathways are unimportant. If indeed, SNL/NM is to evaluate the MWL at some point in the future, the lack of any monitoring data on surface pathways will not provide any basis for judging whether circumstances have changed in a negative way in the intervening years.

My major concern with this closure plan is the near lack of consideration for the post closure monitoring period. Additionally, there is no discussion about decision criteria that would be used to trigger a response to correct problems at the MWL. The lack of consideration for the post-closure period including response action leads to a credibility gap in that it is a generally held consensus by the scientific community that some problems with the containment of waste in the landfill will occur over the time frames involved (see National Research Council, 2000). This places a special burden on the owner of the MWL to identify and resolve problems in real time.

I recognize that the costs of any additional sampling before and after MWL site closure and including possible future corrective actions will fall directly on the taxpayers of this country, not DOE or SNL/NM. Setting aside funding for some unspecified corrective action with a low probability of occurring would not seem to be the best use of financial resources for protecting public health given that the taxpayer will be expected to shoulder the financial burden of any needed fix for the site. In my opinion, I believe secure funding would be better spent on the post-closure monitoring phase for the MWL because a well designed monitoring program with assured continuity will provide early identification of potential problems with the MWL containment system. I believe that early identification of problems with the closure will greatly reduce potential costs of corrective actions required to fix unspecified future problems.

I would like to digress for a moment of reminiscing. Back in the late 1980's, when what is now DOE's Environmental Restoration Program began, my environmental science colleagues at Los Alamos and I observed the influx of huge amounts of money for the "cleanup" of the Laboratory. As a year or two went by and progress remained absent, it became apparent that this new Environmental Restoration Program was a black hole for taxpayer money.

My research colleagues and I soon came to the conclusion that digging the waste up at the various sites under scrutiny for "cleanup" would be less expensive than the approach being used and the progress being made. Unfortunately, we didn't account for the entrepreneurship of the consulting companies that were given contracts to participate in this cleanup program. What used to be a few \$10's/ yd^3 for disposal of low level waste has now become several \$10,000/yd^3 because records of decision have come down that many of the old low level waste sites are now mixed waste sites.

At current costs, it should be obvious that we cannot dig up all of DOE's waste in this country unless they present a clear and present danger. There are some sites, because of technical, regulatory, and socio-economic reasons that should be removed, but not all of them. The same could be said of the 226,000 sanitary landfills in this country.

Whether the MWL requires removal or not is not for me to judge. Based on the documents I reviewed, I do believe that a well designed cap, a financially secured, quality post-closure monitoring plan, and plan of action in the event of a containment problem/s, will likely work for the MWL, at least until re-evaluation of the site is made at some point in the future. However, it appears to me that SNL/NM has done little or nothing of substance on evaluating the surface pathway, developing a quality post-closure monitoring plan, or establishing decision criteria for possible future actions at the MWL.

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G. APPENDIX A- List of Documents Reviewed For This Report

Large documents/binders

- · Deployment of an Alternative Cover and Final Closure of MWL (Sept. 23, 1999).
- · Deployment of an Alternative Cover and Final Closure of MWL, Attachment A. (Sept. 23, 1999).
- · Request for Supplemental Information - Deployment of an Alternative Cover (June 5. 2000).
- · Mixed Waste Landfill Design Report by Dwyer, Stormont, Anderson (Oct. 1999).
- · Phase I RFI (Sept. 1990).
- · Phase 2 RFI (Sept. 1996).
- · Phase 2 RFI: Responses to NNED (Jan. 28, 1999).
- · DOE: Report to Congress on Long-Term Stewardship (Vol. 1 Summary Report).
- Long-Term Institutional Management of US. Department for Energy Legacy Waste Sites - National Academy of Sciences.
- · GRAM, Inc.: Geologic Study of Near Surface Sediments Vols. I and 2 (Sept. 30, 1998).
- · GRAM, Inc.: Geologic Study of Near Surface Sediments Addendum (Dec. 1998).
- · Containing the Cold War Mess: Restructuring the Environmental Management of the U.S. Nuclear Weapons Complex by Fioravanti and Makhijani (Oct. 1997).
- · Citizen Action comments re: the WERC study by Miles Nelson, M.D. (Aug. 2001). (*References to FOIA documents).

Loose reports/papers

NMED Review of MWL RFI Report: "85 Questions in Letter of Denial" and "What's Next for the MWL?"

Sandia National Laboratories: Summary of Mixed Waste Landfill (Sept. 15, 1999).

Mixed Waste Landfill known inventory.

Sandia Report: Application of Non-Intrusive Geophysical Techniques at MWL (March, 1996).

Sandia Report: Tritium in Surface Soils at MWL (April 1996).

WERC Draft Study, Short and Long-Term Performance by Dr. Eric Nuttall (July 9, 2001).

City of Albuquerque Mixed Waste Landfill Data Analysis/Chloride Levels by Doug Earp (Nov. 29, 2000). (*with newspaper article, "Sandia Ground Water Tests' Meaning Debated.")

Western Regional Climate Center (data summary sheet)
Mesa del Sol/La Semilla information packet.
CD rom: Sandia National Labs SWEIS: April 1999 Vols. 1 and 2 (April 1999).

H. APPENDIX B- RESUME FOR T. E. HAKONSON

Personal

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PO Box 315
Daniel, WY 83115
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Education

B.S., Wildlife Management, Colorado State University, 1964
M.S., Wildlife Management, Colorado State University, 1967
M.S., Radiation Health Physics, Colorado State University, 1969
Ph.D, Radioecology, Colorado State University, 1972

Honors

Xi Sigma Pi
Sigma Xi
Post-Doctoral Fellow at LANL 1972-1973
Nominated as a Laboratory Fellow- 1981
LANL Distinquished Performance Award in 1982
ASCE Best Paper Award in 1986

Professional Societies and Committee Assignments

- Society for Environmental Chemistry and Toxicology
- Health Physics Society
- Soil Science Society of America
- Technical Advisory Group For DOE Underground Storage Tank Integrated Demonstration - Barriers Sub-Program
- Technical Advisory Group For DOE Mixed Waste Landfill Integrated Demonstration - Containment Sub-Program
- Technical Advisory Group For The In-Situ Remediation Integrated Program-Containment Sub-Program
- Rocky Flats Local Impacts Initiative

CAREER PROFILE

T.E. Hakonson was a staff member in the Environmental Science Group at Los Alamos National Laboratory from 1972-1993. He conducted research on the distribution and transport of radionuclides in liquid waste disposal areas at Los Alamos, in the fallout area of Trinity Site, and in Plutonium Valley at Nevada Test Site. He directed the radioecological work into research on environmental processes with special emphasis on hydrology in arid/semiarid ecosystems. As leader of Environmental Science, he managed multi- disciplinary programs on surface and subsurface hydrology as it relates to contaminant transport, waste disposal, and landfill remediation technology. He received the Laboratory's Distinguished Performance Award for his work on landfill covers in 1982 and was nominated as a Laboratory Fellow in 1981. Hakonson has over 110 publications in the fields of radioecology, hydrology, ecology, and waste management. He currently is a senior research scientist at Colorado State University in the Department of Radiological Health Sciences.

Professional Experience

July 2001 - Present I consult on a variety of environmental issues including waste disposal, radioecology, hydrology, and contaminant transport. Current projects include assignments for the Rocky Flats Citizens Advisory Group and review of the LANL post fire risk assessment for the State of New Mexico

Nov. 1993 – July 2001 I joined the faculty at CSU to develop an academic, training and research program under the University's Center for Ecological Risk Assessment and Management. I currently serve as Director of the ERAM program. I have a joint faculty appointment in Fishery & Wildlife Biology and Earth Resources and have faculty affiliate status in the Radiological Health Sciences Dept. My current research involves field demonstrations of landfill capping alternatives for DOE's Mixed Waste Landfill Integrated Demonstration In Albuquerque, NM and the US Navy's Marine Corp Base at Kaneohe Bay, Oahu, HI.

1990- Nov. 1993 I returned to research in May 1990 after six years as leader of the Environmental Science Group at Los Alamos National Laboratory. Some recent projects include:

- Landfill Cover Demonstration At Hill Air Force Base, Layton, Utah (DOE/OTD and USAF funding).
- Erosion Control Technologies For LANL Firing Sites. (DOE/ER funding)
- Development Of A Knowledge-Based System For Designing And Evaluating Landfills Covers (Cooperative LANL-USDA- ARS research, DOE/OTD funding).
- Landfill Capping Demonstation For US Navy (Demonstration of cover alternatives on sanitary landfill at the Marine Air Corp Station, Kaneohe Bay, HI)
- Post-Closure Monitoring Technologies For Mixed Waste Landfills. (DOE/OTD funding)

- Review Of Containment Technologies For The DOE Environmental Restoration Program. (DOE Rocky Flats funding)

I also spent 6 months at Colorado State University helping a College Of Natural Resources team set up an education and research program in Ecological Risk Assessment And Management. I developed $340k in LANL environmental restoration program support for CSU to develop a prototype ecological risk assessment methodology using one of LANL's operable units as a test bed.

1984-1990

I served as leader of the 20 person ($2-3m/yr) Environmental Science Group. Duties included all those expected of a line manager in a 7700-person multi-disciplinary research organization and a 20-person soft-money research group involved in science. Special skills were required in marketing research programs, identifying and cultivating funding sources, and assembling productive teams to do the work. Even though funding for environmental research was extremely tight during this period, we maintained technical capability and generated about 160 publications on contaminant transport and waste disposal. I was required to be knowledgeable in many technical disciplines including terrestrial and aquatic radioecology, geology, hydrology, biology, and geochemistry with a focus on contaminant transport and waste disposal. I am also conversant with DOE, EPA, and NRC regulations pertaining to radioactive and hazardous waste disposal and have used that knowledge to identify technological needs and successfully secure research funding.

1972-1984

In 1972, I joined Los Alamos National Laboratory as a post-doctoral fellow to begin an environmental science program with a focus on the distribution and transport of radionuclides, particularly plutonium, in treated liquid waste disposal areas at Los Alamos, in the fallout zone resulting from the world's first atomic bomb test at Trinity Site in New Mexico, and in the safety shot areas at Nevada Test Site. One of the more important contributions I made during this period was to identify the dominant role of physical processes (i.e. wind and water erosion of soils and sediments) in the environmental transport of radionuclides, including their movement into biological pathways. This led naturally to my interest in water balance relationships, including runoff and erosion, in disturbed ecosystems.

PUBLICATIONS

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