PNL-7302
UC-610

2F

Strategy for Identifying Natural Analogs of the Long-Term Performance of Low-Level Waste Disposal Sites

J. C. Chatters
W. J. Waugh
M. G. Foley
C. T. Kincaid

July 1990

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

Battelle

PNL-7302

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE MEMORIAL INSTITUTE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831;
prices available from (615) 576-8401. FTS 626-8401.

Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.

NTIS Price Codes, Microfiche A01

Printed Copy

Price Code	Page Range	Price Code	Page Range
A02	1- 10	A15	326-350
A03	11- 50	A16	351-375
A04	51- 75	A17	376-400
A05	76-100	A18	401-425
A06	101-125	A19	426-450
A07	126-150	A20	451-475
A08	151-175	A21	476-500
A09	176-200	A22	501-525
A10	201-225	A23	526-550
A11	226-250	A24	551-575
A12	251-275	A25	576-600
A13	276-300	A99	601-Up
A14	301-325		

PNL-7302
UC-610

STRATEGY FOR IDENTIFYING NATURAL ANALOGS OF THE LONG-TERM PERFORMANCE OF LOW-LEVEL WASTE DISPOSAL SITES

J. C. Chatters
W. J. Waugh
M. G. Foley
C. T. Kincaid

July 1990

Prepared for
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Richland, Washington 99352

EXECUTIVE SUMMARY

The U.S. Department of Energy's (DOE) Low-Level Waste (LLW) Management Program has proposed the study of natural analogs to support assessments of the long-term performance of waste disposal facilities. For LLW applications, natural analog refers to geochemical systems, pedogenic (soil formation) indicators, proxy climate data, and ecological and archaeological settings that portray long-term changes in waste site environments and the survivability of proposed waste containment materials and structures. Analog data consist of estimates of validation parameters that can be predicted by performance assessment (PA) models, and model input parameters that define possible future condition and environmental states of disposal sites. Model validation using natural analogs has been studied for high-level waste management models. Results indicate that natural analog studies could play an important role in predictions of the long-term behavior of LLW disposal sites. That experience has been used to better target potential analogs for LLW facilities and processes.

Pacific Northwest Laboratory convened a workshop March 28 and 29, 1989, which was attended by LLW performance assessment modelers and experts in geochemistry, soil physics, hydrology, geology, ecology, paleoecology, paleoclimatology, and archaeology with knowledge of applications of natural analogs to problems of radioactive waste management. The objectives of the workshop were to identify key issues addressed by federal regulations and PA models, to assess whether analog studies are appropriate for model parameterization and validation relevant to these issues, and to begin designing studies to exploit those analogs for LLW management.

Workshop participants concluded that natural analogs were appropriately used in sensitivity analysis, as a basis for defining controlled experiments, to identify input data and parameters for PA models, and to establish whether processes important to LLW disposal facility performance act as predicted in the long term. Two sets of applicable federal regulations (10 CFR 61 and 40 CFR 193) require performance on different time scales and address different public exposure scenarios (500 years, intrusion and indefinite time, ground water contamination, respectively). Components of the LLW performance system relevant to these performance issues are climate, intrusion into closure caps, water infiltration into closure caps, contaminant release from waste containers and barriers, contaminant transport in ground water, and exposure when ground water reaches the surface. Subissues within each of thes issues were developed and analogs identified.

Analogs considered to be relevant and feasible for study are paleoclimates, ancient man-made and natural mounds, soil development, plant community succession, and ancient concretes.

<u>CONTENTS</u>

1.0 INTRODUCTION

The U. S. Department of Energy's Low-Level Waste (LLW) Management Program has asked Pacific Northwest Laboratory (PNL) to explore the feasibility of using natural analogs of anticipated waste site and conditions to help validate predictions of the performance of LLW disposal sites. Current regulations require LLW facilities to control the spread of hazardous substances into the environment for at least the next 500 years. Natural analog studies can provide information about processes affecting waste containment that cannot be fully explored through laboratory experimentation and modeling because of the extended period of required performance. For LLW applications, natural analogs include geochemical systems, pedogenic (soil formation) indicators, proxy climate data, and ecological and archaeological settings that portray long-term changes in disposal site environments and the survivability of proposed waste containment materials and structures. Analog data consist of estimates of performance assessment (PA) model input parameters that define possible future environmental states of waste sites, validation parameters that can be predicted by PA models, and descriptive information that can build public confidence in waste disposal practices.

Pacific Northwest Laboratory has attempted to apply natural analog studies to various aspects of performance assessment for commercial high-level radioactive waste and uranium mill tailings. This experience has shown that any application of natural analogs should be preceded by careful examination of the purpose of the application and the details of the performance assessment for which the application is made. These considerations are the basis for feasibility analyses that determine the utility of a study and define the general nature of the analog before analog sites are considered and studies initiated. An efficient approach for pursuing studies of this type is a facilitated brainstorming workshop, followed by development of a technical issues hierarchy if the proposed study is considered suitable. Pacific Northwest Laboratory held a workshop March 28 and 29, 1989, which was attended by PA modelers for LLW, experts in soil physics, geochemistry, hydrology, geology, ecology, paleoecology, paleoclimatology, archaeology, and natural analog applications. The objectives of the workshop were to identify key requirements of PA models, assess circumstances under which analog studies are appropriate for model parameterization and validation, and begin designing studies to exploit those analogs for LLW management.

This document describes PNL's overall stategy for identifying analogs for LLW disposal systems, reviews lessons learned from past analogs work, outlines the findings of the workshop, and presents examples of analog studies that workshop participants found to be applicable to LLW performance assessment. The lessons from the high-level waste analogs experience and workshop discussions will be used to develop detailed study plans during FY 1990.

2.0 STRATEGY AND APPROACH FOR IDENTIFYING ANALOGS FOR LOW-LEVEL WASTE DISPOSAL SYSTEMS

Scientists at PNL have had extensive experience with natural analogs in various aspects of performance assessment for commercial high-level radioactive waste (HLW), uranium mill tailings, and other programs requiring predictions of the long-term behavior of engineered structures. This experience is the basis for the strong belief that this proposed application of natural analogs to performance assessments for defense LLW should be preceded by careful evaluation of the purpose of the application and the details of the performance assessment for which the application is to be made (Section 3.0). Such an evaluation should consist of feasibility analyses in which the usefulness of analog studies to the assessment of performance is demonstrated (application defined), and the general characteristics of the analog are described relative to the eventual state or condition of the waste site. Only then should the types of natural analogs and potential analog sites be considered and planning and execution of analog studies be initiated.

A two-part approach was taken to accomplish this end. First, the results of natural analog studies that had been conducted were reviewed to evaluate performance assessment models for the Hanford Protective Barrier Development Program. Through this review analog research approaches were identified that had been unproductive in the past, and isolated research areas that were likely to be most applicable to the LLW effort. Second, a facilitated brainstorming workshop was convened to explore the feasibility of proposed studies, and then a technical issues hierarchy was developed once proposed studies were considered suitable for continued effort.

Development of the technical issues hierarchy is a relatively formal process using either a forward-chaining or backward-chaining approach. A forward-chaining approach has been described that begins with the highest-level performance assessment issues (both regulatory and related to protection of public health and safety) and derived the subsidiary data and analyses needed to support the key issues. Section 4.0 presents proposed analog studies in a forward-chaining issues hierarchy format.

3.0 LESSONS LEARNED FROM HIGH-LEVEL WASTE ANALOG STUDIES

Past analysis of the applicability of natural analogs to high-level nuclear waste disposal centered on natural geochemical systems. These studies attempted to relate the geological evolution of stored waste and surrounding geologic media to interrelated mechanisms or processes that could be assessed reasonably independently (Chapman, McKinley and Smellie 1984, Come 1987, Come and Chapman 1986). Natural analogs were assigned to each of these processes to reveal largely qualitative information. The following key processes were identified (Chapman, McKinley, and Smellie 1984) that were thought to be important to aspects of the high-level waste disposal systems proposed by the Swedish and Swiss governments:

1. thermal chemical breakdown of buffer and seal materials (principally bentonite)
2. waste-package corrosion
3. waste-form dissolution and breakdown
4. solubility and speciation of radionuclides
5. high-temperature mineralogical fixation
6. radiolysis
7. redox equilibration
8. retardation during transport
9. matrix diffusion.

Items 1, 5, and 6 may not be processes of significance to LLW disposal, and may not need to be addressed by further study. The remaining geochemical processes relevant to LLW storage and disposal requiring further study include the following:

2. waste-package corrosion
3. waste-form dissolution and breakdown
4. solubility and speciation of radionuclides
7. redox equilibration
8. retardation during transport
9. matrix diffusion.

Chapman, McKinley, and Smellie (1984) make a number of observations regarding natural analogs that are worth repeating:

- To be useful a natural analog must be tightly constrained to some particular process, with the boundary conditions well defined. Analogs of a complete disposal system do not exist, since even in the case of the nearest approach (fossil reactors) the boundary conditions are significantly different or unknown. ..... In order to provide either validation or benchmarks, the analog must be tied to a particular process, or combination of processes, critical to the overall model.

- The role of a natural analog should be to confirm a) that the process is in fact something which can or will occur in practice as well as in theory, and in nature as well as in the laboratory, b) where, and under what conditions it can occur, c) that the effects of the process are those envisaged in the model, and d) that the magnitude of the effects in terms of physical scale and time are similar to those predicted for a similar set of conditions.

- All of the processes outlined earlier are essentially chemical or physio-chemical in (character), and consequently the analog to seek lies in natural geochemical systems.

This last observation is important because natural analogs have been used almost exclusively to study geochemical processes. Natural analogs of such processes are slow to evolve and, the process are, therefore, not feasible to study in the laboratory.

Some quantitative information has been developed regarding diffusion and colloidal transport processes. However, the studies of large-scale mobility of uranium, such as Alligator Rivers (Chapman 1987), have been only a qualitative success. Quantitative validation must await more analytical information to constrain the models. Inferences drawn from analog studies relative to fast, dynamic, and short-term hydrologic processes remain speculative because analogs represent an integration of numerous events over the long term. Available information is usually insufficient to completely define all aspects of the flow problem throughout the period of study. Thus, for hydrologic models, natural analogs may play a supportive or qualitative role but not a definitive or quantitative role in validation exercises. Except for parallels drawn from the HLW experience, the applicability of geochemical analogs to the study of LLW processes (particularly hydrologic flow and transport models) must be questioned because of the time scale of interest. If the time scale of interest for LLW processes is too short, natural analogs identified for HLW processes may no longer apply.

Questions asked and answered regarding the survivability of materials from the HLW programs are another source of information for the LLW program. Assessments of waste forms and containment structures may use these completed research efforts. Examples include the characterization of cement-based ancient building materials (Roy and Langton 1983) and the characterization of ancient man-made earthen structures (Lindsey et al. 1983). However, because studies of durability of structures and materials involve the study of survivors, they may be biased.

In addition to the qualitative and quantitative information available on the geochemistry of natural analogs, some researchers have emphasized that lessons learned from natural analogs plays an important role in building public confidence (Chapman 1987; Winograd 1986). This is qualitative, but perhaps critical to public acceptance of waste isolation practices.

Although the value of natural analogs for validation of geochemical and hydrologic models has not been demonstrated by HLW studies, and applications of the high-level analogs are doubtful for LLW management (Chapman, McKinley, and Smellie 1984) report an accepted framework in which to develop and document useful natural analogs. First, the evolution of the geohydrologic and physicochemical systems are detailed during placement, release, and migration of the waste. Second, independent, but interrelated, mechanisms and processes are identified. Finally, natural analogs are identified and used to draw inferences concerning individual mechanisms and processes.

4.0 NATURAL ANALOG STUDIES WORKSHOP

A facilitated brainstorming workshop was held March 27 and 28, 1989, for PNL staff with expertise in a range of disciplines relevant to the issues of LLW performance and the application of natural analogs (Table 4.1). A facilitator was used to enhance communications, promote creative technical exchanges among participants, and focus discussions by summarizing, synthesizing, and limiting digressions. The workshop opened with a description of the LLW natural analogs task, then addressed , in turn, the proper role of analogs, federal regulatory requirements for LLW management, performance assessment models currently in use and their data needs, and then extracted the key issues relevant to the performance of LLW disposal facilities. Proposed analog studies were then discussed in the context of these issues (Section 5.0).

Table 4.1. PNL Staff Who Attended LLW Natural Analog Studies Workshop

Name	Expertise
Chatters, J. C.	Archaeology, paleoecology, paleoclimatology
Fayer, M. J.	Hydrology, soil water balance models
Foley, M. G.	Surface processes, application of natural analogs
Hoover, K. A.	Overland flow processes, geomorphology
Jones, T. L.	Soil physics, LLW field lysimeter applications
Napier, B. A.	LLW regulations and performance assessment
Serne, R. J.	Geochemistry, carbonate mineralogy (concretes)
Walters, W. H.	Climate change, overland flow, HLW analogs
Waugh, W. J.	Terrestrial ecology, soils, climatology, HLW analogs

4.1 THE APPROPRIATE USE OF ANALOGS FOR PERFORMANCE ASSESSMENT

Logical analogy, according to Webster's Unabridged Dictionary, is "the inference that certain admitted resemblances (between phenomena) imply probable further similarity." An analog is "that which corresponds to something else in construction function, qualities, etc." and by logical reasoning, is similar to it in its properties.

In the opinion of workshop participants, the appropriate use of this form of reasoning in performance assessment is

- in sensitivity analysis, to understand what components of the natural system are important to facility performance
- as a basis for defining treatments for controlled experiments

- to identify input data and parameters required by PA models
- to establish whether or not processes operate or facilities perform in the long term as predicted by PA models. This application is important for developing public confidence in facility designs and PA model results.

Participants were emphatic that analog studies could not serve as substitutes for controlled experiments. To do so, analogs would have to be identical to waste disposal facilities, and such analogs do not exist that are old enough to be useful for validation of long-term model predictions. Model validation also requires quantification of initial conditions, bounding conditions, and process drivers. In contrast, analog data are often limited to a snapshot of an inferred final condition.

4.2 REGULATORY CONCERNS

The key regulatory issues raised during discussions were the 1) required duration of facility performance, 2) radiation dose limits, and 3) pathway of exposure. Applicable regulations are U.S. Nuclear Regulatory Commission regulation 10 CFR 61 and U.S. Environmental Protection Agency (EPA) regulation 40 CFR 193, with which DOE Order 5820-2A requires DOE sites to comply within 2 to 3 years.

The NRC regulation (10 CFR 61) assumes 100 years of active institutional control, after which waste sites may revert to public uses, such as agriculture or urban development. Performance requirements are concerned primarily with intruder scenarios. Intruders into waste sites cannot receive more than 500 mrem/year within 500 years, after which most radionuclides in LLW sites are expected to have decayed to harmless levels. Contaminant migration is of greatest concern for three relatively mobile, long-lived radionuclides: ^{129}I, ^{99}Tc, and ^{14}C.

The EPA regulation (40 CFR 193) concerns ground-water contamination, the dose from which must be kept below 4 mrem/yr total from all sources. For sites with naturally high levels of radionuclides, or for sites such as Hanford, with a long history of waste disposal, this may mean that releases of contaminants into ground water must be kept near zero. No time limit is placed on this requirement; dose limits must be maintained indefinitely. A figure of 10,000 years is being used by modelers as a working limit.

4.3 PERFORMANCE ASSESSMENT MODELS AND KEY ISSUES

Following the regulations, PA models are required to facilitate design of covers, waste forms, containers, and other components of waste disposal facilities that will accomplish the following:

- prevent intrusion resulting in more than 500 mrem/year dose to the intruder for 500 years
- prevent infiltration of water into the waste medium and/or transport of radionuclides from the source to groundwater for at least 10,000 years.

The principal parameters of intruder scenario models, such as those in the GENII code (Napier et al. 1988), are the elapsed time before first intrusion, the magnitude of the intrusion, the type of intrusion (i.e., how waste material is exposed to the environment), and the number of people exposed. From the point of view of a large population, the worst case scenario would be the large-scale mining and recycling of waste material soon after burial and subsequent habitation of the mined-out area.

Water balance models assess performance of waste disposal sites for preventing water movement through covers into waste media and into the ground water. Five principal issues are relevant to performance: climate, water infiltration through the closure cap into the waste form, release of radionuclides from waste containers, transport into and through ground water, and exposure to humans as ground water reaches the surface by various routes.

5.0 EXAMPLES OF LOW-LEVEL WASTE PERFORMANCE ISSUES AND ANALOG STUDIES PROPOSED TO ADDRESS THEM

Six key issues have been identified for LLW performance assessment: climate, water infiltration, radionuclide release, radionuclide transport in ground water, exposure to the public through groundwater, and exposure to the public through intrusion. The last two issues may be considered under the single heading of exposure. Each of these issues can be addressed through modeling, and workshop participants found that analog studies were potentially applicable to climate, infiltraton, release, and exposure through intrusion. Transport and exposure are best studied through experimentation.

This section discusses, for each key issue, the relevant types of PA models, subissues related to the models, and analogs to address the subissues. A study is outlined for each suggested analog, including practicality, required expertise, and what, if any, ongoing DOE research is generating relevant data.

5.1. CLIMATE

Models of water flow in closure caps, closure cap erosion, and waste container durability all should contain meteorological parameters that are a function of the climate. These parameters are known for the present climate, but not for any future changes in climate. Performance assessment model simulations often assume no major changes in climate (Gilbert et al. 1988). To the contrary, changes in climate during the next few decades and beyond could far exceed climate changes in historical times (Ramanathan 1988). There is mounting evidence that the global climate system has been thrown off balance by a global rise in atmospheric concentrations of carbon dioxide, methane, and other greenhouse gases. According to the greenhouse theory, the climate system will be restored to equilibrium by a warming of the lower atmosphere. Surface warming as large as that predicted by some models is unprecedented during the present interglacial period.

Issue: What impact will the predicted global warming from greenhouse gases have on the local climates surrounding low-level waste disposal sites?

Government agencies such as the DOE, EPA, and the National Science Foundation are funding extensive efforts to model global circulation in an attempt to predict the magnitude and impact of global warming from the buildup of greenhouse gases. However, these general circulation models (GCMs) lack the precision needed to predict the impact of warming on regional and local scales, particularly in mountainous areas where climate is heavily influenced by topography. One thing is certain from global circulation models, however, and that is that the mean annual temperature of western regions will be elevated between 1.5 and 5°C.

Analog: The mid-Holocene Hypsithermal and its impact on regional or local climate, hydrology, and ecology at each proposed disposal site.

More precise information on climate change impacts than that provided by general circulation models can be obtained from the paleoecological and paleoclimatic records of analogous periods of climatic change. During the mid-Holocene (an interval from approximately 9000 to 5000 years B. P.), global temperatures were between to 1 and 2° C warmer than at present (Kutzbach 1987). Evidence of the regional (and often local) ecological, hydrological, and climatic conditions that characterized portions of that period is available from fossil tree lines, fluvial sediments, lake basin deposits, eolian landforms, and archaeological sites on or near DOE facilities. These sources can provide proxy evidence for a wide variety of climatic variables, such as dominant patterns of atmospheric circulation (Nielson 1986), seasonal variation in temperature and precipitation (Fritts 1976), runoff characteristics of trunk streams (Kochel and Baker 1982), and distribution and content of plant and animal communities (articles in Ruddiman and Wright 1987) that can be expected to occur under conditions warmer than those of today. This information can be used, in conjunction with results obtained from archaeological analog studies and concrete analog studies, to develop waste disposal strategies that will be most suitable for the conditions expected at each proposed waste site.

Practicality: Information pertaining to the mid-Holocene has already been collected from the vicinity of most of the proposed LLW disposal sites. This information exists in the paleoecological, paleoclimatic, archaeological, and geological literature, and new information is printed monthly. Regional summaries exist that address categories of data (vegetation, animal communities, hydrology; e.g., articles in Ruddiman and Wright 1987), but for most regions, supporting data sets have not been incorporated into multi-dimensional reconstructions of environmental conditions. This sort of synthesis could be accomplished with the cooperation of university specialists in the various related paleosciences, and any information gaps could be identified and addressed through collection of new data.

Expertise required: Paleobotany, climatology, geomorphology, archaeology, paleontology, and paleohydrology.

Relevant DOE Research: In FY 1989, DOE is funding the Hanford Protective Barrier Development Program (Wing 1989) to develop plans and summarize existing data on paleoclimates and projected future climates of the Hanford Site.

5.2 WATER MOVEMENT IN CLOSURE CAPS

A variety of cap designs have been proposed to stabilize and close LLW sites. The designs range in sophistication from simple soil caps for shallow-land burial sites to multi-layered caps placed over buried concrete vaults (DOE 1988). Components of standard layered designs may include topsoil layers for enhanced water storage, low-permeability clay layers, and sand and gravel drainage layers. To quantify the influence of closure cap designs on assessments of the overall performance of low-level waste disposal facilities, computer models will be used to predict water balance and movement within the cap (Nyhan and Barnes 1988; Fayer et al. 1986; Schroeder et al. 1984). Input requirements for soil water flow models can include soil hydraulic properties, plant transpiration parameters, system boundary conditions that drive infiltration and drainage, and simulation time steps (Fayer et al. 1986). The output parameter of greatest interest is drainage (water movement out of the cover and into the waste zone). Other output parameters may include water content distribution throughout the cover profile, evaporation, and plant transpiration, all three of which are directly coupled to drainage.

As with other types of performance assessment models, water flow models are only as good as our confidence in their predictive power. The model must be validated to measure uncertainty in its predictions. Model validation is done by comparing one or more model outputs with data from the system being simulated. The model should acceptably simulate all output parameters to be valid.

Lysimeter data are often used to validate water flow models for short-term predictions. In lysimeters, model input requirements such as soil hydraulic properties and system boundary conditions, and output parameters such as soil water content and drainage, can be measured with a relatively high level of precision. The greatest uncertainty in such a validation exercise is how closely the lysimeter mimics the water balance of the actual waste disposal environment. Validation of water flow models for long-term predictions is even more complex. Analogs can provide both qualitative and quantitative information to increase confidence in long-term predictions. At least four long-term issues will require analog information: 1) climate change (discussed in Section 5.1); 2) the long-term stability and erosion of closure caps; 3) changes in hydraulic properties, sorption properties, and dimensions of soil and gravel layers as a result of soil development processes; and 4) the effects of changes in the vegetation on evapotranspiration and water flow.

5.2.1 Closure Cap Stability

Issue: Will the preferred closure cap design resist erosion sufficiently to prevent water flow into and through the waste medium for the required 10,000 years?

The preferred design for new LLW disposal facilities includes a mounded, layered closure cap consisting of gravel and sand around and immediately above the waste to promote drainage, low permeability silt or clay cap, and a layer of topsoil. The closure cap surface is an above-grade mound. Effectiveness of the closure cap design for preventing the movement of water into and through the waste medium will depend in part on the long-term stability of the mounded cover. If the topsoil mound is removed, by erosion, clays will be subject to wet-dry cycles, causing the formation of cracks that will readily admit water to the waste medium.

Analog 1: The survival of ancient man-made earthen mounds having a range of design characteristics in various environmental settings.

Man-made mounds as old as 2500 years are found near facilities in the eastern and southwestern United States. Similar, often much older features exist throughout the world in environmental settings resembling those that now, or in the future, may surround waste disposal sites. Design characteristics of these mounds vary, along with the conditions that have existed over many centuries (Lindsey et al. 1983). Some of these man-made deposits often resemble proposed LLW disposal structures closely enough that careful study of their design, soil physical properties, and erosion can be used in the development of performance assessment models.

Studies will focus on deposits less than 3000 years old, and will address the impact of geological and ecological processes, and design characteristics on the structural integrity and erosivity of man-made mounds.

Practicality: This research has already been initiated in support of design studies for uranium mine tailings impoundment (Lindsey et al. 1983). That study included an extensive literature review and a mini-symposium of experts at the Peabody Museum, Yale University. An in-depth analysis of information collected by that study remains to be undertaken, and results of the preliminary work show that such an analysis is warranted. Mound structures exist in China, Korea, Europe, North Africa, the eastern United States, and Central and South America (the Andes). As the most visible residues of ancient human habitation, mounds attract intensive research attention, and many have been excavated. Information would therefore be available from the literature or could be obtained through collaboration with excavators. Many mounds are temple platforms or burial markers and tend to have been constructed quickly; the artifacts they contain provide accurate means for chronological control (Sharer and Ashmore 1978).

The value of such analogs is limited by the imprecision of dating methods and the unlikelihood that rapidly built, layered series of deposits will be identical with proposed closure caps in their absolute thickness, textural characteristics, and construction history. However, information obtained from analog sites might provide insights into which kinds of surface designs would be most effective for varying disposal site environments

Expertise Required: Geomorphology, surface processes, engineering, and archaeology.

Relevant DOE Research: No research is ongoing. The uranium mill tailings study mentioned above (Lindsey et al. 1983; Walters 1987) was not continued to cover the issues proposed here.

Analog 2: Analysis of an ancient natural mound on the Hanford Site

Earthen mounds made up of sediments of similar texture to fine soils planned for use in constructing closure caps occur naturally on the Hanford Site. Inspection of the mounds by geomorphologists showed some of them to be erosional remnants of late Pleistocene slackwater flood deposits that have stood essentially unchanged for between 10,000 and 13,000 years, except for minor wind erosion/deposition, and soil development. They are flat topped, approximately 1.5 to 2 m high, with side slopes of approximately 15%. These mounds provide the opportunity to investigate the potential impact of very long-term soil development and erosion/deposition on the physical properties relevant to water balance models. They also make it possible to investigate the relationship of actual water runoff, infiltration, and plant rooting depth to values of these variables predicted by engineering and water balance models.

One of the mounds is being characterized, and its hydraulic characteristics will later be measured. The characterization data being recorded are topography, sedimentary and textural characteristics, soil development, and carbonate distribution in the middle of the mound and on each of the sideslopes, with special attention to erosional/depositional effects.

Practicality: Work is already under way.

Expertise Required: Geomorphology, soil science, engineering.

Relevant DOE Research: Hanford Protective Barrier Development Program (Wing 1989).

5.2.2 Soil Development in Closure Caps

Subissue: How would soil-development processes alter the hydraulic properties of LLW site closure caps?

Estimates of potential changes in soil hydraulic properties resulting from soil-formation processes will be needed as model input for adequate long-term predictions of water movement in closure caps. Soil formation processes are a complex sequence of events, including both complicated reactions and relatively simple rearrangements of soil materials, that act either to differentiate a uniform soil mass into distinctive layers (horizonation), or conversely to inhibit soil horizonation by mixing horizons formed previously (haploidization). Soil formation processes that could alter water movement and storage in closure caps include both internal processes, such as the illuviation of fine-textured, soluble, and colloidal material from higher to lower horizons in a profile, and external processes, such as the erosion, deposition, or redistribution of surface sediments.

The long-term performance of layered closure caps depends in part on maintaining discontinuity at interfaces of fine-textured and coarse-textured layers. Over time, the possibility exists for the fine-textured soil and soluble salts such as calcium carbonate to settle or migrate downward, either completely or partially filling the matrices of underlying gravel layers. Theoretically, fine-grained and colloidal material could move downward either 1) during the construction of the cap, or 2) accompanying the percolation of water via eluviation/illuviation processes during soil formation. The movement of fines from the topsoil layers of a cap and accumulation in sand and gravel layers below could compromise the capillary break and reduce the water storage capacity of the barrier. The occurrence of present-day calcium carbonate layers in arid-site soils indicates that calcium carbonate accumulation (caliche) will form in LLW closure caps in arid regions. Questions remain, however, as to how much, when, and where carbonate will accumulate. Uncertainty also exists about the effect of carbonate accumulation on hydraulic properties.

The development of soil structure is another soil-formation process that will influence rates and patterns of water movement and might reduce the effectiveness of the closure cap. Soil structure refers to the aggregation of soil particles, or clusters of particles, which are separated from adjoining aggregates by planes of weakness (Soil Survey Staff 1975). Some of these aggregates, called peds, have thin surface films that act to keep them apart. Other peds are held together wholly by internal forces. Soil structure greatly influences water movement and plant growth. Soils with weak spheroidal peds are often more permeable and have a greater water storage capacity than soils with massive or blocky structure. In contrast, some soils with very well-developed spheroidal peds have a low water storage capacity, drain rapidly, and are relatively unproductive, much like a coarse, gravely soil. In these soils, water moves rapidily along the planes of weakness, but does not readily penetrate the peds.

Another soil-forming process that could affect closure cap hydraulic properties, and cap stability, is pedoturbation, a process of mixing that takes place, to some degree, in all soils. The potential for soil mixing deserves particular attention when gravel is applied to the surface of closure caps as an erosion control measure (Waugh 1988). Regardless of how the gravel is initially applied, as a surface mulch or as an admixture, soil mixing processes may alter the surface morphology over time. Some types of pedoturbation act to mix surface layers (Boul et al. 1980) (e.g., mixing by burrowing animals such as ants and rodents, mixing by plant root growth, and mixing by seismic activity). Other processes could cause admixed gravel layers to move toward the surface over time (e.g., the formation of lag layers by winnowing, frost heaving (cryoturbation), movement of gas in soils during and after rain (Evenari et al. 1974), and shrink-swell action of expansive clays (Cooke 1970)). Loess (wind-deposited silts) gradually deposited on a graveled surface can be transported below the gravel in cracks formed in underlying vesicular soil, thus elevating the gravel above the former land surface (McFadden et al. 1987). In addition, burrowing animals and tree roots can penetrate impermeable clay layers, compromising their effectiveness as moisture barriers.

A change in the depth of the cap topsoil, caused by surficial erosion or deposition, could also alter the water balance. Erosion could remove fine soil from the cap and thereby reduce its water storage capacity. Deposition of silt or sand on the cap surface could place the capillary break far enough below the root zone to prevent plant water extraction, and thus result in saturation and drainage of water into the waste zone. Coppice dunes, which are a common microtopographic feature formed by differential erosion and deposition in many arid and semiarid regions, could create spatial variability in closure cap hydraulic properties. Coppice dune morphology consists of many closely spaced mounds, up to 1 m high, that have formed as a result of soil accumulation beneath desert shrubs and soil erosion between shrubs.

Analog: Soil development chronosequences in natural layered deposits.

Naturally occurring, layered sediment profiles of alluvial and eolian origin occur on or in the vicinity of most DOE facilities. Man-made mounds with layered soil profiles as old as 2500 years are found near DOE facilities in the eastern and southwestern United States, and similar structures exist throughout the world in environmental settings resembling environmental conditions that now or in the future may occur at LLW waste disposal sites. These natural and man-made deposits often resemble proposed LLW disposal closure caps closely enough that their careful study can refute or support the predictions of performance assessment models (e.g., Lindsey et al. 1983). The influences of soil-develoment processes (illuviation of fines, calcium carbonate accumulation, the development of soil structure, pedoturbation, erosion, and deposition) on closure cap hydraulic properties could be inferred from the characterization of soil development chronosequences of these analog profiles. A soil development chronosequence would consist of several sites with similar soil parent material, stratigraphy, and climate, that differ in age. Studies would include recently disturbed soils as well as soils that have developed with little or no distrubance for up to 10,000 years.

A study of the origin and hydraulic properties of coppice dunes at Hanford was started in 1989. Coppice dune microrelief occurs at Hanford on Warden silt loam soils that have been selected for excavation for the construction of the topsoil layer of LLW closure caps. Warden silt loam soils developed in Pleistocene slackwater flood sediments deposited between 10,000 and 13,000 years ago. The dunes, which appear to form as a result of sandy soil accumulation beneath two locally common shrubs--big sagebrush (*Artemisia tridentata*) and spiney hopsage (*Grayia spinosa*)--have likely formed, eroded, and reformed repeatedly throughout the Holocene. Following a reconnaissance to determine how extensively distributed coppice dune morphology is at Hanford, dune and interdune soil profiles were characterized to further evaluate their likely origin. It was determined that similar features would likely form on closure caps constructed with Warden silt loam. Hydraulic properties of the coppice dunes will be characterized in 1990.

Practicality: For DOE sites other than Hanford, natural soil analog sites could be found by contacting the U.S. Geological Survey, state geological surveys, and soil scientists, geomorphologists, and archaeologists at universities located near proposed waste sites or in environments analogous to expected local effects of greenhouse warming. Natural soil profiles may be constrained by imprecise dating. Archaeological sites may offer better chronological control. The occurrence of analogs of fine soil illuviation in layered profiles, either in natural soils or at archaeological sites, may be limited by the unlikelihood that layered deposits will be identical to proposed closure caps in their absolute thickness, textural characteristics, and construction sequence. However, analogs of other soil development processes (carbonate accumulation, soil structure, pedoturbation, and erosion/deposition) will likely be present in the soil used for cap construction.

Expertise Required: Soil genesis and morphology, soil physics, soil chemistry, geomorphology, and archaeology.

Relevant DOE Research: As part of the Hanford Protective Barrier Development Program (Wing 1989), PNL contracted with Washington State University in 1989 to study the feasibility of modeling pedogenic carbonate accumulation in Hanford soils as means for assessing the long-term water balance of closure caps. The pedogenic carbonate models would serve two purposes in barrier performance assessment: 1) to reconstruct Holocene water movement from the distribution of carbonates in layered sediments as an analog of future water movement in protective barriers, and 2) to simulate the feedback effect of carbonate accumulation on soil hydraulic properties and unsaturated recharge in proposed protective barrier designs. It was concluded that it would be prudent to abandon the concept that the depth at which carbonates precipitate is the depth below which no unsaturated recharge occurs. The presence of a calcic horizon only indicates that the soil solution became supersaturated with respect to carbonate, not that water flow stopped completely. In 1990, natural analogs will be used to measure hydraulic properties of calcic horizons and to compare them to noncalcic soils to determine the likely influence of carbonate accumulations on water movement in closure caps.

5.2.3 Vegetation Change

Issue: How will long-term changes in the vegetation influence water movement in closure caps?

Parameters of plant transpiration (extraction of water from the soil by plants) are important input requirements for models of water movement in closure caps (Nyhan and Barnes 1988; Fayer 1987). Model simulations have shown that the performance of some closure cap designs in preventing water from infiltrating the waste zone is largely dependent on a combination of evaporation from the soil surface and plant transpiration (Fayer et al. 1985). For long-term performance predictions it will be important to know how changes in the plant community inhabiting a closure cap may influence transpiration.

Plants growing on waste site closure caps will likely change significantly. The plant community may change in response to greenhouse warming (Section 5.1), or to disturbances such as fire or inadvertent cultivation. Changes in climate and disturbances can alter the types and diversity of species, and may be accompanied by changes in the rates of elemental cycling and water extraction. Even under the present climate, and without disturbances, the relative abundance of species, biomass production, and transpiration rates will vary seasonally and from year to year in response to variations in precipitation and temperature. These changes are difficult or impossible to simulate or predict deterministically because of the complex ecological interactions that control plant community development. Competition for limited water and nutrients, allelochemic growth inhibition, symbiotic interactions, parasitism, disease, and herbivory are all important factors.

Analog: Measure influences of plant succession on evapotranspiration in plant community chronosequences.

Perhaps the only unequivocal way to document the influence of plant succession on evapotranspiration would be with repeated measurements following disturbances and as the climate changes. Because we don't have decades to track plant succession, an alternative is needed. Plant community chronosequences offer a reasonable, albeit less certain, alternative. Chronosequences are sites with soils similar to the LLW site closure cap, but differ with respect to the history of disturbance and climate. Possible future climate states or possible future types of disturbances would be defined, plant communities that might be present for these environmental states would be identified, present-day analogs of these states would be located, and evapotranspiration at those analog sites would be measured. The selection of present-day climate-vegetation analog sites would be based on local reconstructions of mid-Holocene vegetation for each disposal site (Section 5.1). Evapotranspiration could be measured at these sites either with monolith lysimeters, whole-plant gas exchange systems, or with micrometeorological instrumentation. The cost and sensitivity and accuracy of each method would have to be weighed in the selection.

Practicality: Plant succession information for DOE sites could be assembled by acquiring literature from the U.S. Forest Service, the Bureau of Land Management, the Soil Conservation Service, and plant ecologists, botanists, and range scientists at universities located near proposed waste sites or in environments analogous to expected local effects of greenhouse warming. At many DOE sites, including Hanford, Los Alamos, Idaho National Engineering Laboratory, Oak Ridge, and Savannah River, succession data should be available from ongoing ecological research programs.

One limitation associated with the chronosequence approach must be recognized. Because agriculture has introduced many non-native plant species, the paleoecology of a waste disposal site may be an inadequate representation of possible future changes in vegetation in some areas of the United States. For example, much of southeastern Washington vegetation is currently dominated by Asian plants such as cheatgrass and Russian thistle, plants that were found only in the eastern hemisphere 150 years ago. These species dominate not only cultivated and overgrazed lands, but are supplanting native species on undisturbed lands (Mack 1986). The dominance of such species appears to alter functional ecological processes such as evapotranspiration, as well as the general appearance of the vegetation.

Expertise Required: Ecophysiology, paleoecology, soil physics.

Relevant DOE Projects: In FY 1990, DOE will fund the Hanford Protective Barrier Development Program (Wing 1989) to begin work on a plant community dynamics task.

5.3 RELEASE OF RADIONUCLIDES FROM WASTE DEPOSITS

For western DOE sites, the keystone of LLW facility performance is water balance. If closure caps fail to keep water from infiltrating into waste media, facilities must prevent release of contaminants to the ground water. The performance of containment media, such as canisters, grouts, and the concrete vaults of many waste facility design is, therefore, critical. Concrete is a commonly used material for waste disposal, both as a container and as a barrier between waste and the surrounding soil. Soils of various kinds are found in sites with and without concrete barriers, and must serve in lieu of the more coherent barrier wall.

5.3.1 Long-Term Performance of Concretes

Issue: A preferred form for low-level waste disposal includes burial in rectangular concrete vaults (DOE 1988). Are concrete boxes an appropriate waste containment medium for long-term (i.e., >1000 years control of contaminant migration? If so, what types of concrete have the most applicability (durability, geochemical containment ability) for waste control at each DOE site?

Current plans call for disposal of low-level radioactive waste into concrete vaults or concrete grout. Vaults and the matrix into which the waste is incorporated must be durable enough to contain waste under extant and changing environmental conditions for hundreds of years. It is possible that the long-term suitability of concrete made by different techniques and containing different mixes of aggregate may vary with environmental conditions. Soil texture, moisture, pH, and seasonal and annual variation in temperature and precipitation are likely to affect various concrete types to different degrees over the long term.

Concretes undergo chemical and physical changes as they age. The calcium hydroxide that initially makes up the matrix is gradually replaced by silicates of calcium and aluminum. The transformation process continues over centuries (Roy and Langton 1983), and is similar to the process of bone fossilization or diagenesis. As diagenesis takes place, porosity, hydraulic conductivity, and pH are also likely to change (e.g., Atkinson et al. 1989; Glasser et al. 1985). The rapidity with which these changes occur under different environmental conditions and the extent to which they affect the ability of radionuclides to migrate across a concrete barrier are currently unknown, but are of critical importance to concrete's ability to retard release of contaminants into the ground-water system.

Analog: Ancient concrete structures and their durability and performance under differing conditions.

Cement and calcareous mortar have been in use for nearly 8000 years (Roy and Langton 1983) in various parts of the world. They were first widely used for engineering works and building construction by the Romans (ca. 300 B. C - 1000 A. D.) and were also used extensively in early China, India, and the native civilizations of Central America (Miao et al. 1981; Zanaczko-Janworski 1958). Many of the concrete facilities and mortared buildings made over the centuries still exist on the surface or underground. Some are still in use.

Early concretes were made by a variety of processes, and concrete experts report that durability is widely variable (Roy and Langton 1983). Durability studies have focused on the Mediterranean, the region where the oldest concretes are to be found (and where freeze-thaw and wet-dry cycles are minimal), but have not addressed the effect on durability of climatic conditions or burial in different sedimentary matrices. Further, they have addressed only the durability of concrete materials, not the survival of structures made from those materials.

Sample structures of various ages, both buried and exposed, in an assortment of environmental settings in Europe, the Far East, MesoAmerica and the eastern United States could be studied for their uptake of soil minerals, porosity, and structural durability. Results of this study would include models of durability for concrete types and structure forms under conditions either typical of or expected to develop at DOE facilities.

Samples of the same concretes, having been characterized by their minerology, pore water pH, and hydraulic conductivity, could be subjected to accelerated diffusion tests using water-containing radionuclides common to LLW disposal sites. The migration of various nuclides across the concretes of different types at varying stages of diagenesis could then be measured.

Practicality: Ancient concrete structures can be found in Europe, North Africa, Asia, and MesoAmerica. More recent structures, (<400 years old) occur throughout the world in settings ranging from mountains to below water level, and in environments ranging from tropical rainforests to deserts. In Europe and the Mediterranean, many ancient sites are documented and have been dated, often to the year of construction. This may also be true of China and Japan. Many structures in MesoAmerica have been dated equally well, but access to information and structures may be more difficult. Dating of more recent structures in the United States can be obtained from cornerstones or written records. Access to structures for scientific purposes would need to be arranged through departments of antiquities of various countries. Because of the minor impact of the study on the structures, and the practical application of the results, this should not be a major stumbling block in countries with strong central governments with which the United States has good relations.

Materials scientists have studied older concretes and have reconstructed early production methods (e.g., Malinowski 1979; Miao et al. 1981; Zanaczko-Janworski 1958). They also have produced a wide body of literature on concrete history and durability (Brown 1987; Roy and Langton 1983). Archaeologists have also become involved in studying concrete, and there are archaeological materials journals (Archaeomaterials, Journal of Archaeological Science) and university departments in the United States (i.e., Massachusetts Institute of Technology) and England that are concerned at least in part with building materials.

Expertise Required: Materials science, geochemistry, archaeology, classical history.

Relevant DOE Research: Studies of the type proposed here are not ongoing. However, a large body of literature has been generated on the short-term durability of concrete and its suitability as a waste medium by a variety of DOE waste management programs.

5.3.2 Contaminant Migration in Waste Site Soils

Issue: What kinds of disposal and containment strategies will be most effective for controlling migration of low-level radioactive waste? Will the same strategy be equally effective at all DOE facilities, or should strategies be tailored to local conditions?

The short-term behavior of elements and many man-made and natural compounds can be and in most cases is understood from laboratory and short-time field experiments. Long-term behavior of the same materials and the impact of changing environmental conditions on that behavior can only be modeled. Without the use of analogs, the validity of such models cannot be established, or at the very least, it is difficult to instill public confidence in the models (Winograd 1986).

Analog: Archaeological sites as natural waste disposal laboratories.

Archaeological sites, including historical industrial sites and dumps, which are common and often well preserved on or near DOE facilities throughout the United States, provide potential analogs to the disposal or long-term storage of waste in near-surface geologic repositories. Depending on the methods used, it is possible to obtain from such old trash or waste deposits a variety of information that can be used in developing waste management strategies (Thomas et al. 1988). Because many inorganic and organic compounds that occur in former dwellings, refuse disposal sites, and industrial sites are analogous or homologous with hazardous or radioactive materials, it is possible use archaeological information to:

- determine element and substance migration rates and distances over time in different burial media and under different environmental conditions
- establish parameters of effective transport and transportation rates of different substances under various conditions
- conduct field verifications of theoretical models of materials diffusion and sorption with long time scales and in a variety of geographic, edaphic, and environmental settings
- determine which soil types (texture, bulk density, pH) or closure cap configurations (textures, permeability and porosity of layers, and sequencing thereof) retard or enhance the migration of materials or the percolation of materials into disposal facilities
- determine the relationship between soil constituents and bioturbation on the effectiveness of burial media.

Information of this kind might be used to solve problems of radioactive and hazardous waste fixation, containment, or disposal, specifically for:

- predicting distances and rates of movement of radionuclides from containment sites to sensitive targets
- estimating the impact of catastrophic events such as floods of marked environmental changes (e.g., the widely predicted increase in temperature from buildup of greenhouse gases) on containment and disposal strategies at DOE sites
- developing waste containment matrices
- maintaining environmental conditions that will minimize migration rates of materials
- establishing siting requirements for containment or disposal facilities
- establishing appropriate containment strategies for different radioactive or hazardous species.

Practicality: On the *pro* side, archaeology, including particularly its historical branch, is especially well suited to the conduct of studies needed to acquire the aforementioned information. Archaeological sites occur throughout the world and range in age from under 50 to over 1 million years, in a variety of soil types, and with diverse environmental and use histories. All these variables can be controlled to some extent. Archaeology already has an extensive body of literature on techniques for measuring time, analyzing soil characteristics, inferring climatic conditions extant at the time of site deposition and environmental changes that have occurred subsequently, analyzing the effects of bioturbation and anthropogenic disturbance on the distribution of buried materials and the diagenesis of refuse constituents (e.g., Sharer and Ashmore 1978). Most materials found in archaeological deposits, particularly those from the Recent epoch (last 10-12,000 years), can still be found in today's environment, so their pre-deposition composition can be determined by laboratory analysis to establish baseline conditions for materials movement.

Archaeologists are active throughout the world, particularly in the United States, where the federal government and many states require their intervention before land development that may affect antiquities. At any time, excavations are ongoing in climates ranging from arctic to subtropical and in edaphic settings from completely dry or frozen to waterlogged. At these excavations, soils, environmental conditions, and ages of the deposits are being determined routinely, and sediment samples are typically taken for a variety of reasons. It would be simple to persuade the directors of a representative sample of excavations to permit the collection of samples for waste management analog studies and even to cooperate in the studies. This is especially true because so many excavation projects are federally funded.

However, this approach is of limited value for radioactive waste management. The key limitation is that the source terms of each analog of a waste species are unknown. Consequently, it would be difficult to establish quantitative measures of material migration. Workshop participants felt it would be inappropriate to pursue analog studies of this kind.

Expertise Required: Geophysics, archaeology, soil science/sedimentary geology, ground water hydrology (specifically the sorption and migration of radionuclides), and soil physics.

Relevant DOE Research: None.

5.4 EXPOSURE BY INTRUSION

Intruder scenarios that have been developed for the GENII dose calculation code include four that are relevant to waste facility design and can be addressed by analog studies (Napier et al. 1988): 1) exploration for resources, 2) discovery of resources (which can include those in the waste deposit), 3) recovery of materials in the waste medium, and 4) recycling of waste materials. Combined, these scenarios address the possibility that people may rediscover usable, locally scarce raw materials beneath waste site closure caps and mine the waste for those materials. If the public is to be prevented from giving itself a dose of more than 500 mrem/year for 500 years, facilities must be designed to minimize the possibility of this kind of exposure.

Issue: How effective are current closure cap designs likely to be for preventing intrusion for resource recovery?

As currently designed, closure caps are readily distinguishable as man-made structures. Therefore, once future residents discover that usable materials, particularly metals, lie beneath their surfaces, and once the knowledge that the contents are dangerous has been lost, these caps are likely to be open to regular intrusion. This would not only result in exposure to the intruders and processors and users of the materials, but would also eliminate the caps as barriers to water infiltration, raising the risk of exposure from contaminated ground water.

Analog: Rates of intrusion into archaeological mounds and other deposits as a function of their distinguishability as man-made.

The study of archaeological mounds can be expanded to include consideration of rates of intrusion and of the time elapsed between construction and first intrusion. Other types of archaeological deposits, such as village sites, could also be investigated to determine the relationship between intrusion rates and the presence of obviously man-made structures.

Practicality: Many types of archaeological sites occur at Hanford, INEL, and on or near other DOE sites in the western U.S. Federal law requires that the DOE maintain an inventory of these sites and establish programs for monitoring the effects of unauthorized collection on them. Therefore records exist now, or will exist in the near future that could be analyzed for the data required by the proposed study. For the discussion of the practicality of conducting a similar study of mounds, see closure cap stability, Section 5.2.1.

Required expertise: Archaeology.

Relevant DOE Research: As a part of the Hanford Protective Barrier Development Program, Westinghouse Hanford Company funded a study of archaeological analogs that was oriented toward developing a system for marking waste sites (Kaplan and Adams 1986). This research focused on markers and the characteristics that promoted long survival of marker objects and marker texts. It did not, however, consider the relationship between the recognizability of a monument as man made and the likelihood of intrusion, as suggested here.

Roy, D. M. and C. A. Langton 1983. Characterization of Cement-Based Ancient Building Materials in Support of Repository Seal Materials Studies. BMI-ONWI-523, prepared by Materials Research Laboratory, the Pennsylvania State University for Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, Ohio.

Ruddiman,W.F., and H. E. Wright, Jr., (eds.) 1987. "North America and Adjacent Oceans During the Last Deglaciation." In The Geology of North America, Volume K-3. Geological Society of America, Boulder, Colorado.

Schroeder, P. R., J. M Morgan, T. M. Walski, and A. C. Gibson. 1984. The Hydrologic Evaluation of Landfill Performance (HELP) Model. Vols. I and II. EPA/530-SW-84-010, U. S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C.

Sharer R. J., and W. Ashmore. 1978. Fundamentals of Archaeology. Benjamin/Cummings Publishing Co. Menlo Park, California.

Soil Survey Staff. 1975. "Soil Taxonomy." Agricultural Handbook No. 46. Soil Conservation Service, United States Department of Agriculture, Washington, D.C.

Thomas, J., L. J. Thibodeau, A. F. Ramenofsky, B. J. Miller, and A. M. Whitmer. 1988. "Archaeological Chemistry." Environ. Sci. and Technol. 22:480-487.

U.S. Department of Energy (DOE). 1988. Proceedings of the Ninth Annual DOE Low-Level Waste Management Forum. CONF-870859, National Low-Level Radioactive Waste Management Program, Idaho Falls, Idaho.

Walters, W. H. 1987. "Construction Methods and Materials of Archaeological Mounds: Implications for Uranium Mill Tailings Impoundments." Nuclear Safety: 28:212-220.

Waugh, W.J. 1988. Field Study of Gravel Admix, Vegetation, and Soil Water Interactions: A 1987 Status Report. PNL-6616, Pacific Northwest Laboratory, Richland, Washington.

Wing, N. R. 1989. Protective Barrier and Warning Marker System Development Plan. WHC-EP-0169, Westinghouse Hanford Company, Richland, Washington.

Winograd, I. J., 1986. Archaeology and Public Perception of a Transscientific Problem-Disposal of Toxic Wastes in the Unsaturated Zone. USGS Circular 990. U.S. Geological Survey, Denver, Colorado.

Zanaczko-Janworski, I. L., 1958. "Experimental Research on Ancient Mortars and Binding Materials." The Quarterly of History of Science and Technology, No. 3:377-407. Warsaw, Poland.

6.0 REFERENCES

Atkinson, A., N. M. Rveritt, and R. M. Guppy. 1989. "Time Dependence of pH in a Cementitious Repository." Material Research Society Symposium Proceedings 27:439-446.

Boul, S. W., F. D. Hole, and R. J. McCracken. 1980. Soil Genesis and Classification. The Iowa State University Press, Ames, Iowa.

Brown, G. E. 1987. "Was Roman Concrete Really that Good?" Concrete Construction 9:792-793.

Chapman, N. A. 1987. "Can Natural Analogs Provide Quantitative Model Validation?" In Proceedings of the 1987 GEOVAL Symposium in Stockholm, pp. 139-149. Swedish Nuclear Power Inspectorate, Stockholm.

Chapman, N. A., McKinley, I. G., and J. A. T. Smellie. 1984. The Potential of Natural Analogs in Assessing Systems for Deep Disposal of High-Level Radioactive Waste. SKB Technical KBS Report 84-16. Stockholm.

Come, B. (ed.) 1987. "Natural Analogs in Radioactive Waste Disposal." In Proceedings From a Symposium Held in Brussels April 28-30, 1987. Reprint of Symposium Proceedings. Vol. 1. CEC Report No. EUR 11037 EN, Brussels.

Come, B., and N. A. Chapman. (eds.). 1986. "Final Meeting Report of CEC Natural Analog Working Group, Second Meeting, Interlaken (CH), June 17-19, 1986." Nuclear Science and Technology.

Cooke, R. U. 1970. "Stone Pavements in Deserts." Association of American Geographers, Annals 60:560-577.

Evenari, J., D. H. Yaalon, and Y. Gutterman. 1974. "Note on Soils with Vesicular Structures in Deserts." Zeitschrift fur Geomorphologie 18:162-172.

Fayer, M. J. 1987. Model Assessment of Protective Barrier Designs: Part II. PNL-6297, Pacific Northwest Laboratory, Richland, Washington.

Fayer, M. J. , W. Conbere, P. R. Heller, and G. W. Gee. 1985. Model Assessment of Protective Barrier Designs. PNL-5604, Pacific Northwest Laboratory, Richland, Washington.

Fayer, M. J., G. W. Gee, and T. L. Jones. 1986. UNSAT-H Version 1.0: Unsaturated Flow Code Documentation and Applications for the Hanford Site. PNL-5899, Pacific Northwest Laboratory, Richland, Washington.

Fritts, H. C. 1976. Tree-Rings and Climate. Academic Press, London.

Gilbert , T. L., S. F. Camasta, and N. K. Meshkov. 1988. "Assessing the Performance of Engineered Barriers and Materials for Confinement of Low-Level Radioactive Waste." In Proceedings of the Ninth Annual DOE Low-Level Waste Management Forum. CONF-870859, National Low-Level Radioactive Waste Management Program, Idaho Falls, Idaho.

Glasser, F.P., M. J. Angus, C. E. McCulloch, D. Macphee, and A. A. Rahman. 1985. "The Chemical Environment in Cements." In Scientific Basis for Nuclear Waste Management VIII, eds, by C.M. Jantzen, J. A. Stone, and R. C. Ewing, pp 849-858. Materials Research Society Symposia Proceedings Vol. 44. Materials Research Society, Pittsburgh, Pennsylvania.

Kaplan, M. F., and M. Adams. 1986. "Using the Past to Protect the Future: Marking Nuclear Waste Disposal Sites." Archaeology 39(5):51-54.

Kochel R.C., and V.R. Baker. 1982. "Paleoflood Hydrology" Science. 215:353-361.

Kutzbach, J. E. 1987. "Model Simulations of the Climatic Patterns during the Deglaciation of North America". In North America and Adjacent Oceans During the Last Deglaciation, eds. W.F. Ruddiman and H. E. Wright, pp. 425-446. The Geology of North America, Volume K-3. Geological Society of America, Boulder, Colorado.

Lindsey, C. G., J. Mishima, S. E. King, and W. H. Walters 1983. Survivability of Ancient Man-Made Earthen Mounds: Implications for Uranium Mill Tailings Impoundments. PNL-4541, prepared for the Division of Health, Siting, and Waste Management, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington, D.C., by Pacific Northwest Laboratory, Richland, Washington.

McFadden, L. D., S. G. Wells, and M. J. Jercinovich. 1987. "Influences of Eolian and Pedogenic Processes on the Origin and Evolution of Desert Pavements." Geology 15:504-508.

Mack, R. N. 1986. "Alien Plant Invasion into the Intermountain West: A Case History." In Ecology of Biological Invasions of North America and Hawaii, eds. H. A. Mooney and J. A. Drake. Ecological Studies, Vol. 58, Springer-Verlag, New York.

Malinowski, R., 1979. "Concrete and Mortars in Ancient Aqueducts." Concrete International, pp.66-76.

Miao, J-S., X-Y Lee, R-K. Cheng, and B-S. Lu 1981. "A Preliminary Investigation of Cementing Materials Used in Ancient China." Research Institute of Building Materials, Wuhan 9:234-240.

Napier, B.A. R. A. Peloquin, D. L. Strenge, and J. V. Ramsdell. 1988. GENII - The Hanford Environmental Radiation Dosimetry Software System, Vols 1 -3. PNL 6584, Pacific Northwest Laboratory, Richland, Washington.

Nielson, R. P. 1986. "High-Resolution Climatic Analysis and Southwest Biogeography." Science 232:27-34.

Nyhan, J. W., and F. J. Barnes. 1988. "Development of an Arid Site Closure Plan." In Proceedings of the Ninth Annual DOE Low-Level Waste Management Forum. CONF-870859, National Low-Level Radioactive Waste Management Program, Idaho Falls, Idaho.

Ramanathan, V. 1988. "The Greenhouse Theory of Climate Change: A Test by an Inadvertent Global Experiment." Science 240:293-299.

DISTRIBUTION

No. of
Copies

OFFSITE

12 DOE Office of Scientific and Technical Information

W. J. Waugh
UNC Geotech
DOE-ID GJPO
P.O. Box 14000
Grand Junction, CO 81502

R. L. Curl
EG&G Idaho
1580 Sawtelle St.
Idaho Falls, ID 83415

K. Grahn
EG&G Idaho
1580 Sawtelle St.
Idaho Falls, ID 83415

ONSITE

9 DOE Richland Operations Office

G. J. Bracken
J. J. Broderick
P. K. Clark
R. D. Freeburg
R. E. Gerton
R. D. Izatt
S. M. Prestwich
G. W. Rosenwald
J. P. Sands

34 Pacific Northwest Laboratory

L. L. Cadwell
J. C. Chatters (10)
L. E. Eberhardt
J. W. Falco
M. J. Fayer
M. G. Foley
G. W. Gee (2)

No. of
Copies

M. S. Hanson
P. C. Hays
J. H. Jarrett
T. L. Jones
C. T. Kincaid
S. O. Link
G. P. O'Connor
L. E. Rogers
J. M. Thomas
W. H. Walters
R. E. Wildung
Publishing Coordination
Technical Report Files (5)