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Geohydrologic Aspects for Siting and Design of Low-Level Radioactive-Waste Disposal

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Geohydrologic Aspects for Siting and Design of Low-Level Radioactive-Waste Disposal

By M.S. BEDINGER

U.S. GEOLOGICAL SURVEY CIRCULAR 1034

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

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By M.S. Bedinger

Abstract

The objective for siting and design of low-level radioactive-waste repository sites is to isolate the waste from the biosphere until the waste no longer poses an unacceptable hazard as a result of radioactive decay. Low-level radioactive waste commonly is isolated at shallow depths with various engineered features to stabilize the waste and to reduce its dissolution and transport by ground water. The unsaturated zone generally is preferred for isolating the waste. Low-level radioactive waste may need to be isolated for 300 to 500 years. Maintenance and monitoring of the repository site are required by Federal regulations for only the first 100 years. Therefore, geohydrology of the repository site needs to provide natural isolation of the waste for the hazardous period following maintenance of the site. Engineering design of the repository needs to be compatible with the natural geohydrologic conditions at the site. Studies at existing commercial and Federal waste-disposal sites provide information on the problems encountered and the basis for establishing siting guidelines for improved isolation of radioactive waste, engineering design of repository structures, and surveillance needs to assess the effectiveness of the repositories and to provide early warning of problems that may require remedial action.

Climate directly affects the hydrology of a site and probably is the most important single factor that affects the suitability of a site for shallow-land burial of low-level radioactive waste. Humid and subhumid regions are not well suited for shallow isolation of low-level radioactive waste in the unsaturated zone; arid regions with zero to small infiltration from precipitation, great depths to the water table, and long flow paths to natural discharge areas are naturally well suited to isolation of the waste. The unsaturated zone is preferred for isolation of low-level radioactive waste. The guiding rationale is to minimize contact of water with the waste and to minimize transport of waste from the repository. The hydrology of a flow system containing a repository is greatly affected by the engineering of the repository site. Prediction of the performance of the repository is a complex problem, hampered by problems of characterizing the natural and manmade features of the flow system and by the limitations of models to predict flow and geochemical processes in the saturated and unsaturated zones. Disposal in low-permeability unfractured clays in the saturated zone may be feasible where the radionuclide transport is controlled by diffusion rather than advection.

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INTRODUCTION

The isolation of low-level radioactive waste is in its formative stage with respect to siting, design, and construction of repositories, handling of the waste, and predictability of site performance. Successful isolation of low-level radioactive waste depends on application of many scientific and engineering disciplines to provide acceptable site selection and repository design and effective repository construction and operation at the site. Examination of the performance of low-level radioactive-waste repository sites indicates that, although many sites are satisfactory with respect to the isolation of the radioactive waste, the coordination among scientific and engineering disciplines has not been accomplished to the point where acceptable siting, design, and operation of a low-level radioactive-waste repository site is a predictable or routine procedure.

The most likely path of radionuclides from a shallow radioactive-waste repository constructed on land to the biosphere is transport by water. However, shallow repositories also are subject to intrusion by humans, plant roots, and burrowing animals, and to exposure by erosion. Migration of radionuclides as gases in the unsaturated zone also is of concern at shallow repositories.

Classification of Low-Level Radioactive Waste

The U.S. Nuclear Regulatory Commission (1982) classifies low-level radioactive waste into three categories on the basis of radionuclide type and radiation emitted. Class A wastes are relatively innocuous, trash-type wastes that contain low activities of radionuclides. Class B wastes are those that have high activities and contain short-lived radionuclides. They require stable waste forms—that is, waste forms that are designed to maintain gross physical properties and identity for about 300 years. Class C wastes are those that contain the highest activities of radionuclides. Class C wastes require not only the stable waste form of class B wastes but also additional measures at the repository site to protect against inadvertent intrusion for about 500 years.

The isolation time required for a radioactive waste is a function of the half-lives of the radionuclides and their decay products present in the waste. A rule of thumb commonly used in the nuclear industry is that radioactive waste should be confined at least 10 times the half-life of the longest lived, dominant radionuclides. The half-lives of the principal components of low-level radioactive waste range from about 3 to 30 years. For waste containing primarily strontium-90 and cesium-137, 300 years of isolation (about 10 half-lives) is required to decrease the radiation to one-thousandth of the initial radiation, and 500 years of isolation is required to decrease the radiation to one-hundred thousandth of its initial activity. Thus, on the basis of half-lives and radiation limits, the waste needs to be isolated from the biosphere for 300 to 500 years. The preparation of longer lived radionuclides, such as carbon-14 and plutonium-239, within the waste should not exceed the limits established by regulatory authorities.

Purpose and Scope

This report reviews the problems and experiences at selected low-level radioactive-waste repository sites, the development of the current technical rationale for the isolation of low-level radioactive waste, and the site suitability requirements of the U.S. Nuclear Regulatory Commission. Additionally, this circular presents the application of hydrologic principles to engineering design of repositories and includes conclusions reached from studies of low-level waste disposal. This report is concerned only with hydrologic and related geologic factors of waste isolation and repository siting. Social, economic, demographic, political, and other nongeohydrologic factors are significant in repository siting, but these factors are beyond the scope of this report.

PERFORMANCE OF SHALLOW LOW-LEVEL REPOSITORIES, SITING GUIDELINES, AND ENGINEERED BARRIERS

Historical Perspective of Low-Level Radioactive-Waste Disposal and Repository Siting

Disposal of waste from radioactive-element refining operations in the early 1900's was commonly at the processing site with little or no regard for the health and environmental risks posed by the waste. An example of early disposal of waste was revealed in 1979 when radioactive waste from pre-1920 radium-refining operations was discovered in the Denver, Colo., area. Beginning with the discovery of radioactive waste at the site of the long defunct National Radium Institute in February 1979 (Strain, 1979a, p. 1), 30 additional radioactive-waste dumps from the pre-1920 refining era were discovered by mid-June 1979. Popular belief prevailing prior to 1920, as revealed in a Denver Post article (Strain, 1979b, p. 42), was that the radioactive element radium was beneficial in the treatment of many health problems, and, concomitantly, there was an apparent total ignorance of the health risks associated with radioactivity. Realization of the health risks associated with radioactivity was slow; recognition of the need for isolation of wastes was even slower.

The earliest repositories for radioactive waste were established by the Federal Government for waste from national defense and research operations. Until 1962, nuclear waste from commercial operations was commonly disposed on federally operated sites. The method of disposal was commonly burial at shallow depths in trenches, as at the Savannah River Plant, S.C., Palos Forest Preserve, Ill., Oak Ridge National Laboratory, Tenn., and Nevada Test Site, Nev. (fig. 1). Apparently, problems of waste migration were not anticipated; little concern during the first disposal operations was given to methods of packaging the waste, to the geologic and hydrologic characteristics of the burial site, and to the backfill and capping materials of the waste trenches.

Recognition that radioactive waste was not being completely contained in many of the early disposal sites and increased awareness of the hazardous nature of radioactive waste brought about concern for the manner in which such waste was disposed. Between 1962 and 1971, six commercially operated land burial sites commenced operation (Maxey Flats, Ky., West Valley, N.Y., Richland, Wash., Beatty, Nev., Sheffield, Ill., and Barnwell, S.C., fig. 1). Siting requirements were not rigorous, but efforts to provide greater confinement of radioactive waste at most of the humid sites involved the excavation of the burial trenches in fine-grained low-permeability formations and also capping the trenches and backfilling of the waste packages with fine-grained material, such as silt and clay. The prevailing rationale was to cover the waste with a material that would inhibit infiltration of water into the trenches and to bury the waste in a medium that would retard transport of the radionuclides from the waste site by ground water.

Problems with the containment of waste in the trenches developed at many of these sites (Fischer, 1986). The capping layers of many of the trenches developed collapse structures resulting from differential compaction of trench materials, caused in part by the deterioration and compaction of the waste packages and backfill material. In addition, desiccation cracks developed in clay-rich caps during extended periods of dry weather. The cracks allowed water to enter the trenches; water accumulated in many of the trenches, thus saturating and promoting the leaching of the waste. Radionuclides were transported from the trenches by ground-water flow and by overflow of water from the trenches at the surface. These problems and other experiences at selected low-level radioactive-waste sites are reviewed in the following sections.

Studies at Selected Low-Level Radioactive-Waste Repository Sites

Hydrologic studies at five of the commercial low-level radioactive-waste sites and one federally operated site are reviewed in this section. The sites include a range of distinctly different geohydrologic settings and climates that range from arid to humid. The review of conditions at the sites provides a background of useful information that should be considered in establishing a rationale for site selection and design and for evaluating the performance of future repository sites.

Oak Ridge National Laboratory, Tennessee

Burial of radioactive waste at Oak Ridge National Laboratory began in 1944 and has continued to the present (1988). The earliest disposal of low-level radioactive waste at Oak Ridge National Laboratory was not given special siting, design, or operational considerations (Mezga, 1984). As problems of waste containment became obvious, more rigorous disposal procedures have been introduced. Oak Ridge National Laboratory, in the Valley and Ridge province (Webster, in press), is underlain by consolidated Paleozoic formations of shale and limestone. Burial sites are excavated in the regolith or zone of weathered material overlying the consolidated rock. Regolith of limestone consists of silt and clay; the limestone regolith ranges in thickness from zero to 7 m. Regolith of the shale consists of silt, clay, pebbles, and rock fragments and has the deformed structure of the bedding still clearly visible. The shale regolith ranges in thickness from about 1 to 12 m. Hydraulic conductivity of the shale regolith ranges from 1.1×10^{-1} to 1.8×10^{-2} m/d; that of the shale from 1.1×10^{-2} to 3.0×10^{-3} m/d (Webster, in press). The first burial sites were developed in Bethel Valley (burial grounds 1, 2, and 3), which is underlain by limestone (fig. 2). Because the movement of

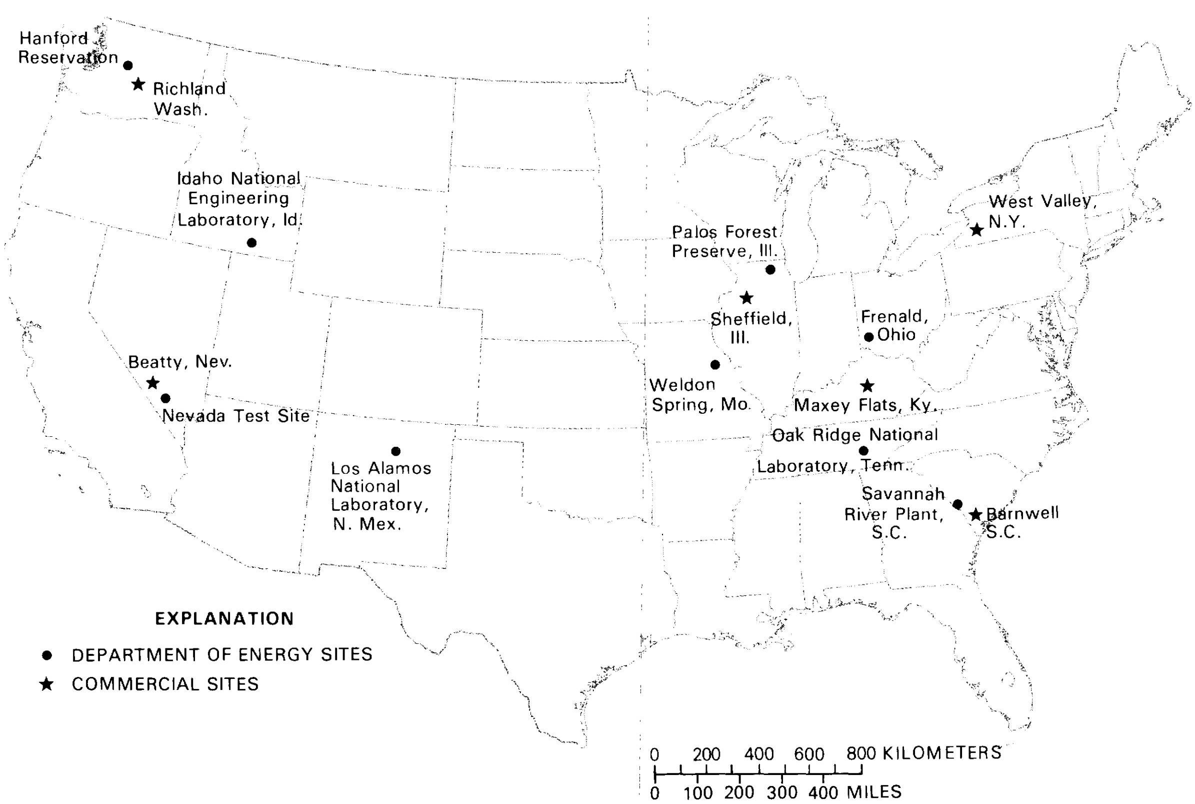


Figure 1. Locations of commercial and major Department of Energy low-level radioactive-waste burial sites in the United States.

water and contaminants was considered unpredictable in the cavernous limestone, subsequent burial sites (4, 5, and 6) were located in Melton Valley, which is underlain by shale. Average annual precipitation at Oak Ridge National Laboratory is about 130 cm/yr (Webster, in press), greater than that at any other low-level radioactive-waste-repository site in the United States.

Early waste-disposal operations at Oak Ridge National Laboratory are described by Webster (1979; in press) as being relatively simple. After clearing an area of

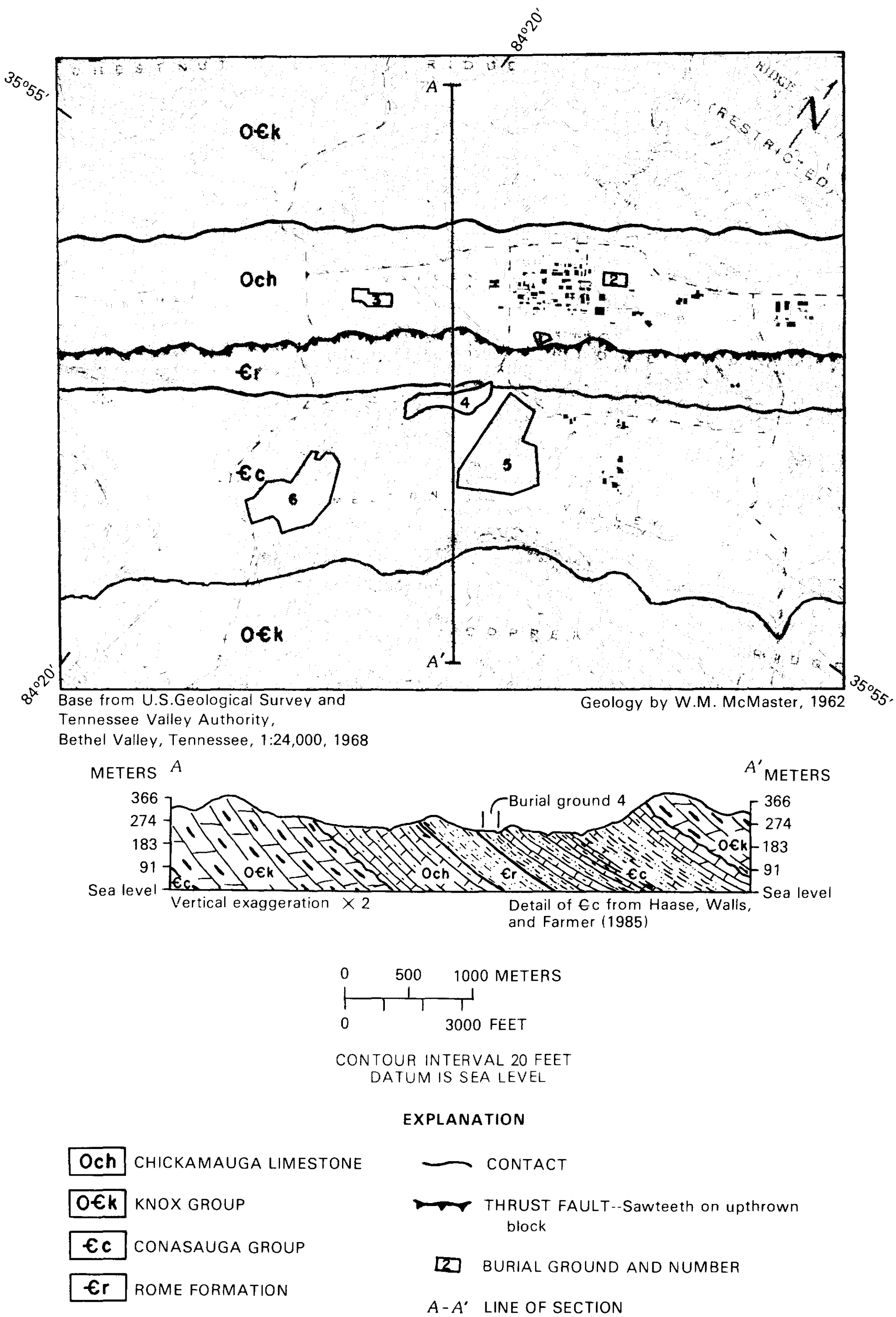


Figure 2. Locations of burial grounds at Oak Ridge National Laboratory, Tenn.

trees, trenches were cut to depths of as great as 4.5 m and to widths of 3 m. Lengths have been variable; the longest trenches exceed 150 m and are oriented down the topographic slope. The common practice was to dump low-level radioactive waste in the open trenches (fig. 3) until the trenches were nearly filled and to fill the remaining space with spoil material from the excavation. As burial areas have been phased out, they have been seeded with grass. Burial ground 3 was closed in 1951 and trees were allowed to reestablish. In addition, radioactive-waste burial equipment was stored above ground within the burial ground. Subsequently, the area was cleared of trees and contaminated equipment, and grass was sown in 1979. Figure 4 shows burial ground 3 in 1987. The trenches have not been mounded nor have monuments been emplaced to mark them, although access to the burial grounds is controlled. In the earlier years of disposal, the presence of water in the trenches was not considered a problem and trenches commonly were constructed within the fluctuating zone of the water table. Waste in some trenches is perennially saturated (Webster, in press).

A photograph of a trench in burial ground 5 that intersects the water table is shown in figure 5. Webster (in press) observed that the depth to water table has risen 1.8 to 2.7 m above predisposal levels in one area because of the greater permeability of the trench-cap material than the natural ground and because of reduced transpiration as a result of removal of deep-rooted trees. Duguid (1979) and Webster (in press) note that water in many trenches, especially the long downslope-oriented trenches, has accumulated at a rate greater than it can flow out to the undisturbed regolith. The trenches have become filled with water at the lower ends and seeps have formed by overflow along the regolith-spoil contact (fig. 6). Stueber and others (1978) determined that the discharge of strontium-90 from burial ground 5 was 0.45 curie (Ci) in 1978 and remained fairly constant from year to year despite variability in annual precipitation. In a subsequent study, Stueber and others (1981) determined that the discharge of strontium-90 from the burial ground 3 area averaged 6.4 μCi per month for a 7-month period, with the monthly discharges from this site being related to precipitation. The principal mode of transport

Figure 3. Trench at burial ground 6 at Oak Ridge National Laboratory, Tenn., partially filled with randomly deposited low-level radioactive waste. Structure of bedrock is retained in wall of trench excavated in regolith of shale. Photograph by David Webster, 1982.

of radionuclides from burial ground 3 appears to be by ground water moving through a solution-cavity system (Stueber and others, 1981). At burial ground 4 transport is both by ground water and trench overflow (Huff and Farrow, 1983), whereas, at burial ground 5 transport is by ground water moving through the weathered regolith (Cerling and Spalding, 1982). Considerable evidence has been collected to show that radioactive contaminants have been transported by ground water in both the regolith and the bedrock to the local streams (Webster, in press).

Maxey Flats, Kentucky

Maxey Flats (fig. 1) is an isolated plateau in northeastern Kentucky. The radioactive-waste burial site, which was operated from 1963 to 1977, is located on the plateau, about 90 to 120 m above the surrounding valleys. The rocks in the Maxey Flats area are almost flat lying and consist of fractured shale and sandstone of Mississippian to Silurian age. The rock units, in descending order, are the lower part of the Nancy Member (shale) and Farmers Member (sandstone), including its basal Henley Bed (shale), of the Borden Formation (Mississippian), the Sunbury, Bedford, and Ohio Shales (Mississippian and Devonian), and the upper shale part of the Crab Orchard Group (Silurian) (fig. 7).

The waste burial trenches at Maxey Flats are excavated in the regolith, the weathered zone, of the Nancy Member. Two sandstone beds of variable thickness, fracturing, and occurrence are encountered within the depth excavated for the burial trenches. The lower bed is at the level of buried waste in the trenches and appears to control the movement of leachate (Lyverse, in press). Most trenches are about 100 m long, 17 m wide, and 7 to 8 m deep. Waste was covered with excavated regolith material as the trench was progressivly filled. A compacted clay and crushed shale cap at least 1 m thick covers the trenches.

Most of the waste was buried in solid form, except for tritium, which was buried typically as tritiated water enclosed in glass containers packed in steel drums (Lyverse, in press). Each trench was designed with sump pipes at a low point of the trench to provide for water-quality monitoring and removal of water that might infiltrate and accumulate in the trenches. In 1977, radionuclides were detected having migrated from a closed disposal trench to an adjacent trench. Subsequent ground-water studies of the site have indicated that contaminated water has migrated from the site through the fractured sandstone (Lyverse, in press). Water containing tritium concentrations as large as 3.5 μCi/mL has been sampled from wells as far as 70 m from the trench area. Wet-weather seeps on hillsides surrounding the trench area have contained tritium concentrations as large as 2,500 pCi/L. Zehner (1983) estimated cobalt-60 and manganese-54 in water in the lower sandstone bed to migrate about 17 m per year.

Clay layers were compacted over the trenches to minimize infiltration. However, infiltration through the

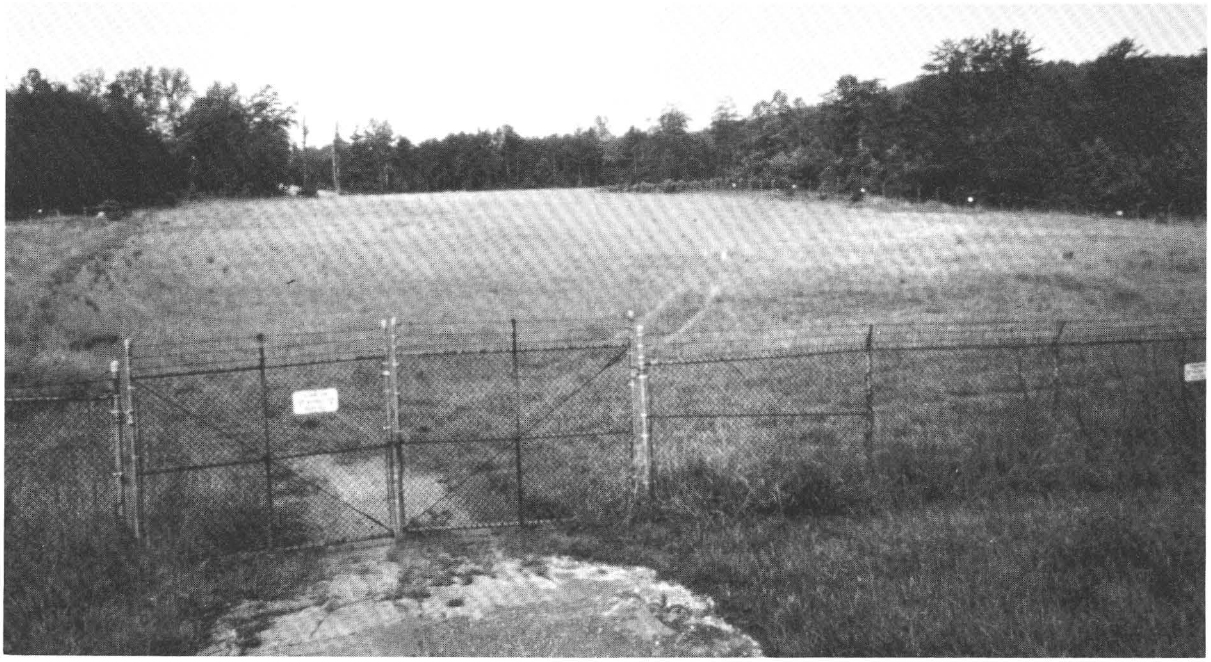


Figure 4. Burial ground 3 at Oak Ridge National Laboratory, Tenn. Photograph by David Webster, 1987.

clay caps has been recognized as a continuing problem at Maxey Flats burial site. Water accumulating in the trenches is pumped out and evaporated. To reduce infiltration into the trenches, 0.38- to 0.51-mm-thick PVC (polyvinylchloride) covers were placed over the trenches. Because of deterioration of PVC by exposure to ultraviolet light, the covers are replaced at intervals of 18 to 30 months. Infiltration after emplacement of the PVC covers was 2 to 7 percent of precipitation, a decrease of from 5 to 37 percent compared to before emplacement of covers (Lyverse, in press). Because the impermeable trench covers increased runoff from the trench areas, erosion has increased downslope from the trenches.

The geohydrologic conditions at Maxey Flats are particularly unsuitable for disposal of radioactive waste. The fractured sandstone and shale provides localized pathways for rapid migration of leachate from the waste. Where the host medium is less permeable, the trenches accumulate water. The effort to provide an impermeable clay cover by compacting natural materials failed; infiltration into the trenches from precipitation, which averages 117 cm/yr (Lyverse, in press), is a significant problem addressed by pumping of the accumulated water from the trenches. The water is then evaporated.

Figure 5. Low-level radioactive-waste burial trench at Oak Ridge National Laboratory, Tenn., intersecting water table. Photograph by David Webster, 1979.

West Valley, New York

The radioactive-waste burial grounds near West Valley are in western New York (fig. 1). The State-licensed burial ground was opened in 1963, and burial ceased in 1975. Twelve of the 14 trenches filled with waste are between 115 and 215 m long, 11 m wide at the top and 8 m wide at the bottom, and about 6 m deep. A gravel-filled sump was constructed at the lower end of some of the trenches and equipped with a riser pipe for pumping out water, if necessary. The trenches were capped with compacted and graded till. Bedrock is a thick, monotonous sequence of shale and minor siltstone. Overlying the bedrock is a relatively thick sequence of fine-grained lake-bottom deposits alternating with clayey tills rich in reworked lacustrine sediment, with few sand or gravel units (fig. 8). The burial trenches are excavated in an upper unit of silty clay till that overlies a unit of silt and clay. The upper 2 to 3 m of till are oxidized and contain a network of abundant intersecting fractures. Till at greater depth is gray, plastic, and unoxidized, but fractures having firm, oxidized borders a few millimeters wide extend downward into the unoxidized till to a depth of about 5 m.

Ground water moves slowly downward through the till to the unit of lacustrine clay and silt (fig. 8), which acts as an underdrain. In the silt and clay unit, flow is lateral toward Buttermilk Creek, which is the local discharge area. Prudic (1986, p. 44) estimates that ground-water travel time from a trench to Buttermilk Creek would be about 800 to 2,800 years.

The average annual precipitation at West Valley is about 100 cm/yr (Randall, in press). The potential for accumulation of water in the trenches was recognized immediately (Kelleher, 1979) and, in fact, did occur. In three trenches completed by 1969, water rose above the top of the undisturbed till and into the cover by 1975, and seepage out to the land surface was observed. From 1975 through 1983, water accumulations in several trenches were removed by periodic pumping, and the water was treated chemically. Efforts to eliminate or lessen the accumulations of water in the trenches included increasing the cover thickness from 1.2 to 2.4 m, imposing a surcharge load to the filled and capped trenches by temporarily piling spoil, and grading land surface to drain water away from the trenches. Infiltration into the trenches was decreased but not eliminated (Randall, in press).

Over the long term, improved cap design and reconstruction could do no more than delay the effects of decay, collapse, and desiccation cracks that provide a means for infiltration into the trenches (Randall, in press). Matuszek (1986) and Matuszek and Robinson (1983) argue that only incineration would yield a product that could be buried without the prospect of collapse. Even with a stable waste form, means for infiltration may be provided by desiccation cracks after a long dry period, as determined by Prudic (1979) following the summer of 1978.

The natural travel time of flow from the trench area to Buttermilk Creek through the ground-water flow system would afford adequate time for low-level radioactive waste to decay to innocuous levels. However, the trench caps admitted infiltration of precipitation into the trenches at rates that exceeded the quantity of flow into the till at the base of the trenches. This caused water levels to rise in several trenches until water seeped to the land surface or was pumped out.

Barnwell, South Carolina

The radioactive-waste disposal facility near Barnwell, S.C., is one of three commercially active sites in the United States (fig. 1). Disposal began in 1971 and is scheduled to continue until 1992. Average annual precipitation at Barnwell is about 117 cm/yr (McMahon and Dennehy, in press). The disposal facility located in the Coastal Plain is underlain by a thick sequence of unconsolidated deposits ranging in age from Cretaceous to Quaternary. The burial trenches are excavated in a sequence of sand intermixed with clay (zone 1 of Cahill, 1982a) that is overlain by a sand layer as much as 1 m thick. Underlying zone 1 is a sequence of very fine to medium sand (zone 2 of Cahill, 1982a). Local recharge in the repository area moves downward through zone 1 to zone 2, where it moves to the south and discharges into Marys Branch 330 m south of the site. Cahill (1982a) estimated the minimum travel time of ground water migrating from the burial site to Marys Branch to be about 50 years.

The following description of trench construction is from McMahon and Dennehy (in press). The initial step during trench construction is to excavate and remove a 3-m-wide perimeter of the surface sand, including about 0.3 m of underlying clay, around the designated trench area. Clay is placed in the excavation and compacted. The compacted clay serves as an upper barrier wall (fig. 9*A*) to prevent the upper wall of the trench from caving and to

Figure 6. Leachate from burial ground 5 seeping from depression formed by uprooted tree in Melton Valley, Oak Ridge National Laboratory, Tenn. Photograph by David Webster, 1975.

limit infiltration into the trench. The trench is excavated within the clay barrier perimeter to a depth of about 7 m, but the depth may vary to maintain a minimum of 1.5 m between the bottom of the trench and the water table. Trench floors are sloped to one side and along the long axis of the trench to promote drainage. Monitoring pipes and sumps are placed at regular intervals along the drain. Sand is placed in the trench floor and is used to backfill between waste packages. A minimum of 0.6 m of clay is added to the top of the trench and compacted with a vibrating compactor. At least 1 m of material is added over the clay, and the trench cap is contoured and sowed with grass seed. Pre-1976 trenches were constructed similarly except for their having shorter surface dimensions and no barrier of compacted clay around the trench perimeter.

Infiltration of water through the trenches has been studied by Dennehy and McMahon (1985). They determined that the compacted clay barrier (fig. 9*A*) reduced the water infiltrating the trenches compared to the trenches without the barrier (fig. 9*B*). Water ponded in the bottom of a trench with a compacted clay barrier to a depth of 0.3 m and in a trench without a clay barrier to a depth of 2.3 m (fig. 9). Cahill (1982b) reported tritium and organic constituents greater than background concentrations in water at a well 3 m from a trench with no barrier and traces of cobalt-60 and tritium greater than background concentrations in water beneath the trench floor.

Sheffield, Illinois

The Sheffield disposal site is about 5 km southeast of Sheffield, Ill. (fig. 1). The trenches are excavated in glacial deposits including lacustrine sediments, till, outwash deposits, and aeolian silt and sand. A few of the trenches were constructed above the original grade with berms of surficial material. The glacial deposits are underlain by shale and mudstone of Pennsylvanian age. Trenches excavated in the glacial deposits range from 10 to 170 m long, 2.6 to 23 m wide, and 2.6 to 8.6 m deep (fig. 10). The trenches were bottomed at least 3 m above the saturated zone, although seasonal water level fluctuations may be at levels of the waste in some trenches. The trenches were covered with a layer of silty clay that was capped by a layer of clayey silt to silt. The cap was compacted by operating heavy machinery over the

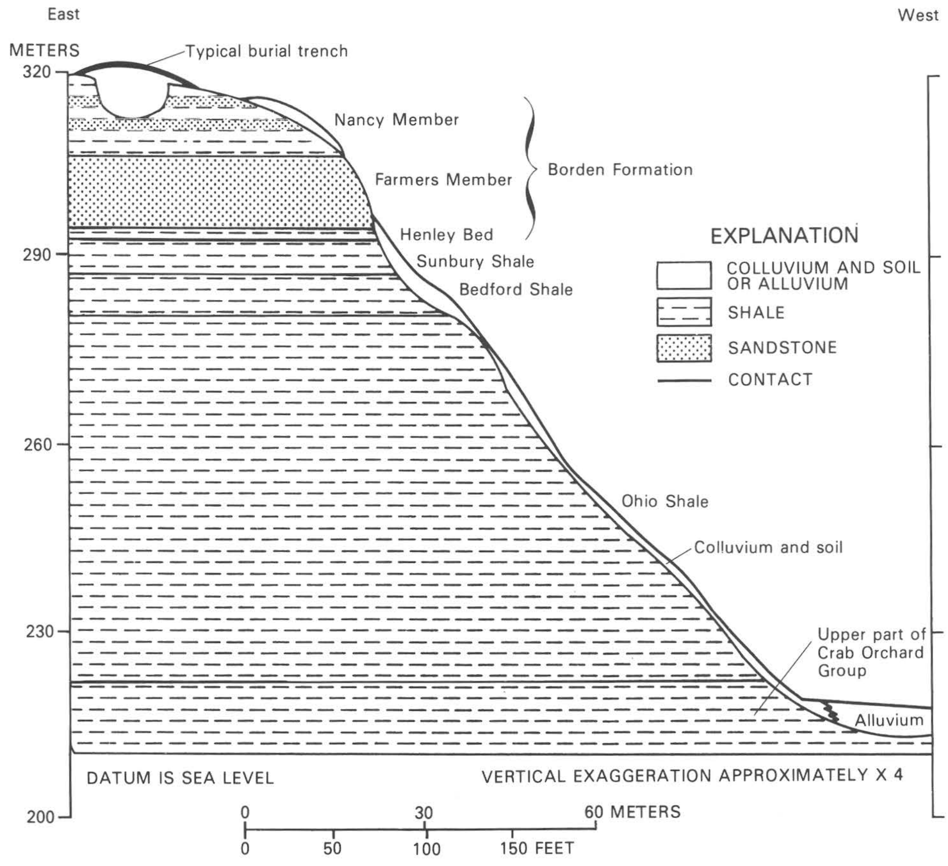


Figure 7. Geologic section and location of typical burial trench at Maxey Flats, Ky.

trenches. The cap supports a growth of brome grass. The disposal site and a strip mine lake near Sheffield, Ill., is shown in figure 11.

Precipitation at the site averages about 88 cm/yr (Healy, in press). Recharge to the saturated zone is estimated to be about 5 cm/yr, runoff from the site is about 23 cm/yr, and evapotranspiration is about 60 cm/yr. Infiltration in the burial area is primarily along the periphery of the caps and secondarily through the center of the caps as indicated by data collected from instruments installed to indicate water movement into the trenches (Healy, in press). Thus, the intent of the compacted clay cap to limit infiltration is in part successful.

The outwash deposits, a pebbly sand unit, underlie about two-thirds of the burial site. The pebbly sand unit is a permeable zone that drains water which infiltrates into the trenches; the unit minimizes the water-level fluctuations and reduces the risk of water accumulation in the trenches. Ground-water velocity in the pebbly sand was measured at about 750 m/yr; the unit conveys tritiated water from the burial site to a strip mine lake (Healy, in press) (fig. 12). Organic contamination of ground water at the Sheffield site has been described by Goode (in press).

Runoff from the burial site was 23 cm/yr compared to 4 cm/yr for an undisturbed area. The increased runoff is attributed to the compacted clay caps over the trenches and to the shorter, less dense vegetation than in the undisturbed areas. Sediment yields from the undisturbed area were about two orders of magnitude smaller than yields from the burial site (Gray, in press).

Collapse cavities in trench covers have been documented from October 1978 through September 1985. A total of 302 collapse cavities (fig. 13), having a cumulative volume of 497 m^3, occurred during this period. Most collapses were recorded following periods of rainfall when soil moisture was near maximum (Gray, in press).

Beatty, Nevada

Low-level radioactive solid wastes have been buried in trenches at a site near Beatty, Nev., since 1962 (fig. 1). The waste burial facility is in the Amargosa River valley, a desert valley in southern Nevada (fig. 14). An active (1988) waste burial trench is shown in figure 15. This trench is about 17 m deep, 90 m wide, and 180 m long. The mean annual precipitation is 11.4 cm at Beatty, 18 km north of the site, and 7.4 cm at Lathrop Wells, 30

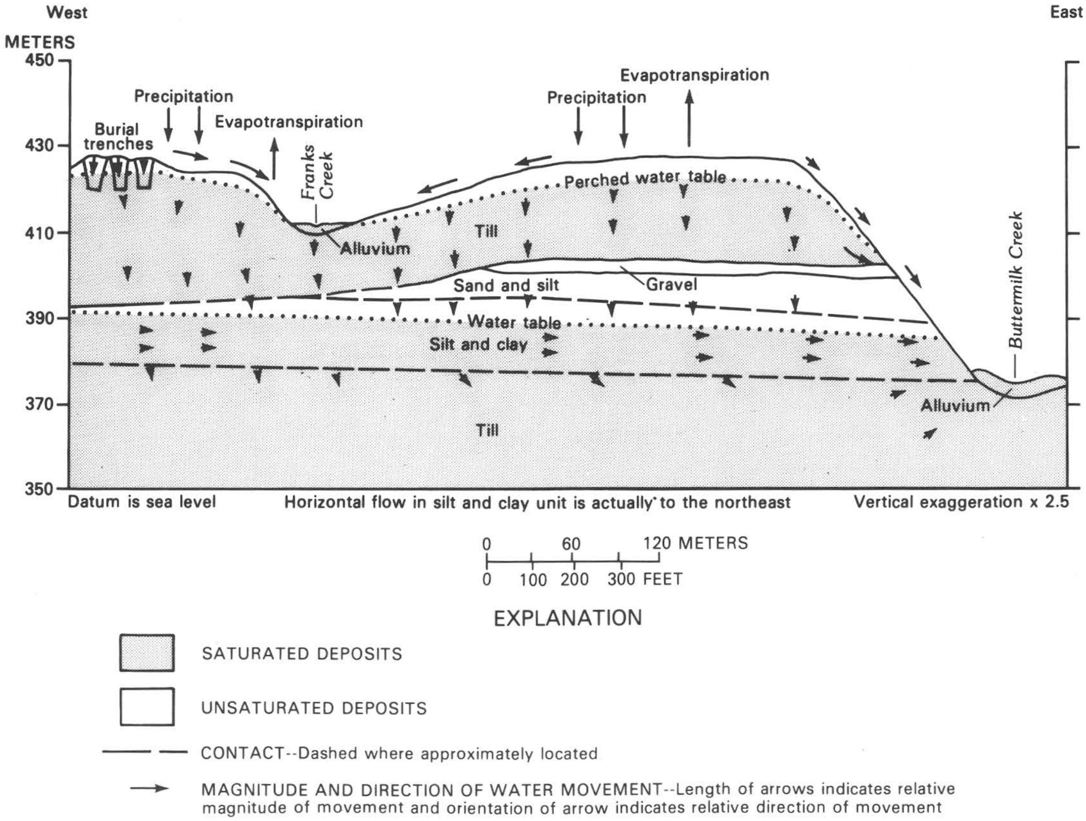


Figure 8. Vertical section through trench burial area near West Valley, N.Y., showing weathered zone, glacial deposits, and direction of ground-water flow.

km southeast of the site (Nichols, 1985). The site is underlain by more than 170 m of unconsolidated alluvial-fan, fluvial, and playa deposits. The upper 30 m of which are an unconsolidated mixture of poorly sorted cobbles, gravels, sands, and silts. Burial trenches are excavated in the unconsolidated alluvial deposits (fig. 16). The waste is backfilled and covered with the material removed from the trenches. The depth to water near the site ranges from 85 to 115 m below the surface. Ground-water movement beneath the site is to the southeast; the nearest downgradient natural discharge is in Ash meadows, about 40 km southeast of the site. The dry channel of the Amargosa River passes about 3 km west of the burial site; surface runoff in the channel is rare and limited to a few days following major storms.

The study of the site by the U.S. Geological Survey has concentrated on the unsaturated zone and the potential for recharge (Nichols, 1985; Fischer, in press). It is through the unsaturated zone that any radionuclides leached from the waste must pass before reaching the saturated zone. Water budget studies by Nichols (1985) indicate that the potential for percolation to depths greater than 2 m does exist despite high evaporation demands. Measurements of soil-moisture tension adjacent to the waste site during a 2.5-yr period indicate no percolation deeper than 2 m (Fischer, in press). Studies to date (1988) indicate that recharge, if it occurs at the site, is episodic and probably small. The extremely small potential for downward percolation suggests small potential for transport of radionuclides.

Development of Siting Criteria

Problems of water accumulation in waste trenches, collapse of trench caps, and leaching and migration of

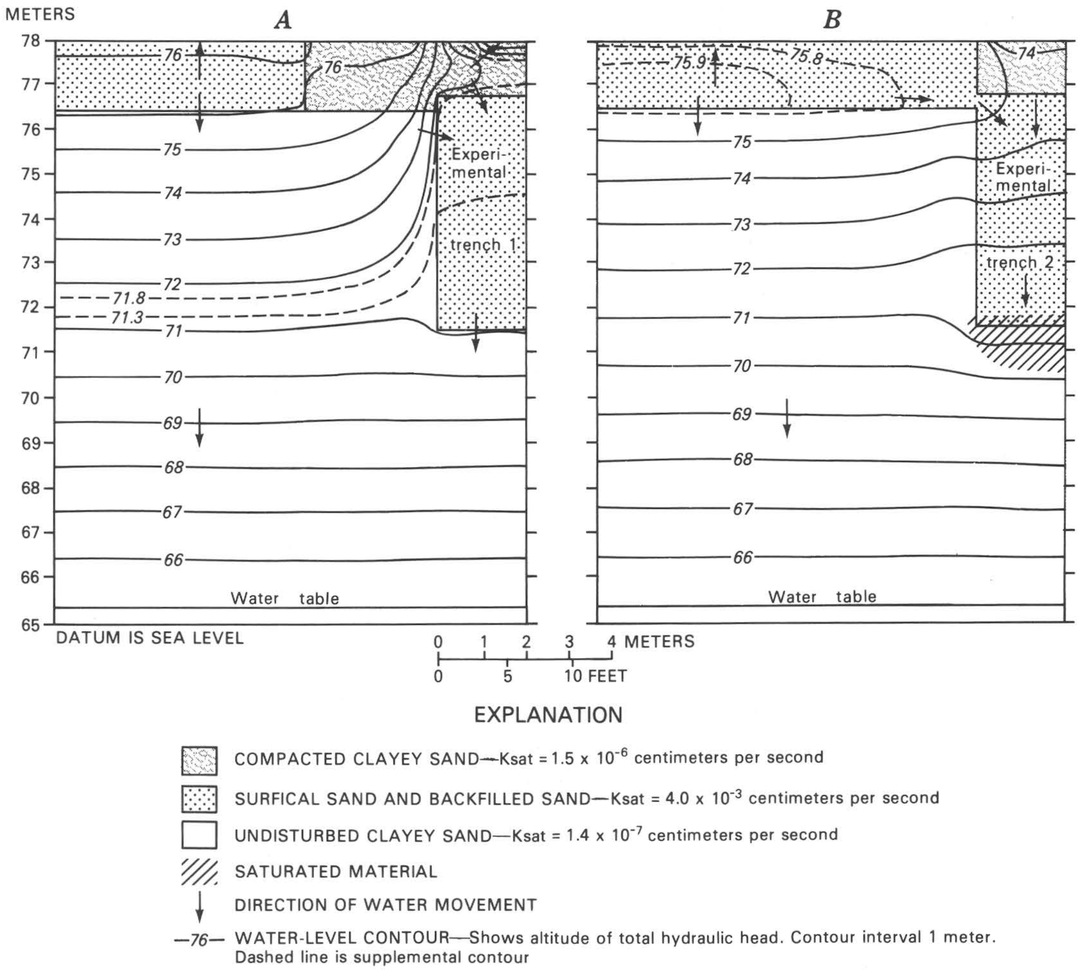


Figure 9. Cross section showing potentiometric-head distribution and flow directions at experimental trenches in May 1984 at burial grounds near Barnwell, S.C. (from McMahon and Dennehy, in press). *A*, Trench design with 3-m-wide clay barrier around perimeter. *B*, Trench design without clay barrier.

waste have been documented at each of the burial sites in humid and subhumid climates discussed in the preceeding sections. From a geohydrologic perspective, the most direct and potentially suitable solution to the problem of low-level radioactive-waste isolation would be to locate suitable burial sites in arid climates. However, isolation of low-level waste is approached as a problem which will be resolved regionally. This has fostered development of measures to mitigate the problems experienced at sites in humid and subhumid climates. Mitigating measures have taken two forms: (1) the development of various geohydrologic repository siting criteria and, (2) the design of engineered barrier systems to prevent migration of the waste. These two avenues of approach to the problem are discussed in the following sections. Geohydrologic siting guidelines have been proposed by investigations sponsored by many groups and organizations (Cherry and others, 1973; Papadopulos and Winograd, 1974; Cherry and others, 1979; International Atomic Energy Agency, 1981, 1982; Falconer and others, 1982; Fischer and Robertson, 1984) to overcome many of the problems associated with existing sites. The following paragraphs discuss many of the applications of guidelines that have been recommended; many of the specific guidelines have been adopted by the U.S. Nuclear Regulatory Commission in site-suitability requirements (U.S. Nuclear Regulatory Commission, 1982) and in their technical position on the siting requirements (Siefken and others, 1982).

The first generation of commercial waste burial grounds was excavated in deposits of low permeability, except for the sites near Barnwell, S.C., and Beatty, Nev. Meyer (1979, p. 661) questioned if a more permeable burial medium would not avoid the problems of the bathtub effect. Fischer and Robertson (1984) recommended that the burial medium be permeable and that it be overlain by a clay cap to provide a capillary barrier to downward movement of water through the waste zone. The recommendation that the host medium be permeable has not been explicitly included as siting requirements of the U.S. Nuclear Regulatory Commission (1982), though permeable media are not precluded as host media. Siefken and others (1982) point out that the backfill should be granular material that drains freely and that water percolating through the disposal unit must drain readily from the bottom of the disposal unit to avoid the bathtub effect. Meanwhile, some current screening studies for low-level radioactive-waste sites have targeted low-permeability formations as the pre-

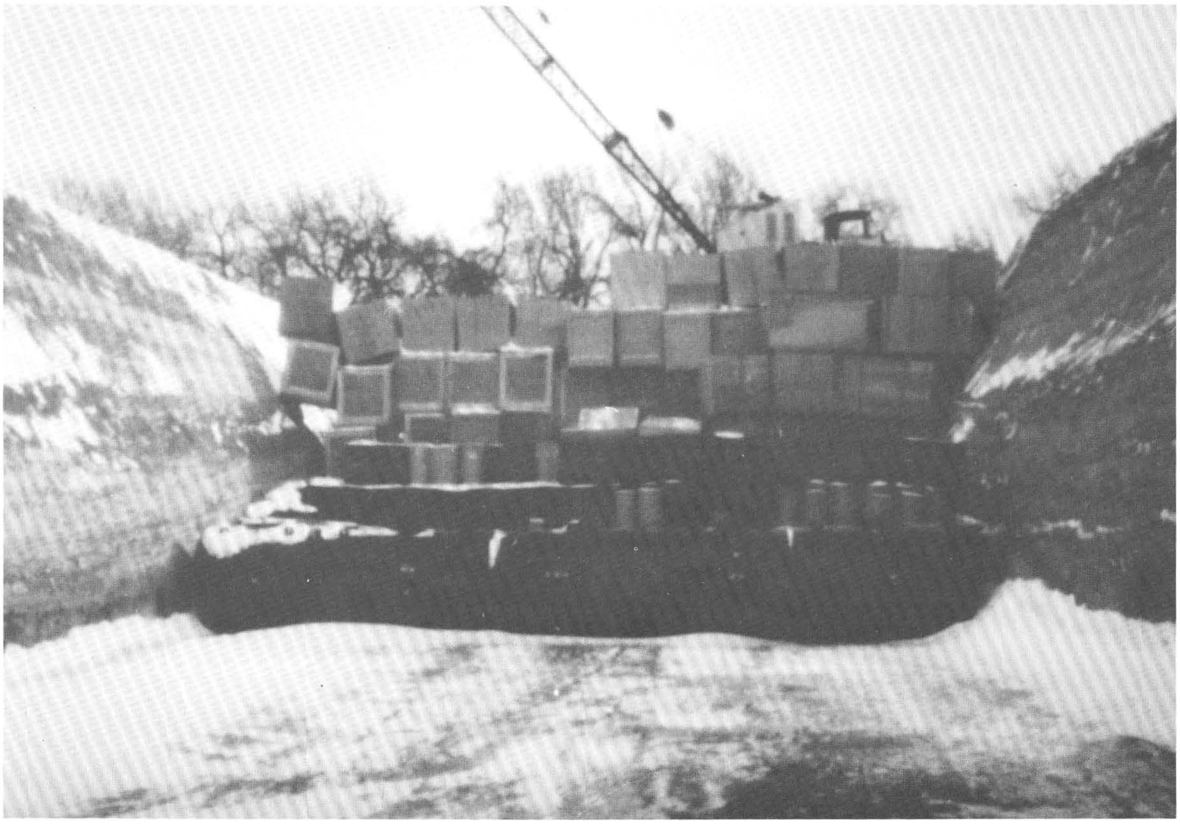


Figure 10. Trench at burial ground near Sheffield, Ill., showing placement of waste packages. Photograph by James Foster, 1977.

ferred terrain for isolation of low-level radioactive waste. Experience has shown that low-permeability material as a burial medium has produced many problems with low-level radioactive-waste containment; satisfactory performance of such a medium cannot be expected without adequate consideration of the geohydrologic and design factors involved in the dynamics of the site performance.

The unsaturated zone is favored for shallow-land repositories (Cherry and others, 1973; Papadopulos and Winograd, 1974; U.S. Nuclear Regulatory Commission, 1982; Fischer and Robertson, 1984) because of the opportunity to minimize the contact of water with the waste. However, in many geohydrologic settings in humid regions, the unsaturated zone may be unsuitable for shallow-land repositories because of the insufficient thickness of the unsaturated zone and the short travel times from the prospective burial site to the discharge area. Cherry and others (1979) determined that in large areas of Canada there is insufficient thickness of unsaturated zone for burial of low-level radioactive waste. Cherry and others (1979) proposed constructing augered holes at depths of a few tens of meters below the permanent water table. The waste would be placed in the augered holes and backfilled with bentonite and clay to provide a very stable, low-permeability barrier above the waste. They further proposed that the permeability of the burial medium be minimal, such that its capacity to transport waste radionuclides by advection would be less than that by diffusion. Burial below the water table is allowed by the U.S. Nuclear Regulatory Commission (1982) where it can be shown that the predominant means of radionuclide movement will be by molecular diffusion.

Extremely important attributes which a flow system should possess are geochemical and hydraulic char-

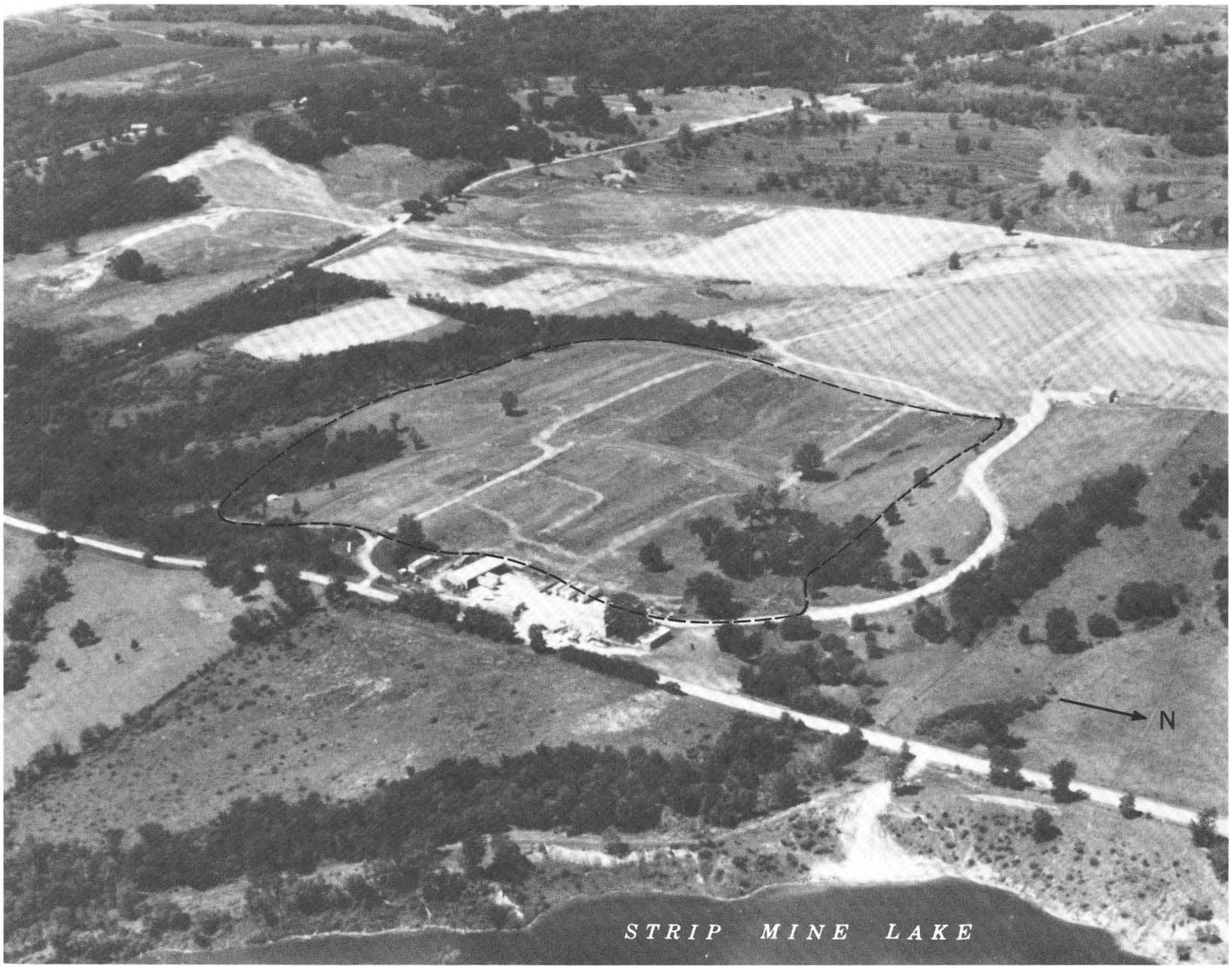


Figure 11. Oblique aerial photograph of low-level radioactive-waste burial grounds near Sheffield, Ill., looking southwestward. Strip mine lake is in foreground; boundary of low-level radioactive-waste disposal site is delineated by dashed line. Photograph by Jerry Abbey, 1985.

acteristics that will afford a long residence time for radionuclides by virtue of geochemical processes that retard the transport of radionuclides and long flow paths and slow ground-water velocities in the ground-water-flow system. These factors come to the forefront of importance in the later stages of waste isolation, after the engineered barriers are no longer effective and institutional control of the site has ceased. This concept of employing multiple barriers that are naturally present by the geochemical and physical nature of the flow system is considered in demonstrating compliance with the U.S. Nuclear Regulatory Commission's (1982) performance objectives. Advocates of the multiple-barrier concept in disposal of low-level waste include Cherry and others (1973), Falconer and others (1982), and Siefken and others (1982). The advocacy of the multiple-barrier flow system concept is a conservative principle that provides added confidence in a disposal system which provides isolation extending in time and space beyond the probable capabilities of the manmade waste-isolation system. The geologic and hydrologic conditons at the site should allow the repository site to be characterized with a degree of confidence to provide for defensible estimates of facility performance.

Characterization of the site provides the basis for determination of ground-water-flow paths, estimation of rates of radionuclide migration, and design of monitoring networks to evaluate the performance of the disposal facility. Characterization includes determination of the variations in physical and hydraulic properties of the saturated and unsaturated zones, the hydrologic balance of the surface and subsurface system, diffusion and dispersion properties of the system, and the geochemical properties of the system. Heterogeneous systems of geologic units that are discontinuous and variable in character and systems in which fracture permeability is a significant component are difficult to characterize with confidence and may not be amenable to prediction of ground-water flow and radionuclide migration. Systems dominated by fracture flow are particularly difficult to characterize. Fractured media have provided relatively rapid migration routes for radionuclides in the near-

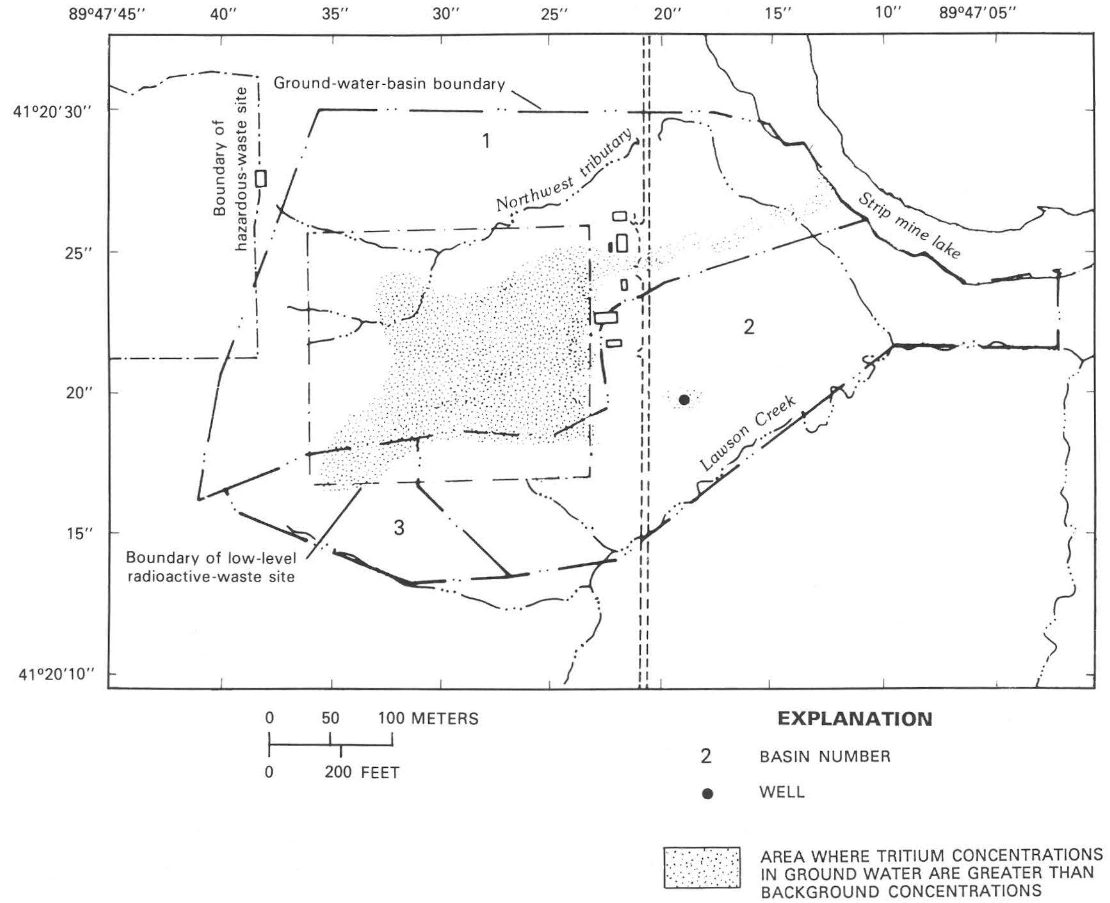


Figure 12. Burial ground near Sheffield, Ill., showing areas where greater than background tritium concentrations were detected in ground water (from Healy, in press).

surface weathered zone of fine-grained till at West Valley, N.Y. (Randall, in press); in consolidated rock at Maxey Flats, Ky. (Lyverse, in press), and Palos Forest Preserve, Ill. (J.R. Nicholas, U.S. Geological Survey, oral commun., 1987); and in weathered rock at Oak Ridge National Laboratory, Tenn. (D.A. Webster, U.S. Geological Survey, oral commun., 1987). Siting guidelines by Falconer and others (1982) recommend that geologic units in which the ground-water flow principally occurs in fractures, joints, or solution voids be excluded from consideration as shallow-land burial sites.

Site-Suitability Requirements of the U.S. Nuclear Regulatory Commission

The site-performance objectives, site-suitability requirements, and the technical position of the U.S. Nuclear Regulatory Commission on the suitability of sites will be preeminent in influencing the next generation of low-level radioactive-waste repository sites in the United States. The performance objectives and site-suitability requirements were published in the Federal Register, vol. 47, no. 248, Monday, December 27, 1982, p. 57463–57482, and are referred to as document 10CFR61 (U.S. Nuclear Regulatory Commission, 1982). The technical position of the U.S. Nuclear Regulatory Commission on implementing the suitability requirements is given in Siefken and others (1982). Weber (in press) discusses the hydrogeologic information needed to demonstrate compliance with the regulations of the U.S. Nuclear Regulatory Commission.

The performance objectives of the U.S. Nuclear Regulatory Commission (1982, Subpart C, 10CFR61.41) state, in part, that

> concentration of radioactive material which may be released to the general environment in ground water, surface water, air, soil, plants, or animals must not result in an annual dose exceeding an equivalent of 25 millirems to the whole body, 75 millirems to the thyroid, and 25 millirems to any other organ of any member of the public. Reasonable effort should be made to maintain release of radioactivity in effluents to the general environment as low as is reasonably achievable.

The site-suitability requirements of the U.S. Nuclear Regulatory Commission (1982, Subpart D, 10CFR61.50) basically incorporate the siting guidelines as discussed in the section "Development of Siting Criteria." The site-suitability requirements as given in 10CFR61 are as follows:

Figure 13. Collapse cavity, approximately 0.8 m wide, at burial ground near Sheffield, Ill. Photograph by John Gray, 1984.

1. The disposal site shall be capable of being characterized, modeled, analyzed and monitored.

2. Within the region or state where the facility is to be located, a disposal site should be selected so that projected population growth and future developments are not likely to affect the ability of the disposal facility to meet the performance objectives....

3. Areas must be avoided having known natural resources which, if exploited, would result in failure to meet the performance objectives....

4. The disposal site must be generally well-drained and free of areas of flooding or frequent ponding. Waste disposal shall not take place in a 100-year floodplain, coastal high-hazard area or wetland....

5. Upstream drainage must be minimized to decrease the amount of runoff which could erode or inundate waste disposal units.

6. The disposal site must provide sufficient depth to the water table that ground-water intrusion, perennial or otherwise, into the waste will not occur. The Commission will consider an

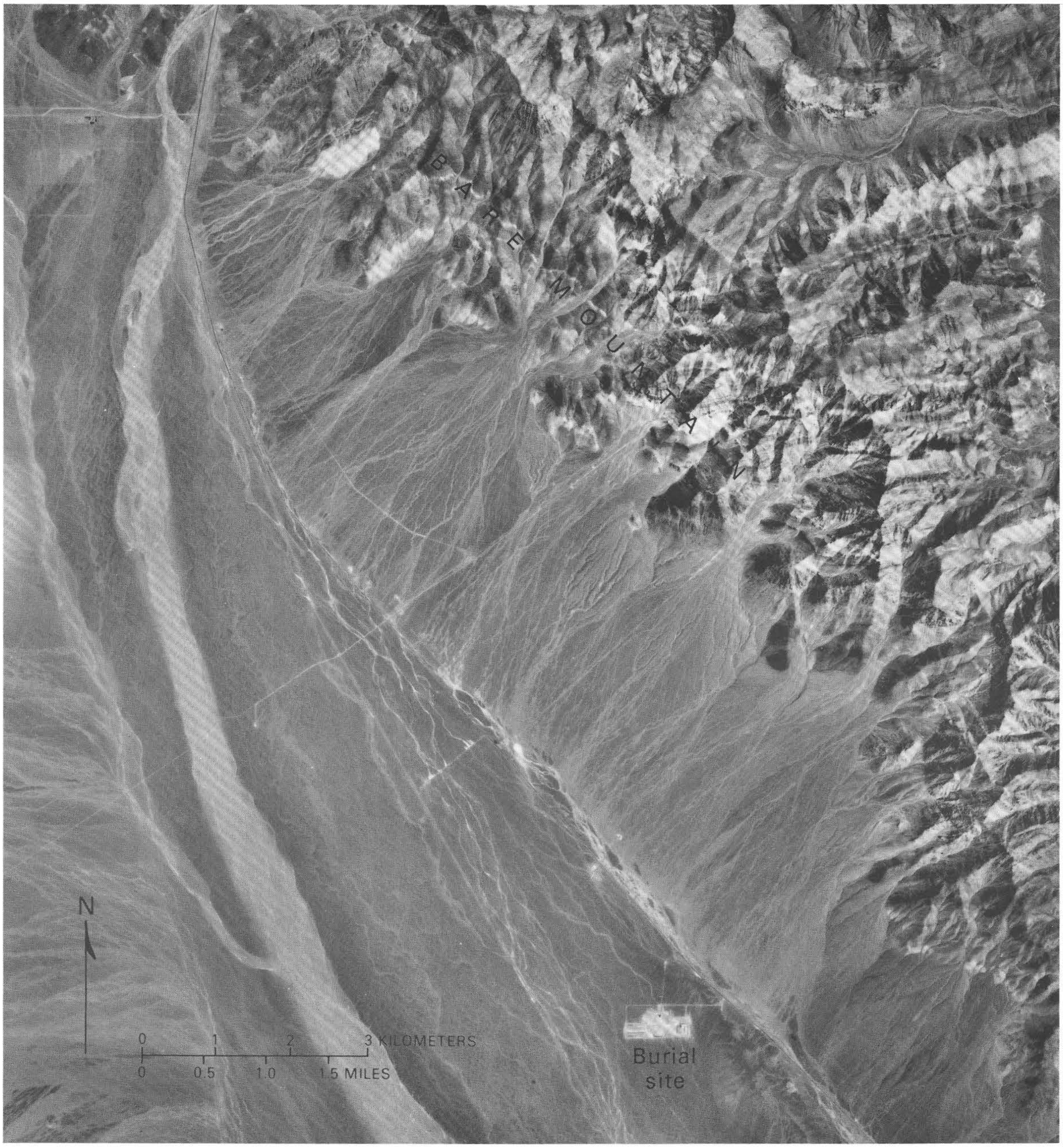


Figure 14. Aerial photograph of part of northern Amargosa Desert showing Bare Mountain, alluvial fans and dry channel of Amargosa River, and waste burial site near Beatty, Nev. Photograph taken June 6, 1976.

exception to this requirement to allow disposal below the water table if it can be conclusively shown that disposal-site characteristics will result in molecular diffusion being the predominant means of radionuclide movement and the rate of movement will result in the performance objectives...being met. In no case will waste disposal be permitted in the zone of fluctuation of the water table.

7. The hydrogeologic unit used for disposal shall not discharge ground water to the surface within the disposal site.

8. Areas must be avoided where tectonic processes such as faulting, folding, seismic activity, or vulcanism may occur with such frequency and extent to significantly affect the ability of the disposal site to meet the performance objectives...or may preclude defensible modeling and prediction of long-term impacts.

9. Areas must be avoided where surface geologic processes such as mass wasting, erosion, slumping, landsliding, or weathering occur with such frequency and extent to significantly affect the ability of the disposal site to meet the performance objectives...or may preclude defensible modeling and prediction of long-term impacts.

10. The disposal site must not be located where nearby facilities or activities could adversely impact the ability of the site to meet the performance objectives...or significantly mask the environmental monitoring program.

Engineered Barrier Systems

The design and use of facilities utilizing extensive engineered features have been prompted by the desire to provide greater confinement of waste than has been experienced at some shallow burial sites. Engineered barriers and repositories, such as below-ground or above-ground vaults, earth-mounded bunkers, tile holes grouted with cement or other low-permeability matrix, high-integrity waste containers, and other designs have been proposed with the objective of providing greater confinement and protection of waste from weathering and transport.

The U.S. Nuclear Regulatory Commission considers engineered structures as part of a redundant barrier system to waste isolation—not a substitute for a suitable site. Thus, site-suitability requirements must be met for any site regardless of engineered structures proposed. Such a requirement is necessary but may not be sufficient alone to assure waste isolation. Engineered features need to be designed with the natural conditions in mind in order to be effective and not to be counterproductive. Similar engineering features, such as simple trench construction and backfill of waste and capped with the excavated material, were employed at the burial sites near Beatty, Nev., and the trenches at West Valley, N.Y. The design is quite adequate at Beatty, but problems with waste containment have been experienced at West Valley. The lesson to be learned is that the design of the engineered features of a repository must be compatible with the natural geohydrologic conditions.

A chief distinction of an engineered facility is one which provides one or more of the following: (1) Mechanical support and stability to the structure, (2) barriers for containment of radioactive waste, and (3) facilities to collect and monitor migration of water within and beyond the facility. A review of engineered near-surface facilities has been made by Schwarz (in press), and the subject has

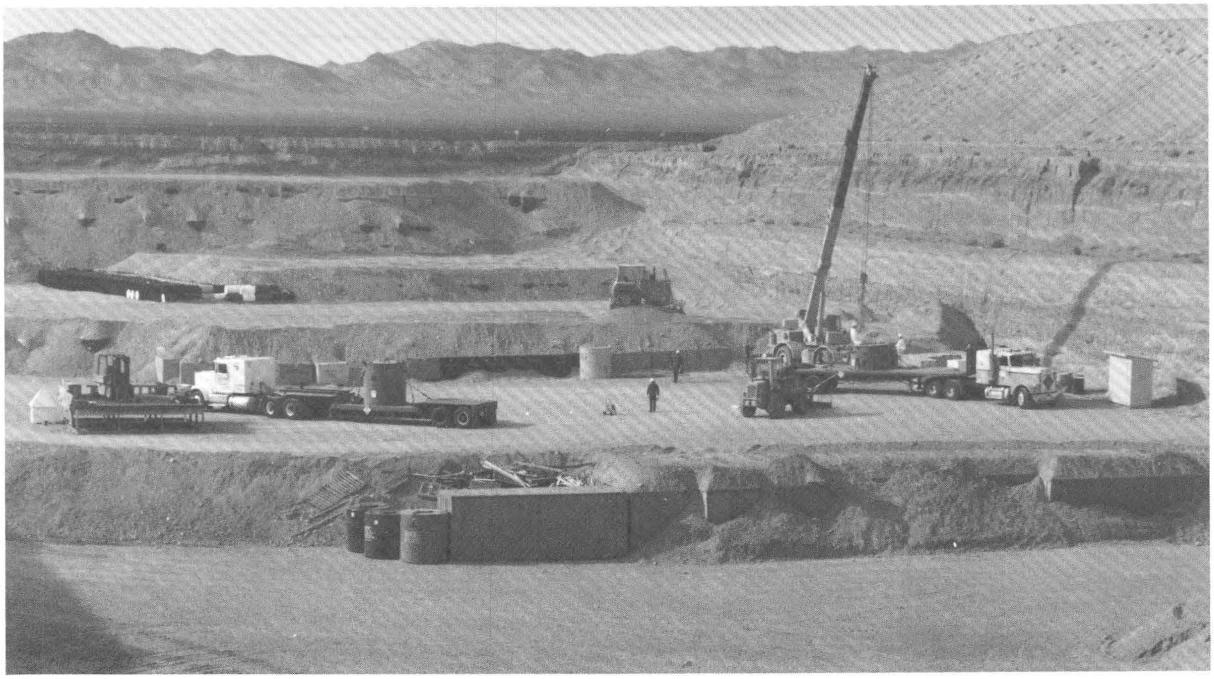


Figure 15. Active waste burial trench at site near Beatty, Nev. Photograph taken in 1987.

been treated in a series of reports by Bennett and others (1984), Bennett (1985), Miller and Bennett (1985), and Warriner and Bennett (1985). Engineered near-surface repositories have been in use for less than 20 years.

Earth-mounded concrete bunkers for disposal of low- and intermediate-level radioactive waste were first used in France (Van Kote, 1982). In the French design of the earth-mounded concrete bunker, low-level radioactive waste with appropriate packaging is stored over the monoliths above the original ground surface in earth mounds. The monoliths rest on a concrete pad containing a drainage system to collect any infiltration that may occur during construction and initial operation (fig. 17).

Below-ground vault repository refers to any enclosed engineered structure constructed below the surface of the earth by cut-and-cover construction or built above ground and then covered with earth. Below-ground vaults constructed of reinforced, cast-in-place concrete walls, roof, and floor have been used at Oak Ridge National Laboratory, Tenn., for retrievable storage of transuranic waste. Below-ground vaults have been used for low-level radioactive-waste storage in Ontario, Canada, at the Chalk River Nuclear Laboratory and in Manitoba, Canada, at Whiteshell Nuclear Research Establishment (Morrison, 1974; Charlesworth and Carter, 1982).

A below-ground vault design is shown in figure 18. Above-ground vaults are similar to below-ground vaults but, as the name implies, are above ground and include no earth cover or earth mound (fig. 19).

Engineered features of near-surface repositories that include various procedures to stabilize the waste are: sorbent barriers (Freeman and others, 1984; Freeman and Buelt, 1986) to reduce radionuclide migration; plastic sheeting, clay caps, and bioengineered barriers to reduce infiltration into and exfiltration from the repository; and concrete roofs and walls around the waste to enhance structural stability. The extent of engineered facilities may range from a single feature incorporated into a trench repository to a completely engineered structure buried, partly buried, or even wholly above the land surface. A design trench incorporating engineered barriers is shown in figure 20.

The long-term durability and performance of concrete and other materials used in engineered barriers and in completely engineered facilities are not fully known (Denson, 1985). There is no long-term experience or basis for predicting the performance of engineered facil-

Figure 16. Alluvial materials in waste burial trench at site near Beatty, Nev. Photograph taken in 1987.

ities over periods of 300 years or longer. Nevertheless, engineered low-level radioactive-waste repositories are being planned in humid areas where experience has revealed problems with simple trench-burial techniques. For example, Illinois is opting for an engineered facility, and Lavallee (1986) proposes an earth-mounded concrete bunker for low-level radioactive-waste disposal in Maine.

Disposal of low-level radioactive waste in shafts has been practiced above the water table and has been proposed for placement below the water table. A design for disposal of low-level waste in a shaft above the water table is shown in figure 21 (Bennett, 1985). The waste packages are backfilled with noncohesive, freely draining materials and capped by concrete. The shaft is free to drain through the host medium to the water table. The

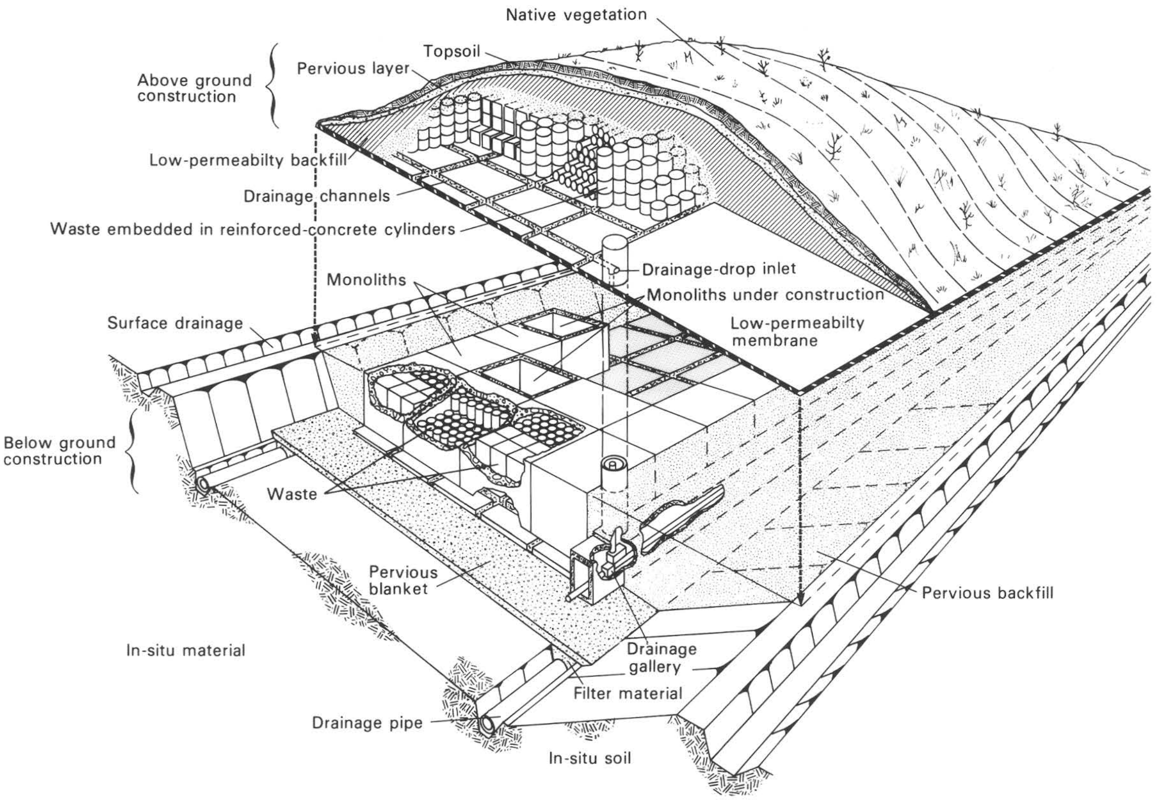


Figure 17. Cutaway view of earth-mounded concrete bunker (modified from Van Kote, 1982).

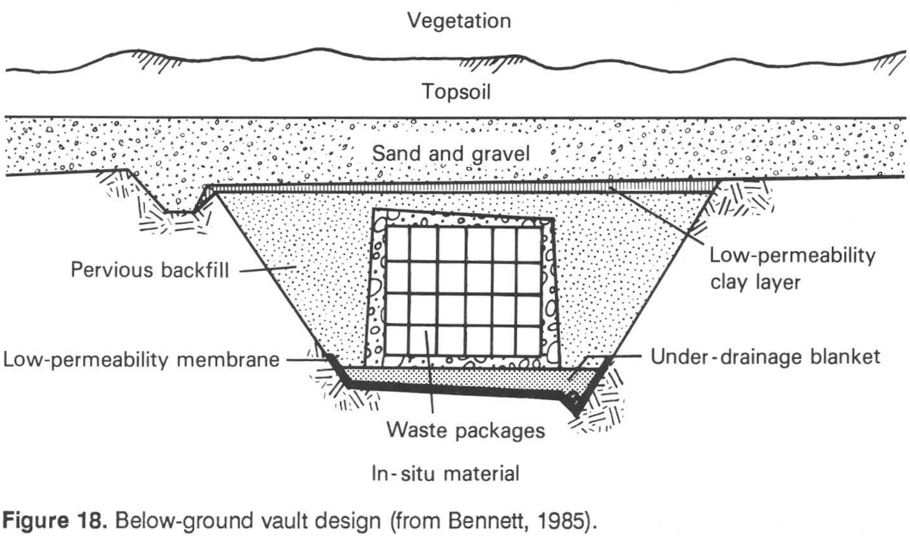


Figure 18. Below-ground vault design (from Bennett, 1985).

below-water-table shaft disposal concept is illustrated in figure 22. The waste is disposed at 5 m or more below the water table; the shaft is sealed by a bentonite or cement grout. Hydraulic conductivity of the host medium is very low and migration of waste is principally by molecular diffusion.

HYDROLOGY OF SHALLOW-LAND DISPOSAL OF LOW-LEVEL RADIOACTIVE WASTE

The site criteria previously discussed, as advanced by various investigators, and the site-suitability requirements of the U.S. Nuclear Regulatory Commission have not yet been applied to shallow repositories. It remains to be seen by the next generation of repositories if the lessons afforded by the first generation of repositories have been learned and if the principles of hydrology will be adequately applied. This section of the report reviews hydrologic principles that are pertinent to analysis of the flow dynamics of a repository, addresses problems of screening data for large regions for potential repository sites, and discusses identification of potentially suitable sites. This section also examines application of the U.S. Nuclear Regulatory Commission's requirements with regard to performance assessment of repositories, and it recommends long-term monitoring for assessing site performance and continued revision of hydrologic models of the flow system.

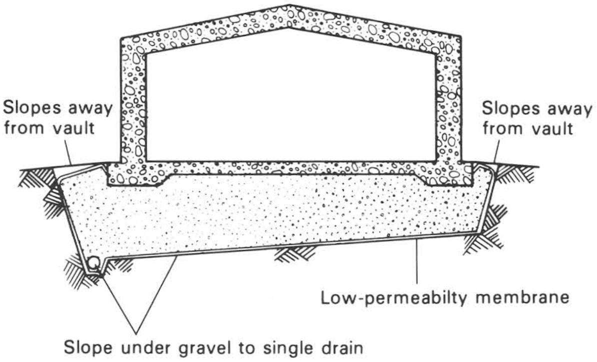
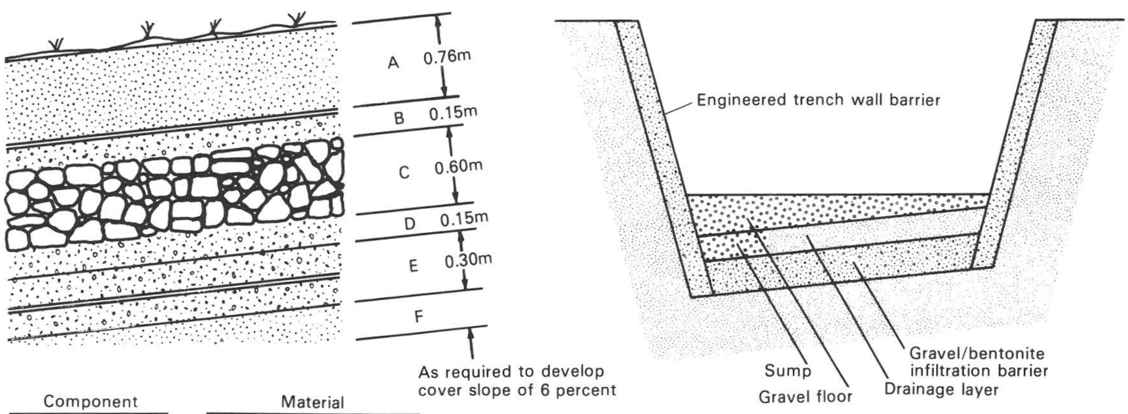


Figure 19. Above-ground vault design (from Bennett and Warriner, 1985).

Climate

Climate and climate related factors are undoubtedly the most important hydrologic factors affecting the suitability of a region for selection of a favorable site for shallow-land isolation of low-level radioactive waste. The quantity and seasonal distribution of precipitation and evapotranspiration influence the infiltration of water into a repository and also the contact of moisture with the waste and the flow of water for transporting waste. Climate affects the thickness of the unsaturated zone, the stream density, and consequently the distance a repository can be located from the ground-water-discharge point. Areas of great aridity are naturally well suited for



Component	Material
A Soil cover	Native soil
B Filter layer	Geotextile layer and 19-millimeter-diameter stone
C Biointrusion barrier	Cobbles
D Drainage layer	19-millimeter-diameter stone
E Infiltration barrier	19-millimeter-diameter stone, granular bentonite filler, geotextile layer, 19-millimeter-diameter stone, and granular bentonite filler
F Soil backfill	Native soil

Figure 20. Trench design incorporating engineered barriers (from Funk and Mills, 1986).

disposal of low-level radioactive waste. A comparison of the hydrologic conditions of the arid site at Beatty, Nev., with the subhumid site at Sheffield, Ill., and the humid site at Barnwell, S.C. (table 1), shows that estimates of several important hydrologic parameters in these varied environments are significant for low-level radioactive-waste repository siting.

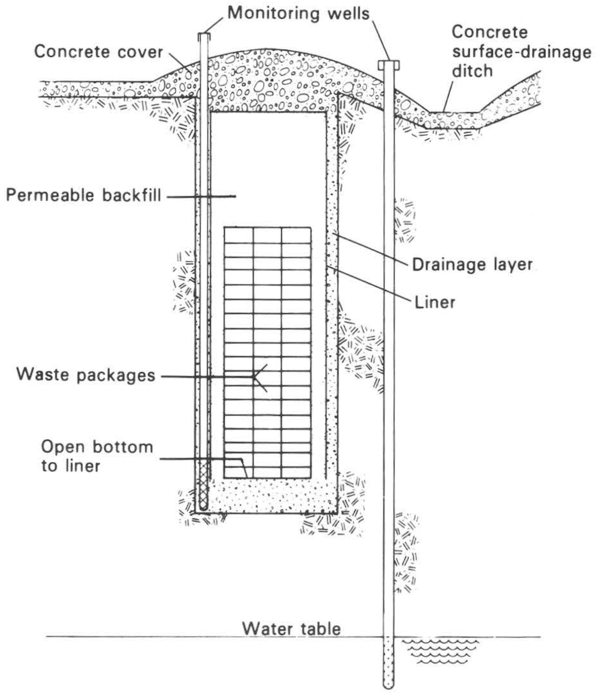


Figure 21. Shaft disposal design above water table (from Bennett, 1985).

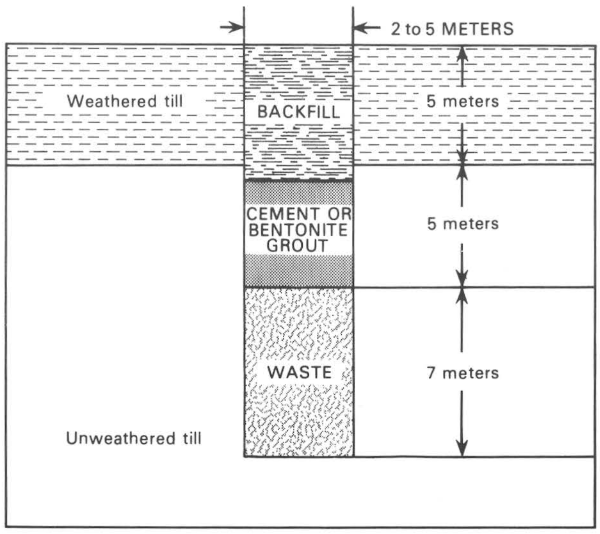


Figure 22. Shaft disposal of low-level radioactive waste in zone of saturation (after Prudic, in press).

In arid regions, potential evaporation greatly exceeds precipitation; recharge is small or nonexistent. Ground-water flow paths from ground-water divides to discharge areas are long; time of travel to discharge areas is correspondingly great. Depths to ground water in arid regions are commonly great. In the arid Basin and Range province, where annual precipitation averages about 280 mm/yr, depths to water are greater than 30 m for more than 90 percent of the province (Bedinger and Langer, 1986). Depths to water are greater than 150 m for more than 20 percent of the province. Similarly, large tracts of land in the Colorado Plateaus, Columbia Plateaus, and other parts of the western conterminous United States have depths to water greater than 30 m (Bedinger and Langer, 1986).

In contrast, in the humid and subhumid eastern and midcontinental United States recharge is relatively great, the density of perennial streams is large, and the depth to ground water is small. Because of these conditions, sites having sufficient depth to water for disposal in the unsaturated zone and having long ground-water flow paths to discharge areas are of very limited occurrence (Ichimura, in press).

Hydraulic Barriers to Flow

Hydraulic barriers are basically low-permeability beds that retard the flow of water. In the unsaturated zone, flow may be retarded by capillary barriers in which a fine-grained layer overlies a coarse-grained layer. Capillary barriers may be created by the lower permeability of a coarse-grained bed under high moisture tension underlying a fine-grained bed. The fine-grained bed absorbs and holds more water by its greater capillary attraction; hydraulic conductivity of the fine-grained bed with large moisture content is greater than the underlying coarse-grained bed with very low moisture content. A diagrammatic representation of a trench repository incorporating a capillary barrier is shown in figure 23.

The proposed use of capillary barriers in the design of radioactive-waste repositories is based on classical theory of fluid flow in porous media, laboratory and field experiments of unsaturated flow, and mathematical modeling of flow in the unsaturated zone. The hydraulic laboratory tank models of Palmquist and Johnson (1962) demonstrated that the interface between a homogeneous layer of silt-sized particles overlying a homogeneous layer of sand-sized particles acted as a barrier to downward infiltration of water in the unsaturated zone. The tank model of Palmquist and Johnson is shown in figure 24.

It has been suggested by some investigators that moisture breakthrough of the capillary barrier does not occur until saturation of the overlying fine-grained layer occurs. However, Palmquist and Johnson (1962) con-

Table 1. Comparison of hydrologic conditions at humid, subhumid, and arid sites

[mm/yr, millimeter per year; m, meter; km, kilometer; yr, year]

	Arid site[1] Beatty, Nev.	Subhumid site[2] Sheffield, Ill.	Humid site[3] Barnwell, S.C.
Annual precipitation (mm/yr)	114	880	1,170
Annual lake evaporation (mm/yr)	1,676	787	1,067
Depth to water (m)	85–115	6–11	8.5
Recharge (mm/yr)	.04	50	380
Distance to ground-water discharge (km)	40	.28	.33
Ground-water travel time, site to discharge area (yr)	500–1,000	.3	50

[1]Data from Nichols (1985) and Bedinger and others (1984).
[2]Data from Gray (in press) and Healy (in press).
[3]Data from Cahill (1982a) and Dennehy and McMahon (1985).

cluded that a breakthrough of flow from a silt bed to a sand bed occurred before saturation of the upper layer when the liquid pressure on the interface was less than atmospheric, a fact that is concurred with by Richards (1950), Hillel and Talpaz (1977), and Johnson and others (1983).

Sand tank experiments indicate that the initial flow through the coarse-grained layer occurs in narrow columns where the moisture content is relatively great (Palmquist and Johnson, 1962). Thus, after the capillary barrier initially ceases to function as a flow barrier, the sand tank models indicate that greater moisture contents are limited to small channels, drainage is relatively rapid, and the bulk of the coarse-grained unit has low moisture content.

The capillary barrier effect of a boundary between two materials is a function of their respective moisture tension versus hydraulic conductivity relations. Consider a layer of clay overlying sand having moisture tension versus hydraulic conductivity as shown in figure 25. These relations are modified from Reed (in press) as computed from the relation between relative hydraulic conductivity and moisture tension expressed by Ripple and others (1972, p. 6). At moisture tensions from about 6 to 46 m of water at the clay-sand interface, the sand has a smaller hydraulic conductivity than the clay, and the sand will retard downward percolation. If the terrain at the interface decreases to below a moisture tension of about 6 m of water, the sand will be more permeable than the clay and the contact will not act as a capillary barrier. The importance of the relation between moisture tension and hydraulic conductivity is further emphasized in the work of Goode (1986).

Herzog and others (1982) reviewed the literature on trench-cap design and discussed several designs employing capillary barriers. However, few capillary barriers have been constructed and reported in the literature. Experimental capillary barriers were constructed in

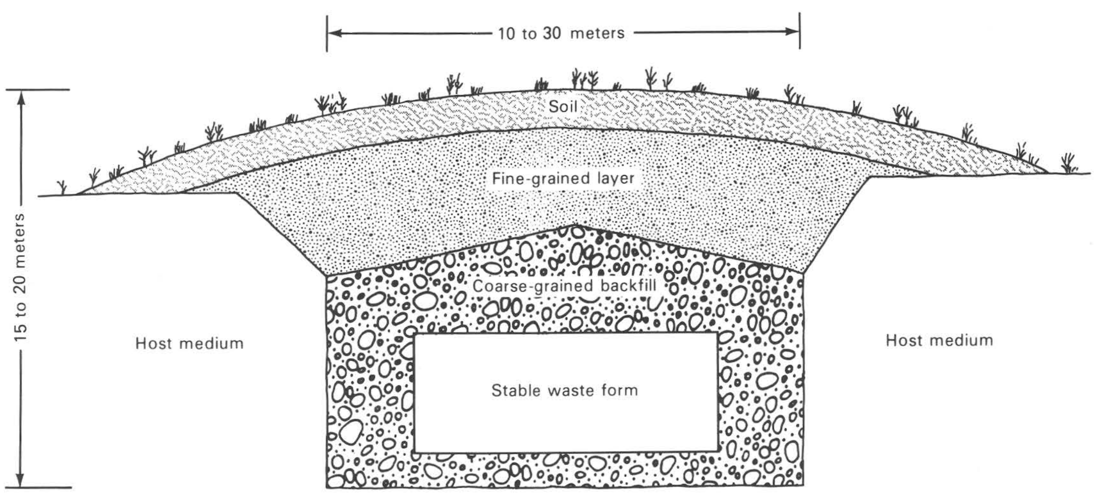


Figure 23. Diagrammatic cross section of simple trench repository showing repository cap, waste, backfill, and host medium.

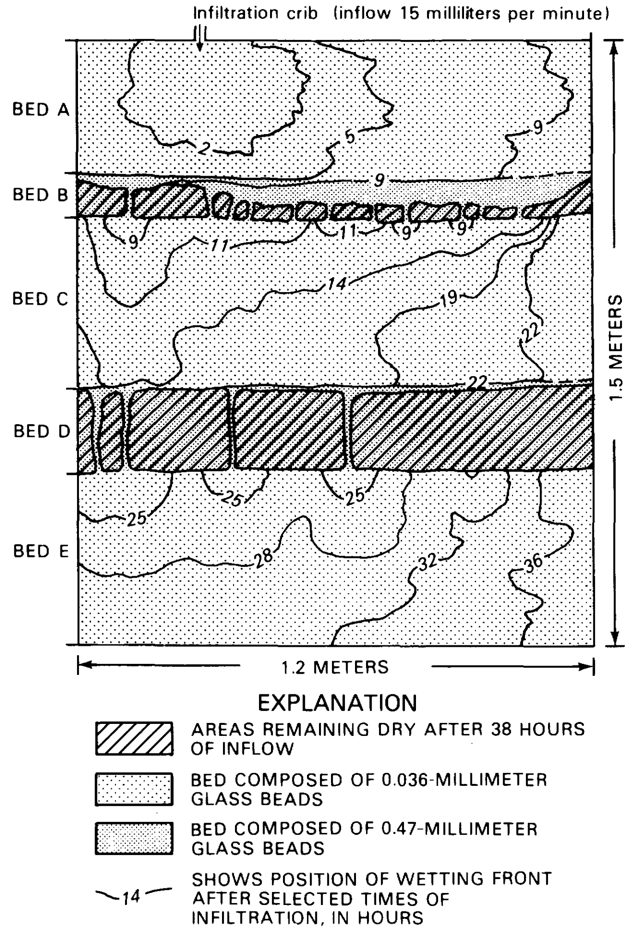


Figure 24. Laboratory tank model showing capillary barriers (from Palmquist and Johnson, 1962).

trenches by Rancon (1979) to test the applicability of these barriers in shallow-land disposal repositories. The experimental trench was excavated in fine soil, filled two-thirds with gravel, and then covered with argillaceous sand forming a dome over the structure. After 5 years of regular monitoring, no appreciable moisture transport was detected across the interface of the argillaceous sand toward the gravel.

The effectiveness of the full-scale trench repositories with capillary barriers are dependent on many factors, including the dimensions and components of the trench, the lithology and unsaturated hydraulic conductivity of the host medium, the climate and related factors such as the infiltration rate into the fine-grained layer and the depth to the water table, and, as has been shown above, the relation between soil moisture tension and hydraulic conductivity of the layers. In addition, the effectiveness of a capillary barrier could be adversely affected by collapse of the waste packages, desiccation of the clay cap, and the penetration of the cap by burrowing animals and plant roots.

Hydrology of Repository Systems

Trench Repository in the Unsaturated Zone

Components of a simple trench repository include the repository cap, the waste, waste packaging, backfill, and host media (fig. 23). As a system designed to provide stability of the repository, lessen infiltration, and minimize moisture contact with the waste, each component

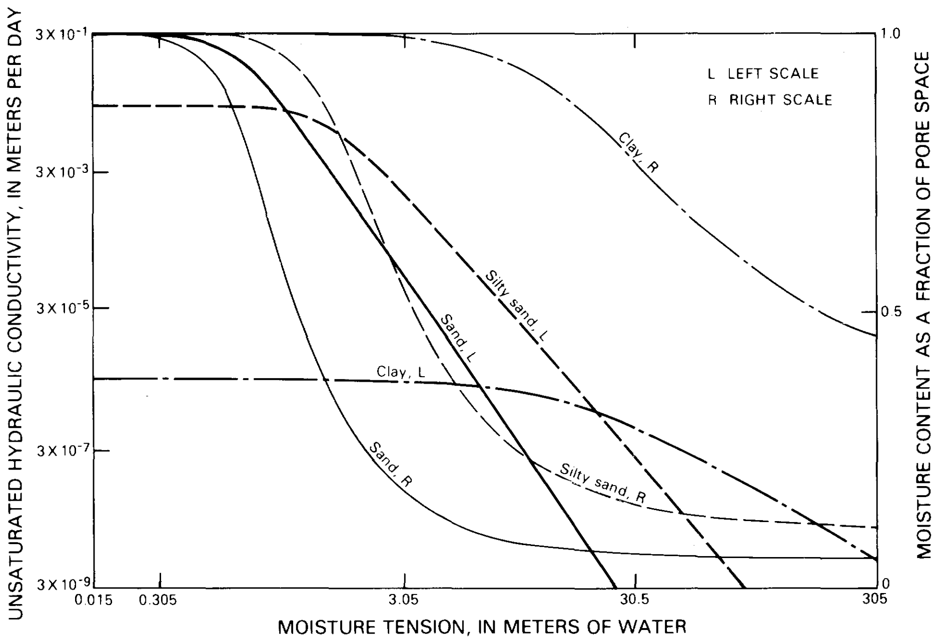


Figure 25. Water content, unsaturated hydraulic conductivity, and moisture tension for three hypothetical examples of porous media (modified from Reed, in press).

must be designed as a part of the whole, with consideration given to the hydrologic interactions of each component with the others.

Trench Cap

Trench caps should function as a stable cover over the repository and, in humid and subhumid regions, limit infiltration into the repository. The low permeability of the trench cap also may lessen gaseous radioactive emissions into the atmosphere. In extremely arid regions where infiltration is low, there may be no need to reduce infiltration. If potential infiltration is significant, as in a humid region, the trench cap needs to be designed to limit infiltration to the repository. Historically, repositories have been plagued by problems of trench-cap instability, which result in infiltration to the repository. As discussed in an earlier section, these problems have resulted from poor drainage of trench-cap areas, unstable waste forms that collapse by weathering and overburden pressure, and desiccation and cracking of trench-cap material. Other processes which may increase infiltration of precipitation in trench caps include weathering and biologic activity, such as growth of plant roots and burrowing of animals. Structural instability of the trench cap caused by weathering and collapse of waste forms and trench components often are detected soon after construction. Collapse features will presumably decrease in frequency over time. However, weathering and biologic activity in the trench cap will be a long-term, continuing process causing progressive deterioration of the trench-cap effectiveness in inhibiting infiltration.

Reed (in press) shows that in a region of potentially large infiltration the clay cap functions as a retardant to infiltration as well as an integral part of the capillary barrier. The effectiveness of the clay cap is subject to severe deterioration by processes that increase the cap's permeability. Effectiveness of the capillary barrier decreases as the infiltration increases and, consequently, moisture content of the clay cap and coarse-grained layer increases. There are many unknown factors concerning the long-term effectiveness of capillary barriers.

Several trench-cap designs have been proposed to reduce infiltration and provide trench-cap stability. These include capillary barriers to reduce infiltration, admixtures or layers of bentonite (swelling clays) to reduce infiltration, stable waste forms to prevent their collapse, and noncompressible backfill to prevent compaction in the repository. The results of trench-cap experiments at Los Alamos National Laboratory are reported by Hakonson and others (in press). The plastic sheets that have been used to cover the trench caps at Maxey Flats, Ky., have lessened infiltration greatly, but also have facilitated a great quantity of overland runoff, which has caused erosion problems downslope from the trenches. In addition, such designs require perpetual maintenance.

In addition, a technique referred to as "bioengineering" has been proposed to reduce infiltration. This technique attempts to cover the cap with impermeable panels separated by vegetated rows. The panels increase runoff from the trench cap and the vegetation intercepts and transpires infiltrating moisture, preventing deep percolation to the repository. Such experiments in bioengineering have been conducted to develop and test techniques for control of infiltration into waste burial trenches by vegetative cover and runoff control in a humid environment at Maxey Flats, Ky. (Schulz and Ridky, 1986; Schulz and others, 1985). The long-term performance of such covers, however, remains to be proven.

The bioengineered trench-cap cover described above may present problems from the following standpoint:

1. If compaction and collapse problems occur, the impermeable panels will fail to efficiently drain runoff and hamper action to fill depressions in the trench.
2. The bioengineered trench-cap cover requires active, continual maintenance to be effective.

Studies in an arid environment with experimental trench-cap designs indicate that deep percolation can be reduced by the combined effects of a capillary barrier impeding infiltration and increased evapotranspiration (Hakonson, 1986). A major drawback to control of the water balance is the permanency of controls established to reduce infiltration. Experience shows that deterioration occurs with time and causes increased capacity of the trench cap to accept infiltration by collapse features, desiccation cracks, and intrusion by plant roots and burrowing animals.

A capillary barrier may be a component of trench-cap design for a shallow repository. Bentonite additions to trench-cap materials have been used in experiments at the U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Miss., and at Los Alamos National Laboratory, Los Alamos, N. Mex. Long-term experimental data on prototype trench-cap designs are not available for evaluation. Such data and experience are necessary for adequate evaluation of cover design. The swelling properties of bentonite that effect its low permeability are complemented by its shrinkage during drying, causing potential stability problems within the cap and possibly rapid infiltration before the clays swell.

Bioengineering includes barriers to prevent intrusion of roots and burrowing animals and a vegetative cover to reduce deep percolation. A biointruder barrier is a layer of boulders that inhibits or prevents root penetration and animal burrowing activities (Hakonson and others, in press). The barrier also may operate as a capillary barrier. However, biologic activity in the overlying soil layer would be expected to develop permeability by root and animal penetration and to reduce the efficiency of the capillary barrier, thus permitting increased infiltration.

To summarize the status of trench-cap effectiveness, trench caps at existing repositories in humid areas have experienced problems of instability. As a result, the caps have permitted infiltration of water into low-level radioactive-waste repositories. Long-term field experiments with careful monitoring are needed to test and refine trench-cap and capillary-barrier designs.

Waste Form and Backfill

The waste form greatly affects the stability of the trench cap. Efforts to enhance the physical stability of the waste form include incineration, compaction, incorporating in a solidification medium such as concrete or bitumen, and enclosing in steel, fiberglass, and plastic containers. Stabilization of the waste form by compaction, incineration, or incorporation in a stable solid form can reduce the magnitude of problems related to instability of the waste form experienced at many low-level radioactive-waste repository sites.

The systematic placement of waste packages in the repository and careful backfilling of voids between packages can greatly improve the stability of the repository. The physical as well as the hydraulic and geochemical properties of the backfill are important in efficient design of a repository. Clay silt or soil backfill has been used in many existing repositories and is commonly included in proposed repository designs. Fine-grained backfill tends to retain a greater moisture content and tends to be unstable because of its compressibility. Backfilling with a cohesionless backfill, such as sand, facilitates filling of void spaces. Sand is less compressible than clay and facilitates drainage of water that penetrates into the repository.

The low-level radioactive-waste facilities at Barnwell, S.C., Beatty, Nev., and Richland, Wash., currently accept waste in stable packages, systematically place the packages in the trenches (as opposed to random dumping), and backfill voids between the waste packages with sand. Such practices enhance the stability of the repository zone by reducing deterioration of the waste form and reducing potential settlement and compaction of the waste and backfill.

Host Medium

Monitoring at existing repositories indicates that repositories in clay deposits tend to accumulate water in the trench from infiltration at a rate exceeding the rate of drainage from the trench. Water accumulates in the trench, promotes leaching of the waste, and may overflow at the surface or flow away from the trench through the weathered zone near the surface. The so-called bathtub effect has prompted the recommendation that the host media be moderately permeable in order to allow seepage from the trench. The permeability of the host medium would ideally be of sufficient permeability to permit drainage of infiltration through the repository, but not excessively permeable, so as to provide for slow movement of water beyond the trench. The flow rate at which water will drain through the host media is greatest when the host media is saturated. An unsaturated buffer zone above the base of the trench and below the base of the waste could provide a storage area for intermittent pulses of recharge without saturating the waste.

Conceptual Flow in a Simple Trench Repository System

The objective of a simple trench repository is to provide a stable system and minimize the contact of water with the waste. The hydrology of the trench is not simple. The construction of the trench is referred to as "simple" because it is contructed of natural materials with none of the enhanced engineered barriers.

The simple trench system considered consists of a shallow excavation constructed in a host medium, filled with waste packages and backfill, capped, and mounded (fig. 26). Idealized relations between the relative grain size of the materials of the major components of the trench repository and their unsaturated hydraulic conductivity at moisture tensions where the capillary barrier is effective are shown in figure 26. The relative saturated hydraulic conductivity is shown for contrast to be the inverse of the relative unsaturated hydraulic conductivity.

The relative unsaturated hydraulic conductivity in figure 26 is simplified. As shown in figure 26, unsaturated hydraulic conductivity is a function of moisture tension, and a capillary barrier is only effective for a specific range of moisture tensions at the interface. Likewise, the relative grain size and saturated hydraulic conductivity are based on granular materials. Goode (1986) has shown that these relations may not be valid for some types of materials. For example, a coarse-grained crushed tuff is shown by Goode (1986) to be ineffective as the coarse-grained layer in a capillary barrier.

A diagrammatic representation of the water balance at the trench and the unsaturated flow of water through the clay cap, host media, and backfill is shown in figure 27. The relative unsaturated hydraulic conductivity of each of these components is critical in effecting a minimum of flow through and moisture accumulation in the backfill. The relative unsaturated hydraulic conductivity is also very complex because each material has a unique relation between moisture content and hydraulic conductivity, and these factors change constantly in response to climatic changes and water-level fluctuations. The water balance is represented in figure 27A. The infiltration of water from precipitation through the clay cap is the residual, I, in the following water balance equation:

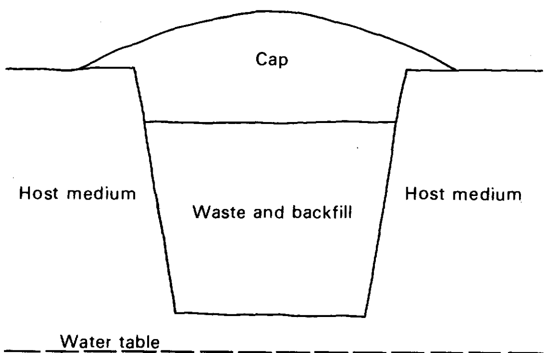
$$I = (S + P - O - E) - C$$

where

S = antecedent moisture content of clay cap,
P = precipitation,
O = surface runoff,
E = evapotranspiration, and
C = moisture storage capacity of the clay cap.

Infiltration into the clay cap could be reduced by increasing the runoff and the evapotranspiration. Trench caps are commonly mounded to increase runoff and are sowed with short-rooted plants to decrease erosion and increase evapotranspiration. Design features to decrease infiltration largely through the use of natural materials have been tested in experimental trenches at the Las Alamos National Laboratory, New Mexico (Hakonson and others, in press). It is anticipated that efforts to decrease infiltration through design of trench cap and cover will meet with greater success in arid and semiarid regions than in humid regions.

Trench-cap material of compacted nonswelling clay will reduce infiltration. The clay cap needs to be of sufficient thickness that desiccation cracks will not penetrate its full thickness. Runoff can only be increased so much before adverse effects of increased erosion become excessive. Vegetative cover, though consuming water, at



IDEALIZED RELATIVE HYDRAULIC CONDUCTIVITY (K) AND MEDIAN GRAIN SIZE (D) OF CAP, C, HOST MEDIUM, H, AND BACKFILL, B.

	CAP		HOST		BACKFILL
UNSATURATED (U) HYDRAULIC CONDUCTIVITY	K_{UC}	>	K_{UH}	>	K_{UB}
SATURATED (S) HYDRAULIC CONDUCTIVITY	K_{SC}	<	K_{SH}	<	K_{SB}
MEDIAN GRAIN SIZE	D_C	<	D_H	<	D_B

Figure 26. Diagrammatic trench repository and idealized relative unsaturated and saturated hydraulic conductivity and median grain size of trench cap, host medium, and backfill.

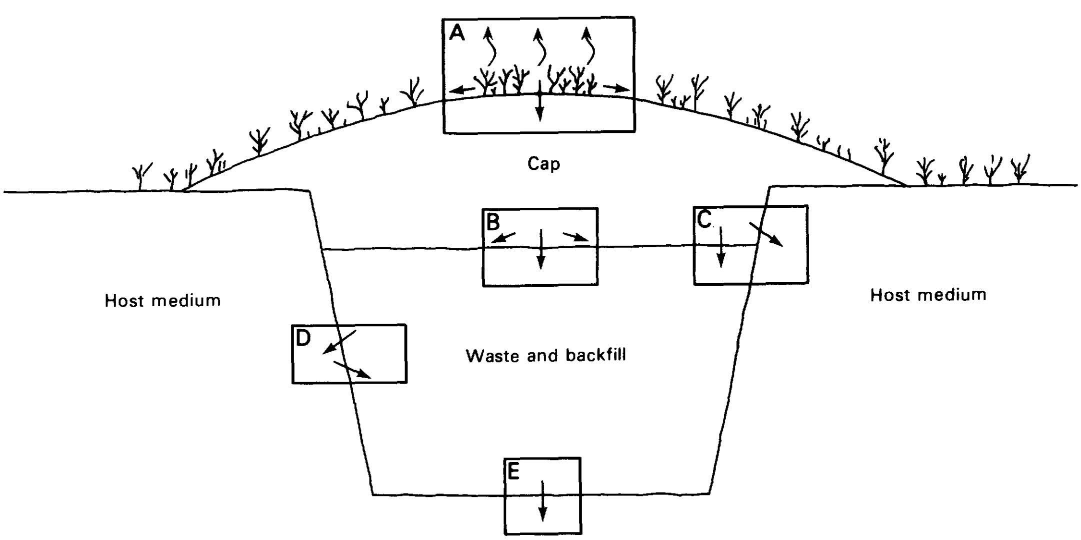


Figure 27. Diagrammatic sketch of hydrology of trench repository. (A) Net infiltration into clay cap is balance of precipitation minus runoff and evapotranspiration, plus or minus change in storage; (B) downward flow from clay cap to backfill may be impeded if backfill is at great moisture tension and low hydraulic conductivity; (C) lateral unsaturated flow of water in trench cap to host medium; (D) water may flow into or out of backfill depending on relative unsaturated hydraulic conductivities of backfill and host medium; (E) moisture in backfill must percolate downward into host medium or "bathtub effect" may occur.

the same time tends to retard runoff. Vegetative cover should be shallow rooted to avoid deep disturbance of the cap and penetration into the waste. Short-rooted vegetation is limited in capacity to transpire large quantities of water. Shallow-rooted plants in arid regions are much more efficient in consuming precipitation in excess of runoff than shallow-rooted plants native to humid regions.

Infiltration through the clay cap will be impeded by the coarse-grained backfill, when according to the moisture tension-hydraulic conductivity relation, the backfill is of lower hydraulic conductivity than the fine-grained cap layer (fig. 27B). If moisture content builds up in the clay cap, the permeability contrast between the clay cap and the host medium (fig. 27C) should permit lateral flow of water into the host medium, rather than flow between the cap and the backfill. A coarse-grained host medium of comparable unsaturated hydraulic conductivity to the backfill might, at times, create a capillary barrier between the cap and the host medium. The potential for flow of water through the near-vertical surface between the host medium and the backfill (fig. 27D) will depend largely on the relative hydraulic conductivity of the host medium and the backfill.

At the base of the trench, moisture in the backfill must percolate downward into the host medium or the so-called bathtub effect will occur. A sump of backfill at the base of the trench and beneath the lowermost waste package would provide a space for accumulation of moisture and provide sufficient hydraulic head to drive water from the base of the trench into the host medium (fig. 27E). At the base of the trench, ideally the host medium would be as permeable as the backfill. However, because the host medium should be fine-grained near the surface, the ideal fine-grained material at the surface and overlying coarse-grained material could tend to create a capillary barrier within the host medium.

Waste Repository in the Saturated Zone

Shallow-land disposal in the saturated zone may be preferable in some environments. In many humid and subhumid regions, the saturated zone commonly is no more than 5 or 10 m below the land surface. Cherry and others (1979) have proposed that low-level radioactive waste be disposed in unfractured, low-permeability clays in the saturated zone well below the zone of water-table fluctuation. In southern Canada, Cherry and others (1979) recommend burial of low-level radioactive waste in the bottom of large holes augered below the water table in dense, relatively unfractured clayey till and glaciolacustrine clay. In such an environment, contaminant movement would be predominantly by molecular diffusion. Cherry and others (1979) propose that in hydrologic studies of prospective repository sites in clayey deposits below the water table, the determination of the age of the ground water by means of naturally occurring isotopes—tritium, oxygen-18, deuterium, and carbon-14—be a key factor. The burial zones need to be determined to have pore water that is very old, thereby indicating extremely slow ground-water velocity and favorable natural conditions for containment of the waste. If such a site is used, as seen by the preceding example, the design criteria are considerably different than for a repository in the unsaturated zone. In the saturated zone, which is not subject to alternate wetting and drying, swelling clay such as bentonite provides a stable, low-permeability, high-sorption barrier to radionuclide migration.

The concept of Cherry and others (1979) has been applied hypothetically to the geohydrologic conditions at the low-level radioactive-waste burial site near West Valley, N.Y. (Prudic, in press) (fig. 8). This concept may be feasible at the site because ground-water velocity in the unweathered till is less than 6 cm/yr, which results in diffusion controlling radionuclide migration (Prudic, 1986). Analyses of radionuclides in water from till samples collected beneath three trenches indicate that detectable concentrations of tritium had migrated less than 3 m in 7 to 11 years. Assuming the water levels in a trench and the concentration of tritium in the trench water remains constant for 100 years, Prudic (in press) projected detectable concentrations of tritium to migrate only about 10 m beneath the trenches after 100 years (fig. 28), mostly by diffusion. Prudic considered projection beyond 100 years to be unreasonable because radioactive decay of tritium in the tenches probably would result in much smaller tritium concentrations in the trench water.

Buffer Zone and Flow System

The buffer zone, as defined in 10CFR61 is a "portion of a disposal site that is controlled by the licensee and that lies under the site and between the boundary of the site and any disposal unit." The repository, including the disposal units and the buffer zone, is thus part of the flow system. As a part of the flow system under control of the licensee, it is the zone in which remedial actions are most likely to be taken, if necessary.

Major natural barriers to radionuclide migration need to be present in the ground-water flow system in the buffer zone and beyond the repository to the natural discharge area. Factors that present major barriers to radionuclide transport include (1) those that result in long ground-water travel time—long flow paths, low hydraulic gradient, and large effective porosity, and (2) those that decrease the concentration of radionuclides in solution—such as decay, sorption, and minimal solubility of waste. Dispersion, diffusion, and dilution are processes that also decrease point concentrations of contaminants but do not decrease the quantity of contaminant in solution.

Site-suitability requirements of the U.S. Nuclear Regulatory Commission specify that the geohydrologic conditions of the area allow reliable performance predictions and that the geohydrologic system must be characterized to enable confident predictions of contaminant movement. Adequate characterization and reliable performance predictions are most readily achieved in areas with simple geohydrologic settings. Many problems of contaminant transport experienced at repository sites stem from complex geologic conditions and hydraulic properties that were not adequately defined; consequent investigations were unable to predict or anticipate the contaminant transport that occurred. The complex distribution of the pebbly sand unit at the burial site near Sheffield, Ill., of the fractured nature of the sandstone beds at Maxey Flats, Ky., and of the heterogeneity of the regolith at Oak Ridge National Laboratory, Tenn., can be cited as instances where the rapid transport of radionuclides to the surface environment was not predicted accurately because of complexities of the ground-water flow system and inadequacies in characterization and analysis of the system.

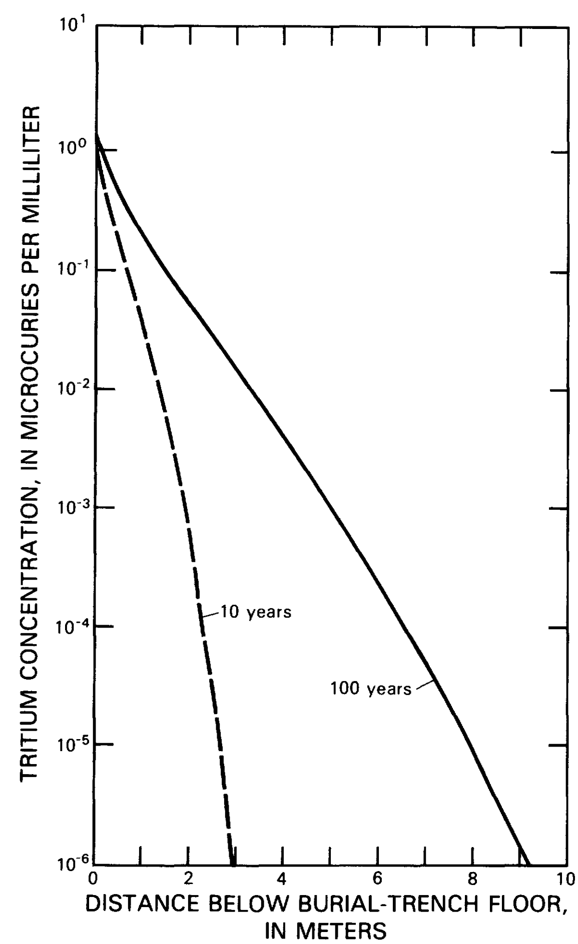


Figure 28. Predicted tritium concentrations beneath trench after 10 and 100 years assuming: constant concentration of 1.44 microcuries per milliliter in trench water, constant water level in trench, porosity of 0.3, specific flux of 0.7 centimeter per year, tortuosity factor of 1.6, diffusion coefficient of water of 475 square centimeters per year, distribution coefficient of 0.0 liter per gram (from Prudic, 1986).

Containment of radioactive waste within the repository for the hazardous lifetime of the waste, with or without engineered barriers, is not considered practicable. The site needs to be selected so the natural geohydrologic flow system affords isolation of the waste from the surface. Monitoring and maintenance of the repository site will be provided for an indefinite period generally considered not to exceed 100 years. Beyond this time, natural processes need to afford adequate isolation time for the waste. Engineered features of the site need to not interfere with the natural isolation afforded by the geohydrologic setting. This principle is emphasized because many engineered barrier systems do not appear to be effective unless continually maintained. For example, drains and sumps collecting infiltration on concrete or impermeable bases require continual maintenance. If infiltration into the repositories occurs and the sumps are not emptied periodically, the repository will emulate the "bathtubs" of the current generation of trench repositories.

The ground-water flow system needs to provide long flow paths with long travel times from the repository. Long travel times may be afforded by low to moderately permeable materials, low hydraulic gradients, or geochemical environments which retard migration of radionuclides.

Hydrologic Modeling

The technical position of the U.S. Nuclear Regulatory Commission (1982) requires that the site can be characterized adequately to model the site to demonstrate compliance with performance objectives and that the natural processes affecting the site be defined such that the modeling of the site represent both present and anticipatable site conditions after closure (Siefken and others, 1982). From the considerations reviewed in this report, it is concluded that modeling of a repository site cannot be done with sufficient confidence for it alone to be used to confirm that a site will be acceptable as a repository site.

The practice customarily followed in design, verification, and analysis of a ground-water model includes, initially, definition of the geology, geochemistry, and hydrology of the ground-water flow system from previous studies and field exploration studies designed to complete the characterization of the system. This first step provides data for definition of the hydraulic and geochemical parameters of the flow system—the framework of the model. The second step is model simulation of stress and response of the system, providing a basis for refinement of the model, a process called calibration of the model. In practice, the historical data on stress and response of the system may be divided by use of part of the data to revise the hydraulic and geochemical parameters of a model and use of the other part of the data to test the ability of the model to simulate the response to stress.

The accuracy of models to simulate the response to stress has recently been examined by Konikow (1987), who examined several cases in which deterministic ground-water flow or solute-transport models were used to make predictions. Konikow (1987) found

> In general, the results of these postaudits did not yield a high correlation between observed and predicted changes. In one case, a 1-year period of detailed observation provided an inadequate basis to predict longer term (10 year) changes in ground-water salinity in an irrigated stream-aquifer system. In another example, it was shown that a 40-year calibration period, in itself, did not provide a reliable basis for predicting changes in ground-water levels for a 10-year period. Although these examples are neither exhaustive in scope nor firmly conclusive in implications, they at least call into question the credibility and validity of predictions of heads and contaminant transport in ground water for perhaps tens, hundreds, or thousands of years in areas where there may be no historical observations, as is required for nuclear-waste isolation.

Konikow (1987) concludes that a large component of the error arises from an overly simplistic approximation of a complex three-dimensional heterogeneous world, but points out that much of the predictive error is attributable to error in the assumed future stresses. It is noted that among the unknowns in the case of a low-level radioactive-waste repository are the future stress on the system and the hydraulic and geochemical properties of the future system as the site is excavated and reassembled as waste, backfill, and trench cap.

Modeling of flow and transport in the unsaturated zone is complex, and models to simulate such conditions are limited. The problems presented in modeling geochemical reactions in an aquifer system are discussed by Thorstenson (in press), who pointed out that none of the modeling efforts he reviewed have produced a completely definitive model in spite of large expenditures of time, effort, and dollars. He concludes that models based solely on aqueous geochemistry are nonunique. Estimates of radionuclide transport are commonly based on flow models and empirical values for sorption of radionuclides based on laboratory experiments rather than data on the chemical nature of the aquifer system under examination.

Thus, from experience with postaudits of ground-water flow models and considering the status of unsaturated flow, geochemical reaction, and transport models, it is apparent that modeling of a potential site is not feasible as the sole means of providing a definitive presite operational performance assessment. Models, however, can play an important and essential role in the overall evaluation of the site during the site selection phase and in evaluation of the operational and postoperational performance of the repository. Such use would need continued revision and refinement of the models. The process of model revision needs to be based not only on routine surveillance but also data collected for the purpose of revising the model periodically during the operational and postoperational phases of the repository.

CONCLUSIONS

Lessons Learned

Experience at low-level radioactive-waste repository sites provides many lessons that can be applied in evaluation of future waste sites, in application of geologic and hydrologic principles to the design of low-level waste facilities, and in monitoring of low-level waste sites in order to evaluate site performance. Some lessons learned are given below.

1. Simple trench repositories filled with waste and backfilled and capped by excavated materials have been constructed at low-level radioactive-waste disposal sites in arid, subhumid, and humid climates in the United States. The performance of repositories in these environments differs markedly in effectiveness of waste containment. The simple engineering design at Beatty, Nev., in an arid climate is apparently adequate, but similar designs at sites in the eastern part of the United States in humid and subhumid climates generally have not performed as well in containing waste.

2. Backfill of waste containers and the integrity of waste containers in resisting compaction plays a large role in the integrity of the capping materials. The collapse problems at the site near Sheffield, Ill., are more completely documented than the other sites, although subsidence and settlement cavities have presented problems also at West Valley, N.Y., Maxey Flats, Ky., and Oak Ridge National Laboratory, Tenn. At each of these sites, trenches have been backfilled with materials containing a large clay fraction. In contrast, current practice at the site near Barnwell, S.C., is to backfill with sand, a material having much less compactibility than clay. Collapse features at Barnwell, S.C., are reported by the operator to be of minor occurrence; data on frequency and volume of collapse are not available.

It was determined from the review of site histories that the construction of clay caps has undergone changes in development in attempts to create a cap which limits infiltration and surface runoff. Caps at the disposal site near Sheffield, Ill., greatly reduced infiltration even though compaction of the capping material was largely a byproduct of operating heavy machinery over the trenches in backfilling the waste and laying the caps. At West Valley, N.Y., compaction of the clay caps was employed specifically to decrease infiltration; compaction methods included load surcharging of the trench cap with material excavated in constructing successive trenches. Infiltration into the trenches at West Valley, N.Y., was decreased, but not to the extent required, and water accumulation in the trenches has been periodically pumped out to prevent overflow. Deterioration of the clay caps has been effected by compaction of the waste, backfill, and shrinkage cracks developed during prolonged periods of dry weather.

3. The hydrologic regime of a site is profoundly effected by construction and engineered features of the waste facility. Studies of the presite operational hydrology are useful and necessary but do not provide direct information on all significant aspects of the hydrology of the site during operation and after closure. For example, disturbance of the site during operation has been shown to affect infiltration at the site and that infiltration may increase or decrease. The effect of trench-cap materials and construction practices on infiltration at the waste site is a question that cannot be answered definitively prior to construction.

4. Suitability of a repository is a function of both the site characteristics and the engineering design and construction of the repository and the waste packages. With the possible exception of the extremely arid environments, there are no intrinsically well-suited geohydrologic environments; likewise, there are no intrinsically well-suited engineered barrier systems.

5. Low-permeability materials are severely limited as suitable host media for low-level radioactive waste in the unsaturated zone. Both the scientist and the layman seem predisposed to select rocks of low permeability as host media for low-level waste. What would be better than to isolate waste in a low-permeability matrix? The problem is that the low-permeability host medium in the coventional low-level radioactive-waste repository does not enclose the waste. The capping materials are not impermeable; experience has shown that they permit infiltration and will become more permeable with time. Moreover, experience indicates that infiltration capacity of a trench cap will increase with time due to biological activity and weathering. The resulting phenomenon is increased infiltration and accumulation of water in the trench, commonly referred to as the "bathtub effect," because the low-permeability host media will not permit the repository to drain as rapidly as water infiltrates the repository. Saturation of the waste promotes its weathering and leaching. Filling of the trench with water results in either overflow of the trench and rapid overland transport of leachate or subsurface migration of radionuclides in the weathered zone of the host rock.

6. Humid and subhumid regions characterized by moderate to large infiltration of precipitation, shallow depths to the water table, and relatively short flow paths to discharge areas are not well suited for the shallow isolation of low-level radioactive waste in the unsaturated zone; arid regions characterized by zero or small infiltration from precipitation, great depths to the water table, and long flow paths to natural discharge areas are naturally well suited to the isolation of low-level radioactive waste.

7. Consolidated rocks of sedimentary, metamorphic, or igneous origin, weathered zones or regoliths of consolidated rocks, and a thin veneer of unconsolidated sedimentary deposits overlying consolidated rocks at shallow depths are poorly suited for the trench disposal of low-level radioactive waste. Thick sequences of unconsolidated deposits having interstitial porosity and permeability are better suited to the disposal of low-level radioactive waste at shallow depths.

Geohydrologic Screening and Site Selection

The following possible alternatives are listed concerning the geohydrologic screening of regions for prospective low-level radioactive-waste repository sites and selection of sites for characterization:

1. Distinguish between geohydrologic criteria for unsaturated and saturated zone burial of waste. For trench disposal in the unsaturated zone, it is desirable that depths to ground water be 15 m or greater.

2. Potential host media in the saturated zone are low-permeability materials in which the rate of transport of radionuclides by diffusion will be greater than that by advection. Host media essentially need to be homogeneous, relatively thick (greater than 20 m) clay. The burial depth needs to be a few meters beneath the weathered zone. Low-permeability capping material needs to extend to below the weathered zone. Consolidated sedimentary, igneous, and metamorphic rocks are not considered suitable host media because of the likelihood of fractured or channel-like flow paths.

3. Potential host media in the unsaturated zone needs to be unconsolidated, granular, bedded, primary sedimentary material with moderate permeability. Host media could be beneficially overlain by low-permeability beds of clay. Consolidated rocks, weathered material, and regolith are considered undesirable host media.

4. Flow system characteristics need to include long flow paths and travel times from the repository to the discharge area. Flow direction needs to be vertically downward in the repository area. Radionuclide isolation time in the repository and the buffer zones needs to be 300 to 500 years.

5. Natural materials that will provide adsorption of radionuclides need to be present in the flow system downgradient from the waste units.

Repository Construction and Maintenance

The following recommendations are made concerning repository construction and maintenance:

1. Repositories need to be excavated to depths allowing burial either fully above the highest fluctuation of the water table or below the lowest fluctuation of the water table.

2. Repositories need to be constructed to provide for burial of waste in unweathered sections of the host media.

3. Trench or auger hole caps above the water table need to be of low-permeability, nonswelling, compacted clay of sufficient thickness to extend below the weathered section of the host medium. Maintenance of the repository needs to provide for prompt filling and tamping of cavities or general subsidence as they occur for the hazardous life of the waste.

4. Backfill of waste packages in the unsaturated zone needs to be with noncohesive, coarse-grained material (that is, medium to coarse sand), free from clay and silt. The backfill needs to fill a thickness of from 1 to 5 m of the trench below the lowest level and above the highest level of the waste.

5. Vegetation of the trench caps needs to be limited to shallow-rooted plants such as grasses.

Subsurface Monitoring and Modeling at Low-Level Radioactive-Waste Repository Sites

Subsurface monitoring at low-level radioactive-waste repository sites may be thought of as being part of the three major phases of a repository site, namely, (1) the characterization phase, (2) the constructional and operational phase, and (3) the postoperational closure phase. As the name implies, monitoring consists of repeated or periodic measurements of hydrologic conditions at selected locations. A subsurface monitoring network is a number of discrete points selected to provide a basis for evaluating changes in processes that occur in a continuum throughout the study region. Monitoring at low-level radioactive-waste repository sites has been comprehensively discussed in a series of reports prepared for the U.S. Nuclear Regulatory Commission. The first report (Lutton and others, 1982b) identifies (1) the parameters that should be investigated and evaluated to determine the suitability of a site, (2) the parameters needed for design and construction of a repository, and (3) the parameters needed to be monitored to evaluate the performance of a disposal facility. The second report (Lutton and others, 1982a) identifies recommended laboratory and field tests for determining the parameters identified in the first report. The third report (Lutton and others, 1983) recommended a program for monitoring during site characterization, construction, operation, and closure. In each of the phases of site activity, the monitoring network can be implemented by hydrologic and geochemical models to assist in evaluating the magnitude and rates of changes occurring throughout the region of interest and to predict the future performance of phenomena within the region. Neither monitoring nor modeling activity provides the whole picture; together these activities can be used conjunctively for mutual enhancement and refinement.

Collection of hydrologic information on the repository site and the flow system needs to continue from the characterization phase through the operational and postoperational phases. Although it is concluded that definitive models cannot be made during the characterization phase, hydrologic models of the flow system are an essential continuing part of the analysis of site performance and an essential tool in early detection and projection of radionuclide migration from the disposal units. The U.S. Nuclear Regulatory Commission (1982) requires monitoring to provide an early warning of radionuclide migration. It is here suggested that hydrologic models are needed, and they need to be maintained and refined concurrently with the monitoring program. Hydrologic models, if revised and refined on the basis of a carefully designed monitoring program can provide increasingly accurate projections of rates of radionuclide movement and a basis for anticipating the need for mitigating or remedial action.

Engineered Barrier Systems

There are neither experimental nor experiential real-time bases for long-term projections regarding the effectiveness of engineered barriers for long-term containment of radionuclides. Engineered barriers may serve a useful purpose for a limited period of time, but they need not be designed in any way that will ultimately reduce the effectiveness of the natural hydrologic system in isolating the waste from the environment. Engineering barriers including those designed to isolate the waste, drain the repository, stabilize the waste or the repository, or prevent the waste from coming in contact with moisture cannot be relied upon to provide long-term (300 to 500 years) isolation for the radioactive life of the waste.

The inherent limitations in the life of engineered barriers for waste isolation and limitations of modeling capability to predict the rate of release and migration of the waste emphasize the need for independent engineered and natural barriers for waste isolation.

Institutional control and maintenance of low-level radioactive-waste repositories are expected to cease by 100 years following closure of the waste site (U.S. Nuclear Regulatory Commission, 1982). Beyond this time, the repository and the geohydrologic conditions need to act passively to effectively isolate the radionuclides for an additional 300 to 500 years. Most engineered barrier systems appear to have been designed independently of the natural geohydrologic conditions. Furthermore, many engineered systems need maintenance in order to perform as designed.

For example, systems that are impermeable containers with drainage sumps could adversely affect the repository if not maintained. Moisture continuing to accumulate will saturate the waste and overflow, releasing radionuclides to the environment. Such problems need to be addressed in evaluation of engineering design of repository facilities.

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Metric Conversion Factors

For readers who wish to convert measurements from the metric system of units to the inch-pound system of units, the conversion factors are listed below.

Multiply metric unit	By	To obtain inch-pound unit
millimeter (mm)	0.03937	inch
centimeter (cm)	0.3937	inch
centimeter per year (cm/yr)	0.3937	inch per year
meter (m)	3.281	foot
meter per day (m/d)	3.281	foot per day
meter per year (m/yr)	3.281	foot per year
cubic meter (m^3)	35.31	cubic foot
kilometer (km)	0.6214	mile

The following terms and abbreviations also are used in this report:

microcurie per milliliter (μCi/mL)
picocurie per liter (pCi/L)

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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