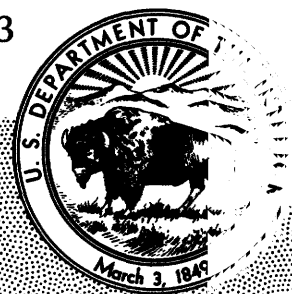


U.S. GEOLOGICAL SURVEY CIRCULAR 973



**Hydrogeologic Factors in the Selection of
Shallow Land Burial Sites for the Disposal
of Low-Level Radioactive Waste**

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By John N. Fischer

U.S. GEOLOGICAL SURVEY CIRCULAR 973

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director



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First printing 1986
Revised 1989

Library of Congress Cataloging in Publication Data

Fischer, John N.

Hydrogeologic factors in the selection of shallow land burial sites for the disposal of
low-level radioactive waste.

(U.S. Geological Survey circular ; 973)

Bibliography:

Supt. of Docs. no.: I 19.4/2:973

1. Hydrogeology. 2. Water, Underground—United States. 3. Radioactive waste
disposal in the ground—United States. I. Title. II. Series.

GB1005.F57 1989 621.48'38 85-600272

Free on application to the Books and Open-File Reports Section,
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CONVERSION FACTORS AND ABBREVIATIONS

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

<i>Multiply</i>	<i>By</i>	<i>To obtain</i>
inch (in.)	2.540	centimeter (cm)
foot (ft)	.3048	meter (m)
yard (yd)	.914	meter (m)
mile (mi)	1.609	kilometer (km)
cubic yard (yd ³)	.7645	cubic meter (m ³)
nanocurie (nCi)	37	becquerel (Bq)

Hydrogeologic Factors in the Selection of Shallow Land Burial Sites for the Disposal of Low-Level Radioactive Waste

By John N. Fischer

Abstract

In the United States, low-level radioactive waste is disposed of by shallow land burial. Commercial low-level radioactive waste has been buried at six sites, and low-level radioactive waste generated by the Federal Government has been buried at nine major and several minor sites. Several existing low-level radioactive waste sites have not provided expected protection of the environment. These shortcomings are related, at least in part, to an inadequate understanding of site hydrogeology at the time the sites were selected.

To better understand the natural systems and the effect of hydrogeologic factors on long-term site performance, the U.S. Geological Survey has conducted investigations at five of the six commercial low-level radioactive waste sites and at three Federal sites. These studies, combined with those of other Federal and State agencies, have identified and confirmed important hydrogeologic factors in the effective disposal of low-level radioactive waste by shallow land burial. These factors include precipitation, surface drainage, topography, site stability, geology, thickness of the host soil-rock horizon, soil and sediment permeability, soil and water chemistry, and depth to the water table.

INTRODUCTION

In the United States, the term "low-level radioactive waste" (LLW) means radioactive material that (1) is not high-level radioactive waste, spent nuclear fuel, or byproduct material (as defined by the Atomic Energy Act of 1954) and (2) the U.S. Nuclear Regulatory Commission (NRC), consistent with existing law and in accordance with (1) above, classifies as LLW (U.S. Congress, 1986).

Low-level radioactive waste consists of a wide variety of material including clothing, animal carcasses, glassware, ion-exchange resins, piping and valves, and paper. Although LLW also is generated in liquid form, the NRC regulation for LLW disposal, Chapter 10 Code of Federal Regulations Part 61 (10 CFR Part 61) (U.S. Nuclear Regulatory Commission, 1960a) requires that liquid LLW be solidified or packaged in material that can absorb twice the volume of liquid present before the LLW is disposed of at a licensed facility. In addition, 10 CFR Part 61 also requires that the amount of liquid in solid LLW be minimized and, in all cases, be less than 1 percent by volume. Most LLW is generated at commercial nuclear power plants; the remainder originates primarily at research laboratories, hospitals, industrial facilities, and universities.

LLW does not generate significant heat in radioactive decay. Table 1 lists the half-lives of typical radionuclides in LLW. Radionuclides decay to 1/10,000 of their original activity after 10 half-lives. However, for some radionuclides, 10 half-lives require the passage of substantial periods of time. For this reason, maximum concentrations are specified for all radionuclides in LLW so that, at the end of a 500-year period, radioactivity will be at a level that does not pose an unacceptable hazard to public health and safety (U.S. Nuclear Regulatory Commission, 1960a).

In the United States, there are six sites where commercially produced low-level wastes have been or are being disposed of. The Department of Energy (DOE) operates LLW disposal sites for waste that is generated through Federal activities. Figure 1 shows the locations

TABLE 1.—*Half-lives and predominant sources of typical radionuclides contained in low-level radioactive waste*
[Modified from U.S. Department of Energy, 1983. —, no data]

Radionuclide	Half-life	Predominant source of radionuclides		
		Nuclear power reactors	Industry	Institutional
Carbon-14	5770 years	—	X	—
Cesium-134	2.2 years	X	—	—
Cesium-137	30 years	X	X	—
Chromium-51 ...	27.8 years	X	—	—
Cobalt-58	71 years	X	—	—
Cobalt-60	5.3 years	X	—	—
Iodine-125	60 days	—	X	X
Iodine-131	8.1 days	X	—	—
Iridium-192	74 days	—	X	X
Manganese-54...	291 days	X	—	—
Strontium-90	28 years	X	—	—
Technetium-99 ..	2.1×10^5 years	X	—	—
Tritium	12.3 years	—	X	X
Uranium-238	4.5×10^9 years	—	X	—
Zinc-65	245 days	X	X	—

of major LLW disposal sites. Of the six commercial sites, those at Barnwell, S.C., Beatty, Nev., and Richland, Wash., remain open at the time of this report (table 2).

The site at Sheffield, Ill., was closed in 1978 when it reached licensed capacity. The commercial disposal site at West Valley, N.Y., ceased disposal operations in 1975 because of water accumulation in the trenches, but the adjacent burial ground formerly licensed by NRC continues to store LLW that is generated on site as a result of site clean up and water treatment operations. The site at Maxey Flats, Ky., ceased disposal operations in 1978 when contaminated water from trenches was discovered to be moving through fractures and along bedding planes in the subsurface (Zehner, 1983). No adverse health effects from the migration of low-level radioactive waste at any commercial or DOE-operated sites have been documented.

In 1986, about 67,000 yd³ of LLW were buried at commercial disposal sites, and about 127,000 yd³ were buried at DOE sites (U.S. Department of Energy, 1987) (table 3). Figure 2 shows volumetric distribution of LLW by site through 1986. Increased efforts to separate radioactive from nonradioactive waste and to compact waste resulted in a decrease in commercial disposal volumes from 1983 through 1986. Further decreases in

volume will occur in the near future due to these efforts. It is uncertain, however, how long this trend will continue.

In the United States, LLW is disposed of by shallow burial in trenches excavated into the natural land surface. In some cases, however, fill has been used to create terrain for trenches. The dimensions of most trenches depend on topography and other local conditions and range from 25 to 50 ft wide, 20 to 50 ft deep, and 125 to 800 ft long. Soil, sediment, and rock structure and stability dictate the slope of trench walls and the spacing between trenches. Trenches are separated by at least 5 ft of undisturbed earth material. Vertical trench walls are preferable because void spaces between the waste and trench walls can be minimized; however, vertical walls frequently are not mechanically achievable because of the instability of host material. Trench bottoms are sloped. A 6- to 8-in. layer of sand is commonly placed on the trench bottom to convey any water that may reach the bottom into french drains and sumps at one side of the trench for removal through shallow wells. Trenches filled with waste are covered with sediment having a high clay content.

Clay-dominated sediments, because of their structure and other physical characteristics, generally have low permeability; this low permeability can reduce the infiltration of water into the trench. The surface of the filled site is contoured to facilitate runoff and to minimize erosion. The trench construction process shown in figure 3 is typical for trenches at the commercial LLW site near Barnwell, S.C. Natural features of the burial environment, such as sediment characteristics and thickness of the unsaturated zone, influence the movement of contaminants away from the waste disposal sites. There are several mechanisms through which this movement can occur. These mechanisms include emission of gases by decaying waste, erosion of overlying soil, tectonic activity, the actions of burrowing rodents, and contaminant transport by ground water. The earth-science community generally agrees that, in a properly selected and designed facility, ground-water transport is the most significant mechanism for LLW migration, although other mechanisms may be important under specific circumstances.

In 1980, the National Low-Level Radioactive Waste Policy Act (PL 96-573) established, as Federal policy, that "each State is responsible for providing for the availability of capacity either within or outside the State for the disposal of low-level radioactive waste generated within its borders * * *" except for waste generated as a result of Federal activities. To provide the necessary disposal capacity, the Act encourages the formation of regional compacts among States to develop new LLW

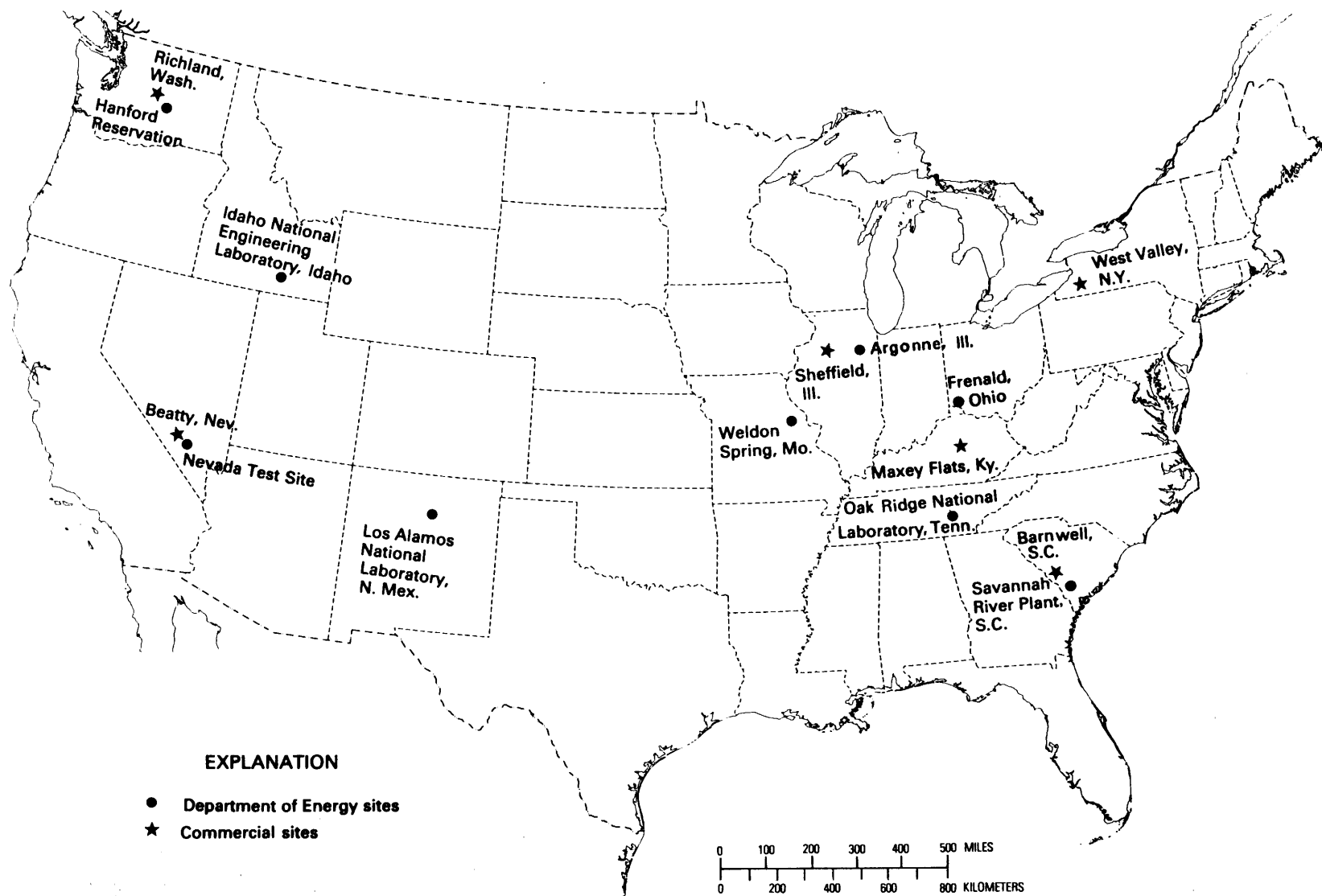


FIGURE 1.—Location of commercial and major Department of Energy low-level radioactive waste burial sites in the United States.
(Modified from Clancy and others, 1981.)

TABLE 2.—*Information about commercial low-level radioactive waste burial sites*

[Modified from Clancy and others, 1981]

Site	Year opened	Licensed land area (acres)	Current status
Beatty, Nev.	1962	79	Open.
Maxey Flats, Ky.	1963	255	Closed in 1978.
West Valley, N.Y.	1963	25	Closed in 1975.
Richland, Wash.	1965	100	Open.
Sheffield, Ill.	1967	20	Closed in 1978.
Barnwell, S.C.	1971	259	Open.

sites and grants to participating States the authority to reject waste from other States with which regional agreements do not exist. As a result of the Act, State compacts have been formed, and efforts are under way to establish new LLW sites.

The U.S. Geological Survey (USGS) has conducted hydrogeologic investigations at all the commercial LLW disposal sites, except the site at Richland, Wash. The USGS also conducted major hydrogeologic investigations at three DOE sites (Argonne, Ill., and Oak Ridge, Tenn., National Laboratories, and the Idaho National Engineering Laboratory). In addition, the DOE, NRC, the Environmental Protection Agency (EPA), and many State agencies have conducted research and other site investigations related to LLW disposal at most of the LLW sites. The objectives of the investigations and research, many of which were conducted cooperatively between agencies, were to describe the hydrogeology of the sites and to gain a better understanding of the hydrogeologic factors and processes that influence the transport of radionuclides from the sites. Reports resulting from these investigations are included in the selected references section of this report.

Existing LLW sites, studies of which provided the basis for much of the information in this report, were licensed before promulgation of the NRC regulation for LLW disposal (10 CFR Part 61). NRC developed this regulation on the basis of experience at the existing sites to improve performance at future disposal facilities.

Purpose and Scope

This report summarizes information gathered in LLW site studies and identifies and quantifies hydrogeologic factors that influence the transport of radionuclides from LLW disposal sites. These hydrogeologic factors are important in the selection of sites for any type of disposal or storage of LLW (for example, shallow land burial,

above-ground vaults, or warehouses). If contaminants escape into the environment from any system, the natural features of the site must provide adequate protection from exposure. The information in this report will be valuable to regional State compacts, other State and Federal agencies, and land and waste managers who are involved in the difficult process of selecting, evaluating, designing, and operating LLW disposal sites.

Acknowledgments

The information in this report is based primarily on hydrogeologic investigations conducted at LLW disposal sites by the following scientists, past and present employees of the USGS: Jefferson C. Bagby, Jack Barracrough, Marcel P. Bergeron, James M. Cahill, James B. Foster, George Garklavs, John R. Gray, Richard W. Healy, Roger Jensen, Kenneth L. Kipp, Barney D. Lewis, Bryan B. McDonald, David Morgan, Peter S. Murdoch, James R. Nicholas, William D. Nichols, Julio C. Olimpio, David E. Prudic, John B. Robertson, Barbara J. Ryan, David Webster, and Harold H. Zehner.

HYDROGEOLOGIC FACTORS

Current regulations require that LLW disposal facilities be sited, designed, and operated in a manner that minimizes the contact of water with the disposed waste. This requirement exists because analyses have shown that the principle potential pathway to the environment and the public is by ground-water transport. Such transport can result in potential environmental exposure to radiation. Geomorphologic processes and container degradation can result in contact between LLW and the disposal-site sediment-rock-water system prior to the time that the waste ceases to present an unacceptable hazard to public health and safety and the environment. The assumption that such contact can occur must be made, not only for disposal located near surface trenches, but also for all other types of LLW disposal and storage. When the contact occurs, and later, when transport begins, the natural environment at the site must protect the biosphere from unacceptable contaminant transport and exposure. Therefore, effective disposal of LLW requires a thorough understanding of the hydrogeology of the disposal or storage site.

The natural site environment is influenced by hydrogeologic factors, several of which are interrelated. Surface runoff and erosion, for example, are dependent variables of precipitation, soil characteristics, and topog-

TABLE 3.—*Historical annual additions and cumulative volume of low-level radioactive waste at commercial sites and at selected U.S. Department of Energy sites*

[Volume in thousands of cubic yards; —, no data. Data modified from U.S. Department of Energy, 1987]

Commercial sites									
Year	Beatty, Nev.	West Valley, N.Y. ¹	Maxey Flats, Ky. ²	Richland, Wash.	Sheffield, Ill. ³	Barnwell, S.C.	Annual addition	Cumulative volume	
Through 1975...	68.7	91.4	155.5	14.7	72.6	77.7	—	480.6	
1976	5.1	—	18.0	3.8	17.6	52.6	97.7	577.7	
1977	6.2	—	.6	3.6	23.1	59.7	93.2	670.9	
1978	11.6	—	—	9.7	2.3	80.5	104.1	775.0	
1979	8.5	—	—	15.9	—	82.5	107.9	882.9	
1980	16.6	—	—	32.5	—	71.6	120.7	1,003.6	
1981	4.4	—	—	53.3	—	51.6	109.3	1,112.9	
1982	2.0	—	—	51.8	—	45.5	99.3	1,212.2	
1983	1.5	—	—	52.9	—	46.0	100.4	1,312.6	
1984	2.7	—	—	50.3	—	45.6	98.6	1,411.2	
1985	1.8	—	—	52.5	—	45.0	99.3	1,510.5	
1986	3.5	—	—	24.6	—	⁴ 38.7	66.8	1,577.3	
Total.....	132.6	91.4	174.1	365.6	115.6	697.0			
Selected U.S. Department of Energy sites									
Year	LANL ⁵	INEL ⁶	NTS ⁷	ORNL ⁸	HANF ⁹	SRP ¹⁰	All other	Annual addition	Cumulative volume
Through 1975...	172.1	111.4	10.9	237.4	457.7	352.0	530.0	—	1,872
1976	11.5	8.1	3.8	5.0	6.1	10.6	23.6	68.7	1,941
1977	4.7	8.5	1.2	3.1	14.1	19.2	7.1	57.9	1,999
1978	9.8	8.8	17.0	2.6	12.9	20.3	8.5	79.9	2,079
1979	6.4	6.9	44.5	2.7	20.7	23.8	5.0	110.0	2,189
1980	6.3	6.7	16.2	2.6	13.9	25.6	4.4	75.7	2,265
1981	7.2	4.1	19.1	1.8	16.9	26.3	5.5	80.9	2,346
1982	6.0	3.9	51.3	1.7	15.3	29.3	9.9	117.4	2,463
1983	4.2	6.5	34.8	2.4	23.5	34.9	13.3	119.6	2,583
1984	7.1	5.0	15.8	2.9	24.5	34.1	28.9	118.3	2,701
1985	8.8	4.1	51.5	2.9	22.2	39.9	29.2	158.6	2,860
1986	5.9	4.4	23.4	2.4	27.7	39.4	23.7	126.9	2,987
Total	250.0	178.4	289.5	267.5	655.5	655.4	689.1		

¹Includes waste at both the commercial State-licensed site and an adjacent NRC-licensed facility. Ceased disposal operations in 1975.

²Closed in 1975. Volumes thereafter resulted from site cleanup.

³Closed in 1978.

⁴Preliminary data.

⁵Los Alamos National Laboratory.

⁶Idaho National Engineering Laboratory.

⁷Nevada Test Site.

⁸Oak Ridge National Laboratory.

⁹Hanford Reservation.

¹⁰Savannah River Plant.

raphy. These and other hydrogeologic factors, such as the depth to the water table, proximity of surface water bodies, ambient water quality, hydraulic con-

ductivity, and hydraulic gradient, form a hydrogeologic system that governs the transport of radionuclides in the subsurface.

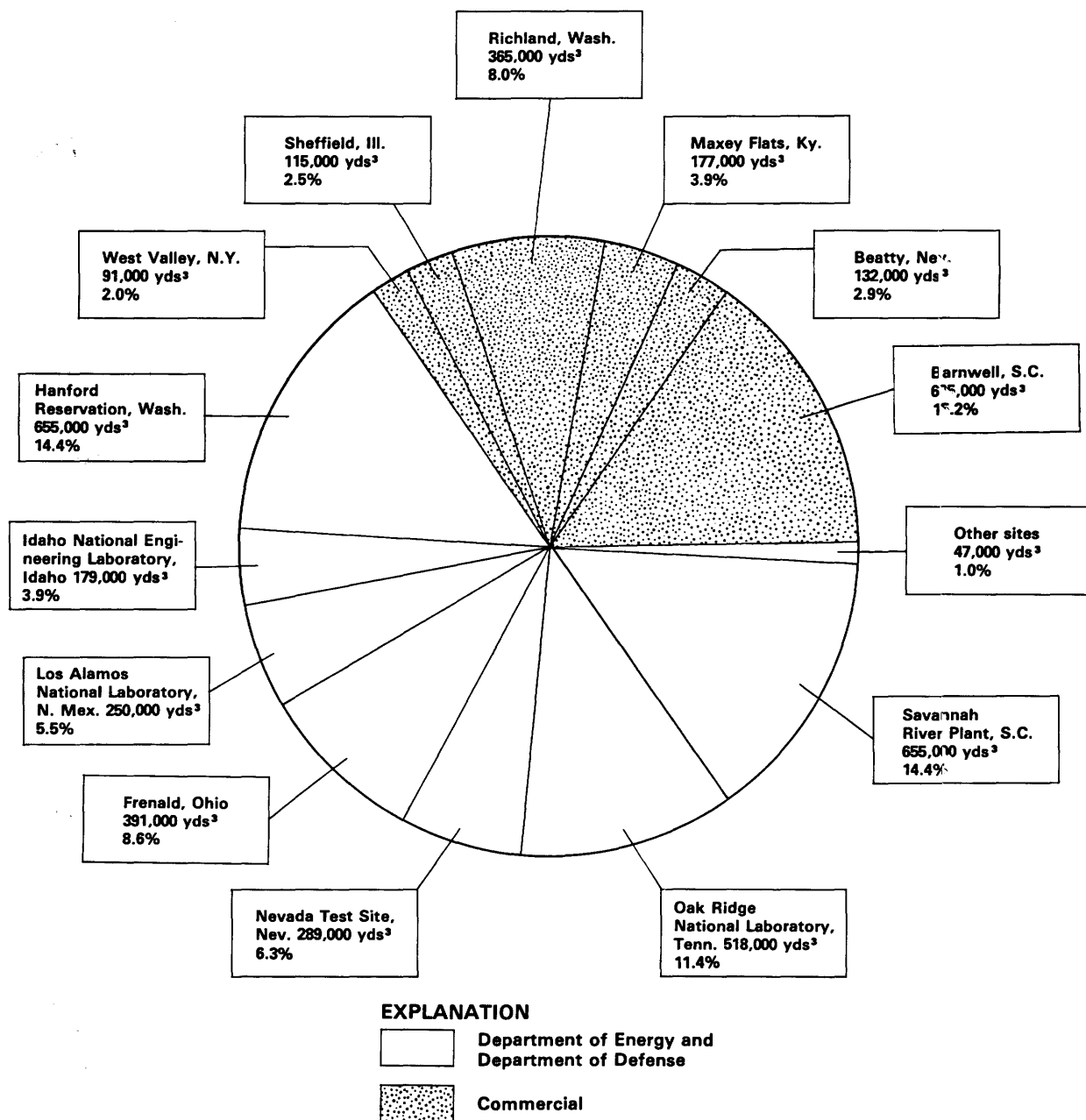
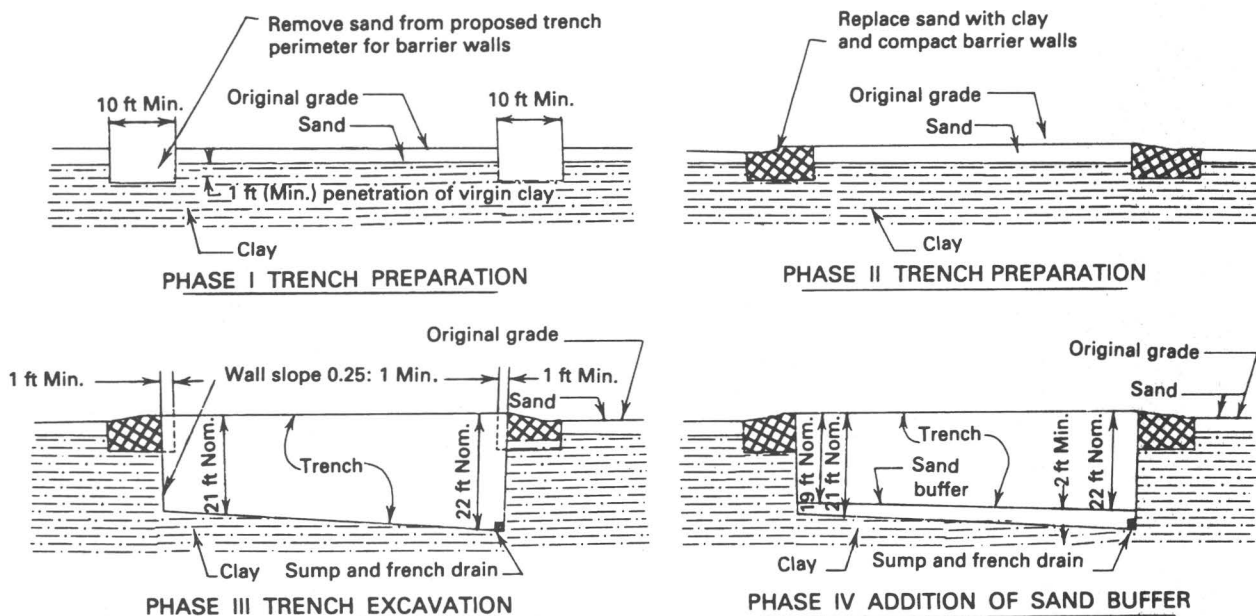


FIGURE 2.—Volumetric distribution of low-level radioactive waste, by site, through 1986, in cubic yards and percentage. (Modified from U.S. Department of Energy, 1987.)

Precipitation

Studies have demonstrated that water is the primary transporter of contaminants away from LLW burial sites (U.S. Nuclear Regulatory Commission, 1982). Because precipitation is the source of water, sites in areas of low annual precipitation have less potential for waste transport by water than areas that have high amounts of

precipitation. In the United States, areas of lowest annual precipitation are in the West (fig. 4). The LLW site at Beatty, Nev., for example, receives an average of 2.9 in. of precipitation annually (W.D. Nichols, U.S. Geological Survey, written commun., 1984); the average annual precipitation at the Richland, Wash., and Idaho National Engineering Laboratory sites is 6.3 in. and 8.5 in., respectively (Clancy and others, 1981). In



BARNWELL DISPOSAL TRENCH CONSTRUCTION TECHNIQUE

FIGURE 3.—Cross sections showing construction processes for a typical low-level radioactive waste burial site near Barnwell, S.C. (From Clancy and others, 1981.)

contrast, at eastern commercial sites near West Valley, N.Y., Maxey Flats, Ky., and Barnwell, S.C., average annual precipitation is 39 in. (Prudic, 1985), 47 in. (Zehner, 1985), and 47 in. (Cahill, 1982), respectively.

Although a high precipitation rate increases the probability of transport in the biosphere, such a rate need not eliminate a prospective LLW site because the combination of natural characteristics, more than individual factors, controls the transport of radionuclides from a burial site. Other factors may provide the necessary protection, despite high precipitation. Nevertheless, sites at which annual precipitation is high require more maintenance and more extensive engineering, such as trench cap design and container construction, than those sites that have less precipitation.

In addition to annual precipitation, the intensity, frequency, and distribution of individual precipitation events in time and space also are important factors in site selection. Intense precipitation events can create pulses of water that may infiltrate and percolate in vertical surges through the soil profile of a waste burial area and contribute to contaminant leaching and transport. In contrast, a corresponding quantity of precipitation occurring in several events over time will be more subject

to evapotranspiration and less likely to contribute to moisture reaching the buried waste. Intense precipitation events also cause increased erosion of trench caps.

A site at which precipitation falls in relatively evenly spaced events during a year is preferable to a site at which precipitation occurs in distinct wet and dry seasons. If precipitation falls in evenly spaced events, and all other factors are equal, water will be less likely to percolate to the buried waste because the surficial soil probably will be unsaturated before the precipitation event and may, therefore, retain the moisture. When antecedent conditions include a saturated soil system, water is more likely to percolate to the waste.

When comparing sites having approximately equal annual precipitation, the form in which precipitation occurs can be important. For example, precipitation that falls as snow is not immediately available for infiltration. If the ground surface is frozen when snowmelt occurs, a large percentage may run off the disposal site and not infiltrate to the subsurface. If the site is located or engineered so that runoff from adjacent areas does not pass over it, then the water available for contaminant transport can be reduced. On the other hand, accumulated snow can melt rapidly, and, if the soils are not

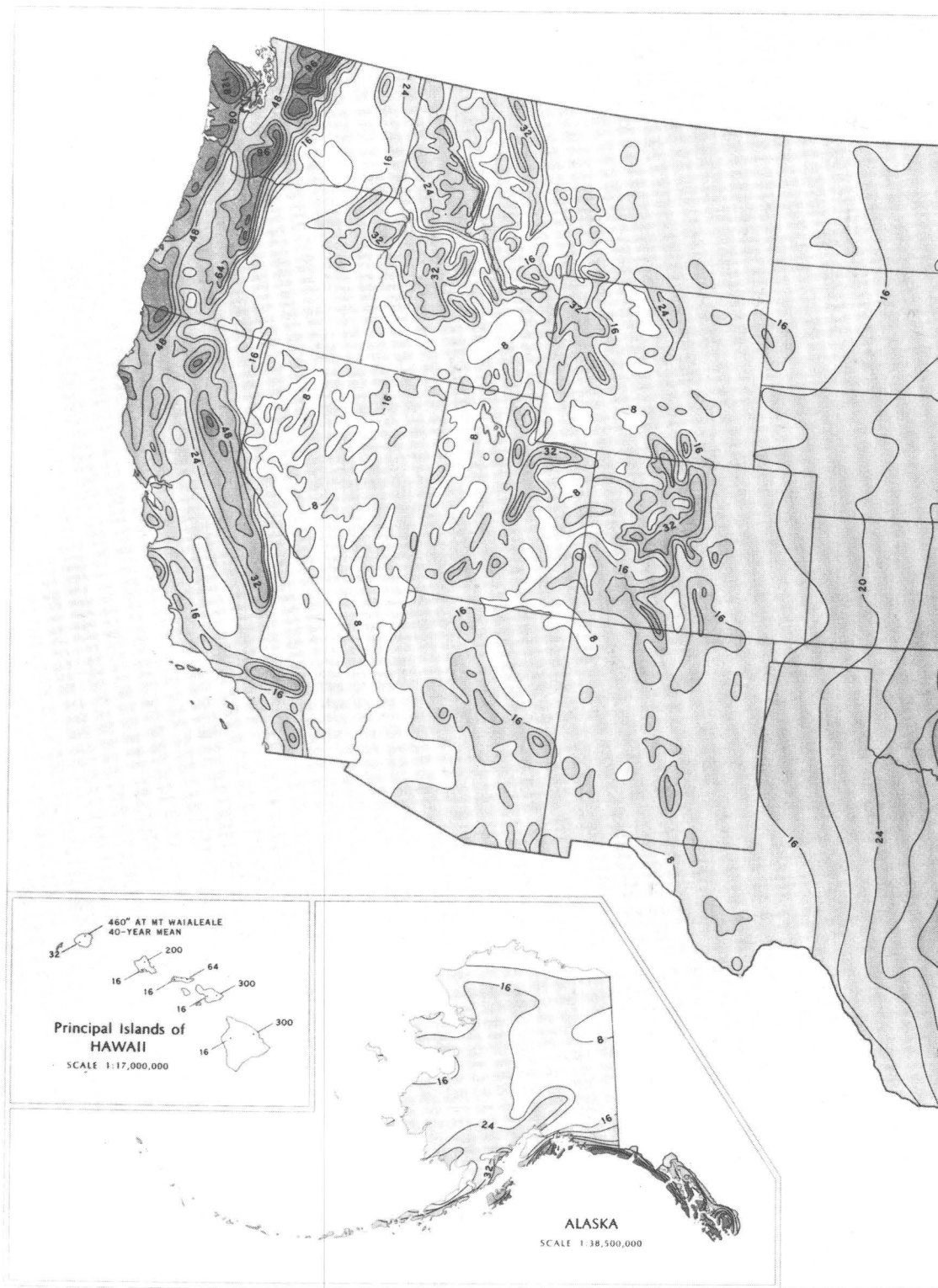
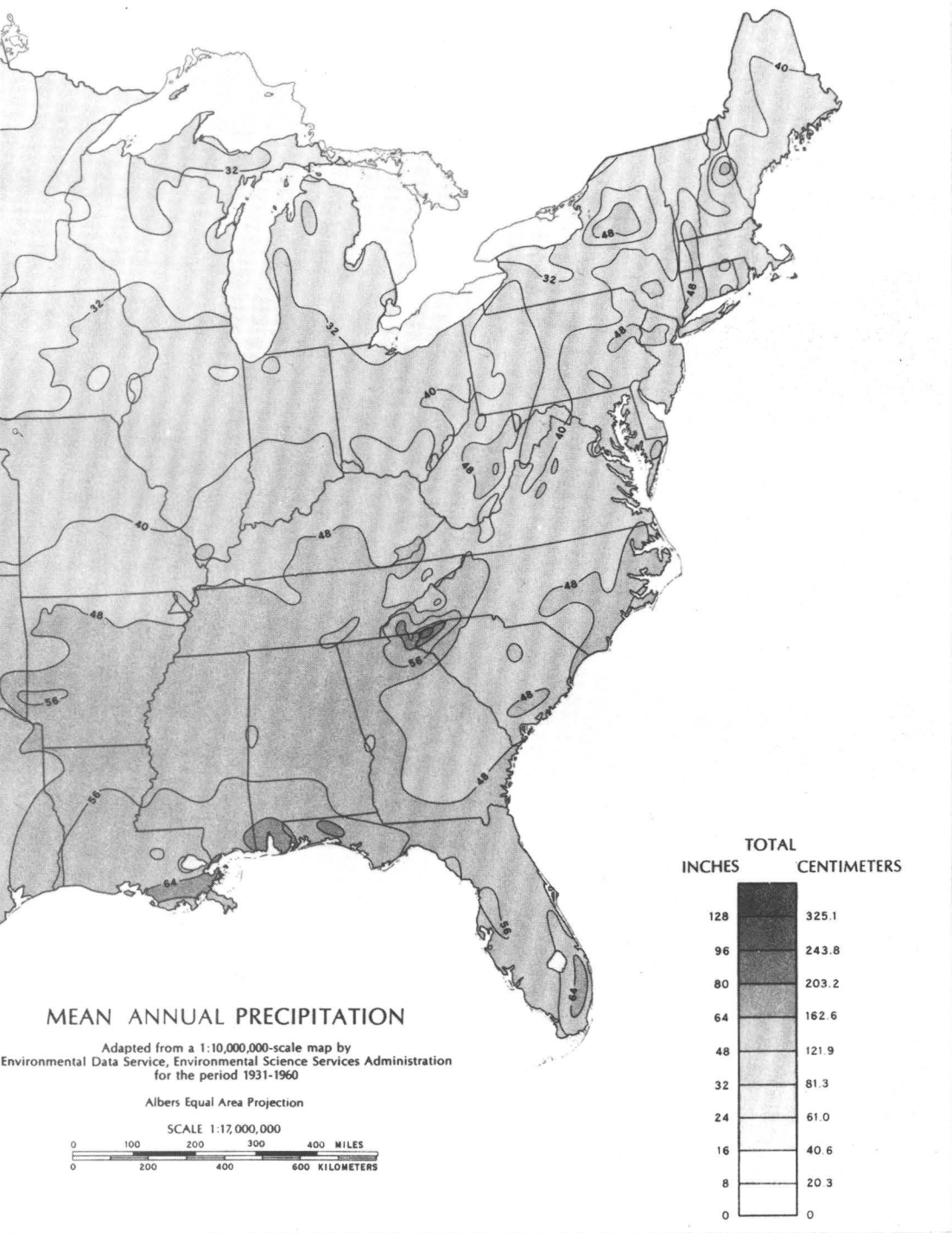


FIGURE 4.—Mean annual precipitation in the



frozen and surface drainage is inadequate, the meltwater can provide a significant source of water, which may infiltrate into trenches.

Ground Water

Under most conditions, the primary offsite hazard to public health associated with the burial of LLW is ground-water contamination. Ground water underlies all disposal sites. When precipitation or surface water infiltrates the ground surface and percolates through LLW waste, the water may leach radionuclides from the waste. Depending on the thickness of the unsaturated zone and other hydrogeologic characteristics, this contaminated water may reside for some time in the unsaturated zone. In most cases, particularly in humid areas, the contaminated water eventually will reach the water table. There, the water can move laterally and may become accessible to wells, or it may appear as surface water in springs, streams, ponds, or other bodies of water and thus expose the biosphere to radionuclides.

One of the important ground-water variables is depth to the water table. In thick, unsaturated zones, contaminants must travel longer distances before arriving at the aquifer. The longer traveltime provides additional time for radioactive decay to occur and reduces the hazard of the potentially contaminated water. Moreover, if the recharge rate is low, the rate of flow in the unsaturated zone can be orders of magnitude less than in the saturated zone and will cause a significant increase in transport time to the accessible environment.

The depth to the water table at the commercial LLW site near Beatty, Nev., is about 280 ft (Nichols, 1986). The depth and the very low recharge rate have been important in the successful containment of radionuclides at that site. In contrast, at the Oak Ridge National Laboratory, Tenn., the water table is less than 20 ft below the ground surface in places, and recharge to the aquifer is substantial (David Webster, U.S. Geological Survey, oral commun., 1983). An investigation by Olsen and others (1983) characterized radionuclide migration from a seepage trench at the site. Leachate from existing Oak Ridge waste disposal sites has a short travel path and traveltime to the water table. Therefore, leachate residence time in the unsaturated zone generally is short; as a result, containment of radionuclides at Oak Ridge is far more difficult than at Beatty.

The velocity of ground-water flow is an important component of site hydrogeologic information because this velocity can be used to calculate traveltime of water from the disposal trenches to points in the surrounding area. The volume of water being transported is as

important as the velocity, however. Large volumes of contaminated water moving at low velocities may present a greater radionuclide flux than small volumes moving rapidly. Therefore, in evaluating site characteristics, precipitation and infiltration rates, which influence the volume of water available to transport contaminants, must be considered along with soil permeability and hydraulic gradient, which are more directly related to velocity.

The quality of natural ground water in the vicinity of a proposed site may be a significant factor in determining site suitability. If the ground water is naturally high in dissolved solids, for example, or has been contaminated by previous human activity, the ground water may already be undesirable for some uses, and the potential risk of additional contaminants from a LLW site may be of less consequence. Also, the quality of existing water can influence leaching rates of the waste (under saturated conditions), solubility of radionuclides, sorption and ion exchange reactions, and other chemical aspects of transport (Kirby and Toste, 1983).

Local and regional water use and the hydrologic effects of that use are other important site selection criteria. For example, in an unconfined aquifer, the pumping of water from wells will cause a cone of depression to form in the water table. Depending on the volume of water extracted and the hydraulic characteristics of the aquifer, the cone may extend some distance from the pumping center. Within the area of the cone of depression, ground-water flow will be in the general direction of the well (fig. 5). Therefore, burial of LLW in areas where cones of depression from existing or future wells might intercept ground water beneath the burial area can result in contamination of water supplies.

In an unconfined aquifer, hydraulic gradient is a measure of the slope of the surface of the water table. Flow always occurs in the downgradient direction; the steeper the gradient, the faster the flow, if the hydraulic conductivity and porosity are constant. A slope of zero indicates that water in the saturated ground-water system is not moving horizontally. The lack of a horizontal hydraulic gradient, or the presence of only a very small gradient, suggests that contaminants might not be transported rapidly in the horizontal direction away from disposal sites when they reach the ground-water table (Cherry and others, 1979). The NRC has made provision for licensing such sites, including those that will result in the burial of waste below the water table (U.S. Nuclear Regulatory Commission, 1960a). However, under 10 CFR Part 61, such a site will be licensed only if it can be shown that molecular diffusion will be the dominant means of radionuclide transport at the site and that such

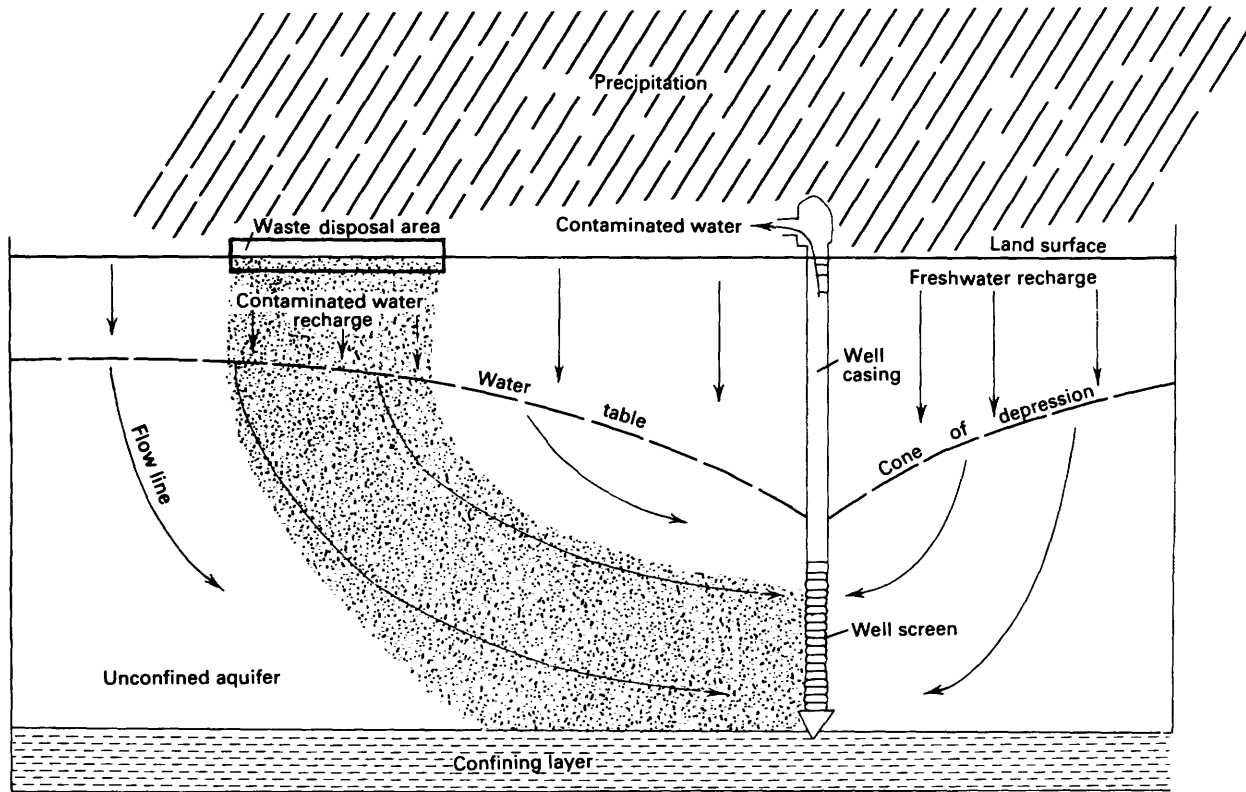


FIGURE 5. — A cone of depression and direction of ground-water flow in an unconfined aquifer from which water is being pumped from a well.

transport will not violate the performance objective in Subpart C of 10 CFR Part 61.

Although burial of LLW below the water table may be appropriate under special circumstances, burial within the zone of water-table fluctuation is not permitted because alternating wetting and drying of the waste will occur within the zone. These processes can hasten the oxidation of metal and the decomposition of containers and ultimately can lead to earlier leaching than will occur if the waste is not subjected to wetting and drying.

Surface Water

Although surface water does not have immediate contact with buried contaminants (unless the water encounters an open trench), surface water can carry off contaminants that may be on the surface of a site through waste handling and emplacement accidents. Surface water also provides a source of water for infiltration, percolation, and subsequent ground-water transport. LLW sites, therefore, should be located so that surface

runoff will not enter the disposal area. This can be achieved by avoiding locations in flood plains, drainage channels, topographic depressions, coastal areas, or areas downgradient from dams. Further protection can be achieved by selecting sites in the upper parts of basins where potential for flooding is diminished through a reduction in upgradient surface area.

Surface water can create several other problems at LLW disposal sites. Streams subject to flooding may cause large volumes of surface water to pass over a burial area. As a result, water may find its way into open trenches and into direct contact with waste. Flooding also increases infiltration and percolation rates through caps and into closed trenches and may cause erosion of trench caps, thereby decreasing the capability of those caps to inhibit infiltration. During a series of runoff and flooding events over the 500-year hazardous lifetime of the site, trench caps could be eroded to the point where waste would be exposed at the land surface. Because one of the primary management objectives at shallow land burial sites is to avoid contact between waste and water, such waste exposure is inadvisable.

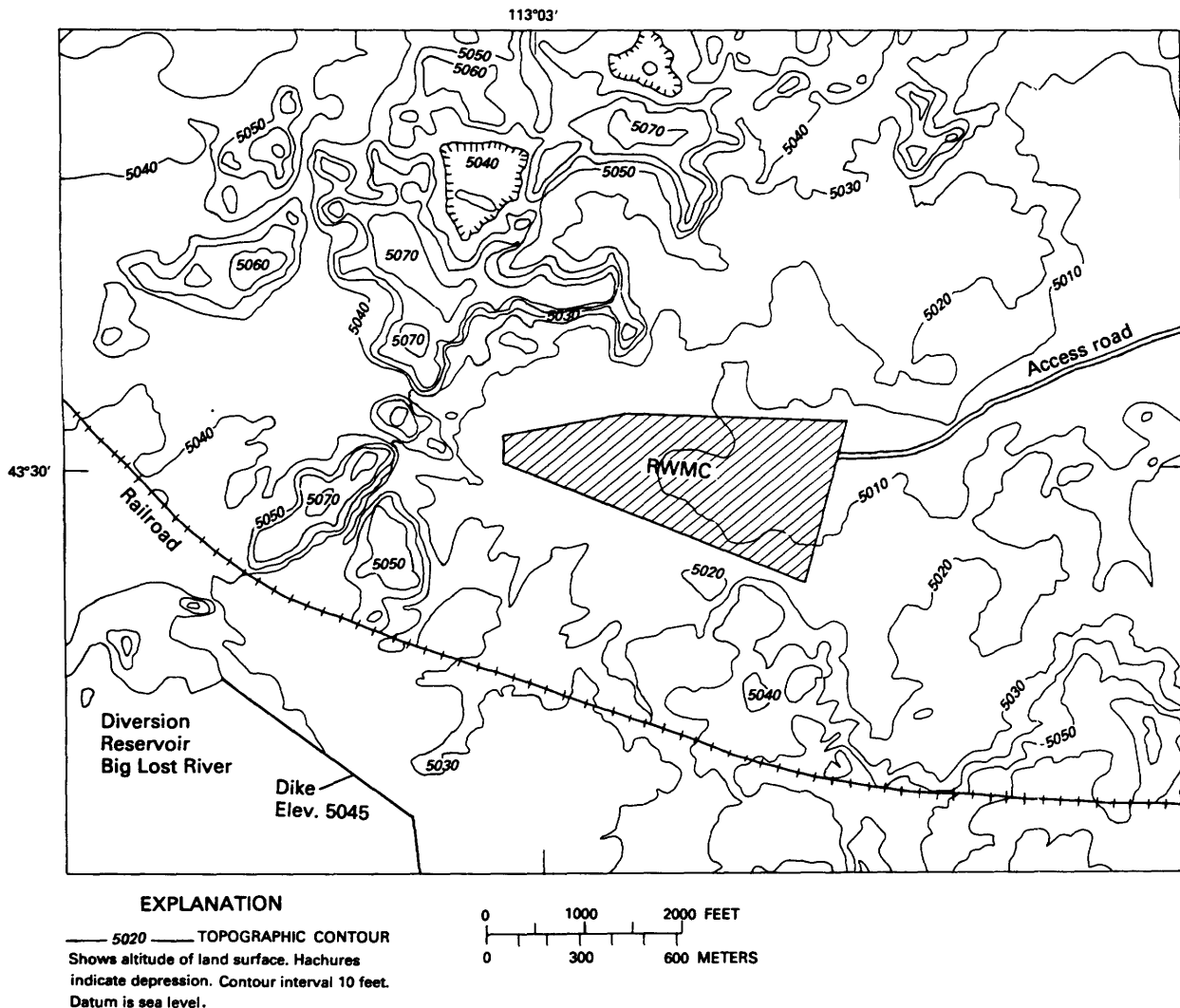


FIGURE 6. —Radioactive Waste Management Complex (RWMC) and vicinity at the Idaho National Engineering Laboratory, Idaho. (Modified from Bagby and others, 1981.)

Another problem streams can pose at disposal sites is the pathway they provide for rapid contaminant transport. Contaminants may move to streams either by overland flow from surface spills, which might occur during waste handling at the site, or by discharge from the ground-water system. Analyses of stream sediments near Maxey Flats, Ky., have shown that cobalt-60, strontium-90, cesium-137, and plutonium-238 moved 2.2 mi from the disposal site during one incident (Zehner, 1983). On the basis of the detection of niobium-95 (which has only a 35-day half-life) in the stream water samples, and a comparison of principal ion concentrations in surface and ground waters, Zehner concluded that the surface water contamination at Maxey Flats resulted from spills within the site boundaries and

subsequent transport by surface runoff to the offsite stream sampling point.

A third potential problem presented by surface water bodies near LLW sites relates to geomorphology. Over time, the development of stream channels may include sloughing of banks and changing of channel courses. These changes in the land surface may destabilize adjacent burial areas and reduce the capability of a burial site to provide long-term protection from contaminant release to the environment.

Topography has contributed to surface water problems at the Radioactive Waste Management Complex of the Idaho National Engineering Laboratory. The complex is located in a topographic low (fig. 6), and, although mean annual precipitation does not exceed 8.5 in. (Clancy and

others, 1981), the site has been subjected to several floods that resulted from rapid snowmelt (Barracough and others, 1976). An extensive system of ditches and dikes has been constructed around the site to reduce the threat of flooding. Natural surface-water barriers, such as a topographic high or a siting near the top of drainage basins, offer attractive alternatives to such engineered structures, however, because these natural barriers probably will last longer than engineered systems.

Geology

The geology of disposal sites plays a major role in controlling the rate of ground-water flow and solute transport, two important related physical characteristics in site selection. Sites that are geologically complex pose problems because of the difficulty in understanding and characterizing ground-water flow. Complex sites are typified by those at Sheffield (glacial deposits) and Maxey Flats (fractured shale). Such sites are difficult to describe and analyze by using hydrologic models. Models are useful tools for predicting future site performance under a variety of conditions. Technical analyses of ground-water, surface-water, and other pathways are required by 10 CFR Part 61. Although the regulation does not require hydrogeologic modeling specifically, in most cases, modeling will be necessary to characterize the hydrologic framework of the site and for the predictions of performance required to demonstrate compliance with regulations.

An essential component for an effective ground-water monitoring system is the ability to accurately describe the geohydrologic system of potential sites. One of the most troublesome aspects of monitoring the now-closed commercial site at Maxey Flats is the difficulty in effectively sampling the ground water, which flows predominately in fractured shale and intercalated sandstone. Many of the fractures at Maxey Flats are not interconnected, and, for those that are, the place and mode of connection are difficult to ascertain. At Maxey Flats, many wells drilled to monitor the ground water have not intercepted fractures and, therefore, yield little or no water. Other nearby wells do provide adequate water for sampling. Although recent progress has been made in characterizing fracture flow (Hsieh, 1983), problems in interpretation, such as those associated with non-Darcian flow, have yet to be overcome.

One of the reasons that the Maxey Flats site was closed was the seepage of contaminated ground water through fractures from an adjacent filled trench into an open trench. In the summer of 1977 workers at Maxey Flats discovered radioactive soil and water in trench 46

(fig. 7). An investigation revealed a subsurface area of increased gamma activity near trench 46. Soil and water having elevated concentrations of cobalt-60 and manganese-54 were found in the clay-filled fractures of a thin sandstone bed that trench 46 and other trenches at Maxey Flats generally intercept. Zehner (1983) concluded that this thin sandstone bed was the transport pathway for contaminants and that the effective velocity for radionuclide movement along the bedding plane was 50 ft/yr. The velocity greatly exceeds the velocity generally associated with unfractured shale and sandstone and far exceeds that originally expected at the site. The incident is illustrative of the difficulty in characterizing fracture flow.

The LLW site near Sheffield, Ill. (fig. 8), provides a second example of a stratigraphically complex system. The site is located in glaciated terrain in an area that was once surface mined for coal. Limited data were available for use in characterizing the hydrogeology at and near Sheffield at the time of license application in 1966. Permeable stratigraphic units were identified in the hydrogeologic characterization, but the units were thought to be discontinuous. In one of those units, a narrow channellike depression filled with coarse, gravelly sand (fig. 8B) was not identified until several years later. On the basis of information collected when the site opened, ground-water velocities were estimated to be 0.01 to 0.05 ft/d (E.H. Baltz, U.S. Geological Survey, written commun., July 1967). At these velocities, ground water will flow from under the site to a small lake 1,100 ft downgradient within 60 to 330 years. However, because of the existence of the gravel-filled channel and its downgradient orientation, ground water has moved that distance in less than 20 years. Concentrations of tritium (a radioactive isotope of hydrogen) of about 400 nCi/L (nanocuries per liter) have been found in ground-water samples from near the site (Goode, 1986). Although significant dilution occurs when the ground water reaches the lake, such unexpected transport illustrates the uncertainty inherent in disposing of waste at sites that are geologically complex.

The maximum permissible concentration for controlled release of tritium to the Sheffield environment is 3,000 nCi/L, as stipulated in Appendix B to 10 CFR Part 20, the regulation in effect at the time of licensing of the site (U.S. Nuclear Regulatory Commission, 1960²). The release limits for a LLW disposal facility are now defined by the requirement of Subpart C of 10 CFR Part 61. Currently, releases are required to be as low as reasonably achievable but in no case may result in annual doses to individuals that are greater than a small fraction of the expected annual dose from natural sources—

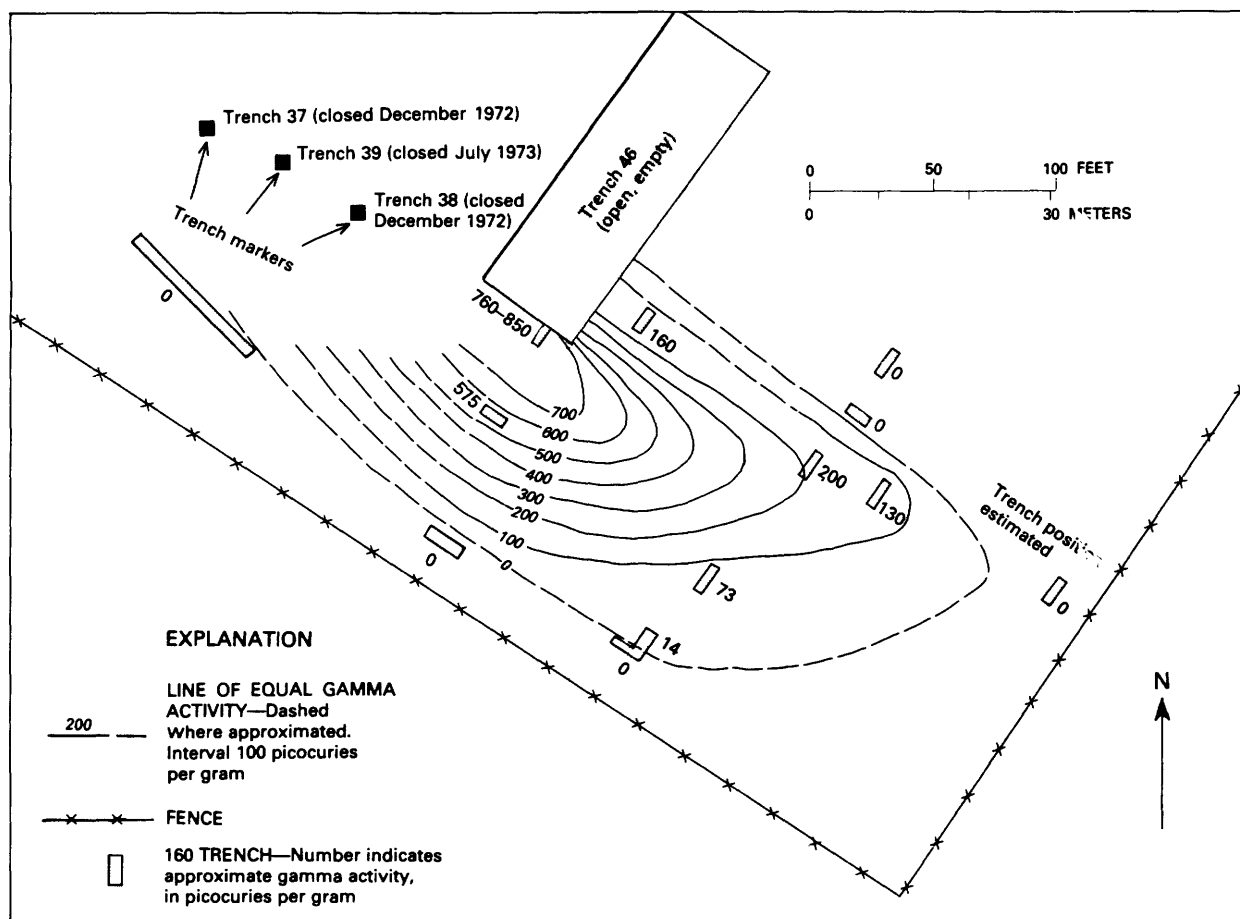


FIGURE 7.—Subsurface gamma activity near trench 46, Maxey Flats, Ky., low-level radioactive waste disposal site. All values indicated are above-background activity levels. (Modified from Zehner, 1983.)

25 millirem to the whole body or any organ other than the thyroid. These release limits apply to all likely pathways for exposure, including ground water, surface water, air, soil, plants, and animals.

In general, sites that are hydrogeologically complex, not only from a stratigraphic standpoint, but also because of variability in other hydrogeologic characteristics such as hydraulic conductivity and porosity, are less suited to modeling and accurate prediction than sites in unsaturated, thick, relatively homogeneous, unconsolidated sediments. More than 49 testholes in a 50-acre area were necessary to confirm the existence of the gravel-filled channel at the Sheffield site and to identify the channel as the pathway for offsite tritium migration (Garklavs and others, 1986). There are two reasons for not conducting extensive drilling at LLW sites. First, drilling is costly. Second, drilling may create vertical pathways for the movement of ground water.

Unconsolidated sediments, in general, are more easily characterized for quantitative ground-water analyses than are consolidated fractured systems. Moreover, ground-water flux is usually less in a fairly homogeneous unconsolidated sedimentary system, particularly if that system is unsaturated, than flux in rock fractures or on interfaces between soil systems and unfractured rocks. This difference occurs, in part, because of the longer flow paths that exist within the sediments. Migration pathways that are long in terms of time and distance, such as those in unconsolidated sediments, also provide added opportunity for radioactive decay and for sorption of contaminants onto sediment surfaces.

The foregoing discussion does not constitute an endorsement of a specific type of hydrologic system for the disposal of LLW. It is important to evaluate a potential disposal environment as a total system. In so doing, a wide variety of factors are considered, and a

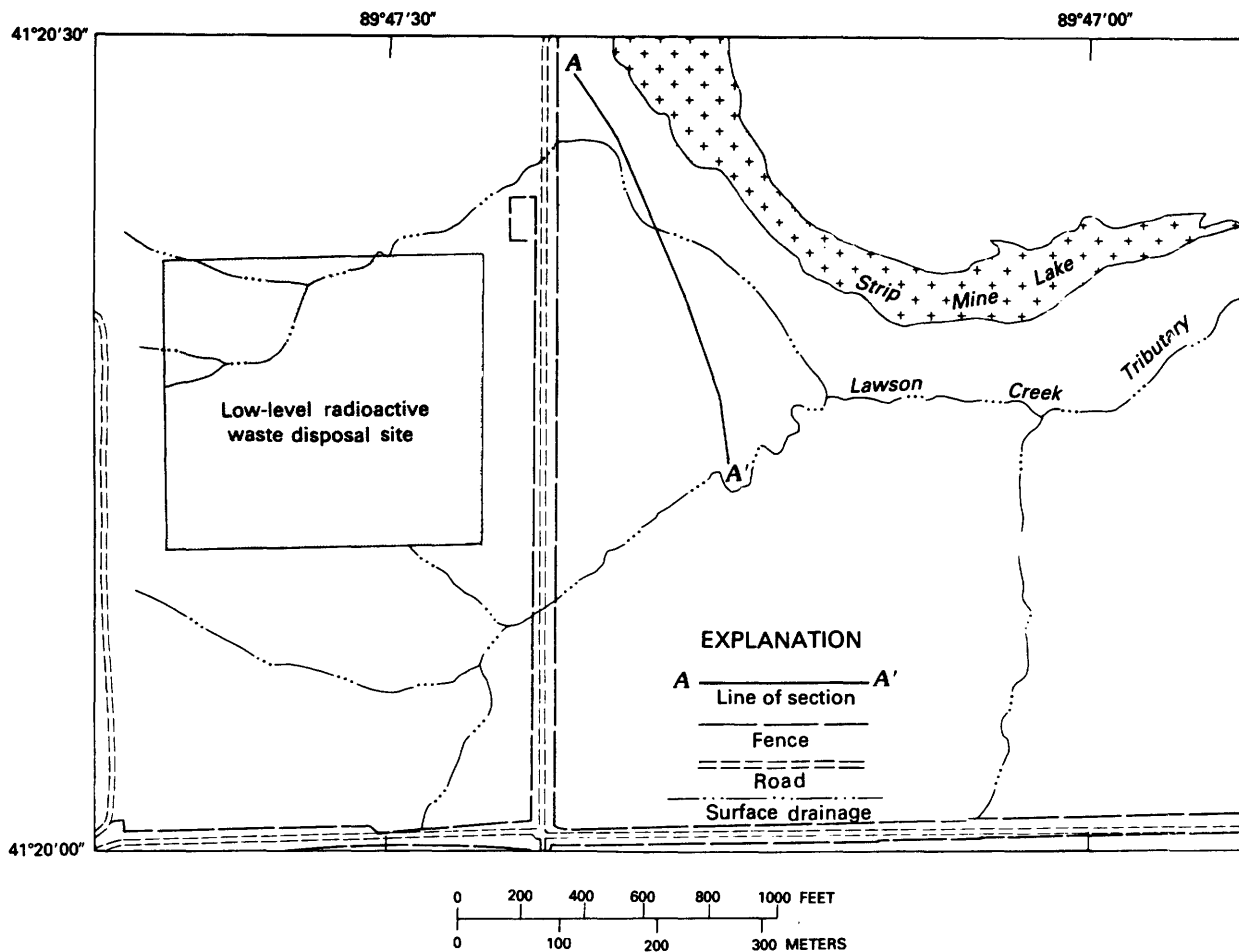


FIGURE 8A.—Location of drainages and line of section A-A' at the low-level radioactive waste burial site near Sheffield, Ill. (Modified from Foster, Erickson, and Healy, 1984.)

system that appears to be satisfactory geologically may not satisfy other criteria.

Hydraulic Conductivity

The shallow land burial method of waste isolation includes the concept of naturally constrained release of contaminants over long periods of time. This approach is particularly appropriate for LLW disposal because, over time, radioactive isotopes decay into stable isotopes that do not present health hazards. Thus, known decay rates can be combined with calculations of transport velocities to help determine the area within which a radioactive hazard will exist. Hydraulic conductivity is a fundamentally important component in these calculations. Table 4 lists the hydraulic conductivity of representative unconsolidated aquifer materials.

In selecting LLW burial sites in the eastern, more humid regions of the United States, host material of low hydraulic conductivity has been sought on the premise that these earth materials retard the movement of ground water and dissolved contaminants away from disposal trenches. The sites at Maxey Flats, Ky., and West Valley, N.Y., were selected, in part, because hydraulic conductivity at those sites was thought to be low. Zehner (1983) calculated that the hydraulic conductivity of the upper members of the unfractured shale at Maxey Flats ranges from 0.3 to 3.7 ft/yr. At West Valley, Prudic (1986) estimated that the hydraulic conductivity of the unweathered glacial till and associated lenses of sorted material, in both the horizontal and vertical directions, ranges from 0.02 to 0.06 ft/yr.

Although the shale at Maxey Flats and the glacial till at West Valley meet the general criteria of low hydraulic

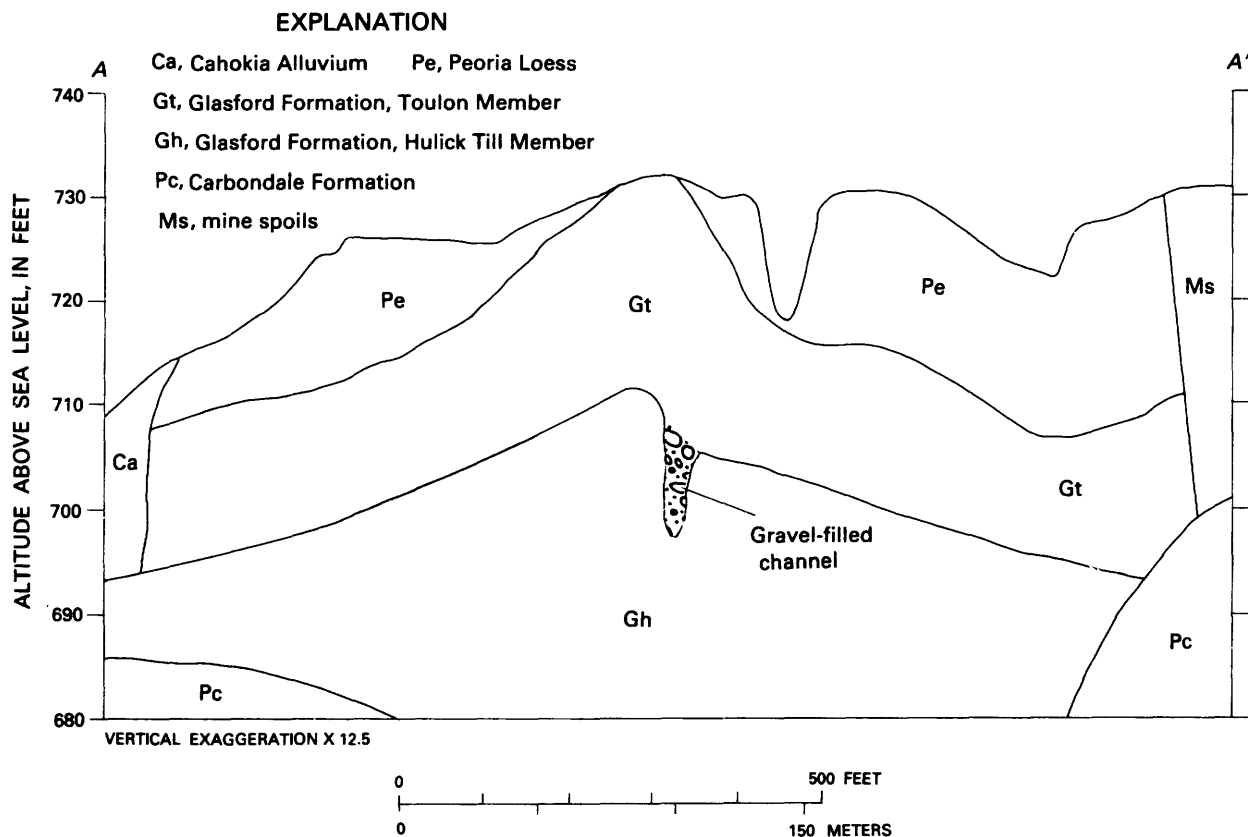


FIGURE 8B.—Geologic section A–A' showing location of buried gravel-filled channel at the low-level radioactive waste disposal site near Sheffield, Ill. (Modified from Foster, Garklavs, and Mackey, 1984. Stratigraphy follows the usage of the Illinois State Geological Survey.)

conductivity, problems occurred at both sites when subsidence in the buried waste caused the trench caps to slump and crack. The cracks created pathways through which large quantities of precipitation and surface-water runoff entered the trenches. There is evidence that lateral migration of water through the upper weathered and fractured till layer may have contributed to the presence of water in trenches at West Valley. Because the earth materials at both sites have low hydraulic conductivity, water passing through the breached cap could not drain rapidly enough from the trenches. Over time, the trenches were filled with water, and a "bathtub effect" was created.

Left unattended, water-filled trenches present several problems. When sediments surrounding the waste become saturated, large volumes of leachate may be generated. Also, as water levels in the trenches rise, the contaminated water may encounter shallow, permeable sediment layers. These layers may not offer a pathway for contaminant transport if they remain in the unsaturated zone, but, under saturated conditions of a water-

filled trench, the layers can provide pathways for rapid lateral migration.

A contaminant plume at the burial ground formerly licensed by NRC at West Valley exists at about 9 ft below ground surface in a weathered, relatively permeable layer of glacial till. Current data indicate that the plume extends about 70 ft downgradient from its probable source and moved that distance in about 12 years

TABLE 4.—Hydraulic conductivities of representative unconsolidated aquifer materials
[Modified from Freeze and Cherry, 1979]

Aquifer materials	Hydraulic conductivity (feet per day)
Clean gravel	10^4 – 10^5
Clean sand, sand and gravel	10^2 – 10^4
Silty sand	10^{-2} – 10^2
Silt, loess	10^{-3} – 10
Till	10^{-6} – 10^{-1}
Unweathered marine clay	10^{-6} – 10^{-3}

(M. Bergeron, U.S. Geological Survey, oral commun., May 1984). These figures suggest a ground-water velocity of about 5 ft/yr, a much larger figure than might be expected on the basis of hydraulic conductivity of the unweathered host sediments reported by Prudic (1986). One explanation for this rapid movement is that water entered the source trench either through the cap or from a transient perched water table that was intercepted by the trench. Due to the low permeability of the unweathered host sediments, water levels in the source trench increased until the water encountered the weathered till. Once in this layer, lateral transport of the water as saturated flow and at elevated velocity was possible (Herbes and Clapp, 1984; U.S. Nuclear Regulatory Commission, 1985). Similar circumstances are believed to have existed along the thin sandstone beds within the fractured shale at Maxey Flats and to have led to the transport of cobalt-60 and manganese-54 (Zehner, 1983).

Water overflow from disposal trenches can result in seepage of contaminants at the land surface. Trenches at the West Valley site did overflow (Prudic and Randall, 1979), and, as a result, the site was closed. At Maxey Flats, trenches had to be pumped because of accumulating water; eventually the Maxey Flats site also was closed. These events led to a reevaluation of siting disposal areas in soils of low hydraulic conductivity.

Generally, trenches in sediments of high hydraulic conductivity material will not fill with water even if trench caps are breeched because water will pass through the trench bottom. However, contaminant transport will be rapid in these materials if water is available, and the process of radioactive decay will have less time to take place before the contaminant travels beyond the control (buffer) area.

Host sediments of an intermediate hydraulic conductivity may be preferable. Such sediments will permit water that percolates through the trench cap to drain through the trench bottom without accumulating. If the flow rate is relatively slow, an unreasonably large buffer zone will not be required to protect public health and safety and the environment. The host soil at the Barnwell, S.C., site, for example, has an intermediate hydraulic conductivity, and the data available at this time, although limited, indicate that waste is effectively contained. Cahill (1982) reported that horizontal hydraulic conductivity of sandy clay, in which the trenches are excavated at Barnwell, ranges from 10^{-7} to 10^{-1} ft/d; vertical values average about 10^{-3} ft/d, a value of sufficient magnitude to conclude that water entering the trenches will not be retained within the trenches. In fact, because trenches at Barnwell commonly do not accumu-

late water, either the trench caps are completely effective in preventing infiltration of surface water or the host sediments are permeable enough to permit the water that does enter to pass through the trench bottom. The latter explanation is more probable.

In more arid zones, hydraulic conductivity, although still important, may be less critical than in the humid parts of the country. The site near Beatty, Nev., for example, is located in valley-fill deposits of the Amargosa Desert where sand and gravel fractions are high. In his investigation of site hydrogeology, Nichols found the saturated hydraulic conductivity of the Amargosa Desert soils to be about 200 ft/yr (W.D. Nichols, U.S. Geological Survey, written commun., May 1984). Percolation to the ground-water table at Beatty is retarded, however, by an unsaturated zone, approximately 280 ft thick, which lies between the waste and the ground-water table. Nichols estimates the unsaturated hydraulic conductivity of the sediments at Beatty to range from 4×10^{-4} to 4×10^{-9} in./d (Nichols, 1986). The steady-state unsaturated flow rate is estimated to be about 0.1 ft/1,000 yr. These figures and the combined effects of low annual precipitation (less than 3 in.) and high annual potential evaporation (about 100 in.) indicate that transport of contaminants to the water table will be very slow and will be strongly influenced by the magnitude and frequency of extreme precipitation events. USGS unsaturated zone studies underway at Beatty will help to quantify unsaturated flux at the site (Schneider and Trask, 1984).

Ion Exchange Capacity

The ground-water transport of radionuclides through porous media is influenced by the characteristics of the radionuclide itself and by soil and water chemistry. The complexity of this relation hinders the quantifiable, predictable, and reproducible interpretation of radionuclide transport in ground water. However, studies at the Idaho National Engineering Laboratory have shown that mineral and water chemistry can be effective in retarding the movement of certain radionuclides (Robertson, 1974).

Attenuation can occur through a variety of physical and chemical processes, but the two most prominent processes appear to be sorption and ion exchange. Sorption involves the adhesion of molecules to the surface of aquifer material; the ion exchange process displaces ions on the surface of minerals by ions in solution. Both processes can result in the removal of contaminants from ground water moving from LLW disposal areas (Brown, 1967). The sorption and ion

exchange processes are caused primarily by the electrical surface charge in mineral particles, generally clay-rich materials that carry an excess of negative charges. Studies by Olsen and others (1983) at disposal sites at the Oak Ridge National Laboratory reaffirmed that illite clay retards the migration of cesium-137. In his investigation of the hydrogeology at the West Valley, N.Y., commercial LLW site, Prudic (1986) found that the transport of cesium and strontium was retarded because of ion exchange between the contaminants in solution in ground water and the clay component of the glacial till. In contrast, investigators at a cold-scrap recovery plant in Rhode Island found that the clay-free sands did not retard significantly the transport of strontium-90 (B.J. Ryan, U.S. Geological Survey, oral commun., 1984). Thus, the clay fraction and clay type play key roles in sorption and ion exchange processes, and their determination is an important element of the site-selection process.

Geomorphology

Certain low-level wastes require stabilization for at least 300 years because of their half-life or concentrations of radionuclides. Others need to be isolated from accidental direct contact by humans for at least 500 years. To ensure that waste in the facility is adequately contained, stability of the site for 300 to 500 years must be ensured. Because of the long times involved, the projected geomorphic change at potential sites is an important component of site evaluation. Of particular interest are the processes of erosion and slumping, which may occur naturally or may be stimulated by the burial activity.

Important factors influencing erosion rates are rainfall and rainfall intensity, vegetative cover, slope, water velocity (a function of slope), wind velocity and direction, and soil characteristics. The potential for the flow of water over the land surface can be reduced through proper site selection; however, some surface-water flow at LLW disposal sites is inevitable, particularly because trench caps are constructed of low-permeability material and are mounded to inhibit infiltration and percolation of surface water into the filled trenches. The rejected infiltration becomes surface-water flow.

The selection of sites that have minimum slope and no nearby surface-water courses can minimize erosion and reduce other site stability problems. Minimizing slope reduces the velocity and thereby minimizes the erosiveness of surface runoff; eliminating surface-water courses diminishes the likelihood of surface flow from outside site boundaries over or around the site during floods.

Sediment and Rock Stability

Stability problems have occurred at the commercial LLW sites at West Valley and Maxey Flats. The sediment in which waste is buried at West Valley is fine, unconsolidated glacial till (Prudic, 1986), which is susceptible to slumping along the walls of incised streams and gullies. This slumping has, in fact, occurred near the West Valley site (U.S. Nuclear Regulatory Commission, 1985). Through erosion and slumping sequences, gullies have cut into the till near the West Valley site, and, if allowed to continue, some buried waste may become exposed while still hazardous. Ensuring site stability probably will be a necessary element of site maintenance at West Valley for an extended period to ensure that natural geomorphic processes do not expose the waste.

The Maxey Flats, Ky., facility is situated on a flat-topped hill located 300 ft above the surrounding valley floor. In his description of the hydrogeology of the site, Zehner (1983) estimated the slope of the hillsides extending from the burial area to the valley floor to be between 30° and 40°. In closing the site, an impermeable cover on the land surface was emplaced to decrease leachate formation within the waste-filled trenches (Kentucky Department of Environmental Protection, 1983). As a temporary measure, membranes of polyvinylchloride, 0.08 in. thick, have been placed over the area in which trenches have been completed. This cover has been effective in reducing infiltration, but the cover has also caused a substantial increase in surface runoff. The runoff is directed to retention areas constructed at the south and east sides of the site, which serve to diminish peak flows from runoff events. However, very large volumes of runoff from the polyvinylchloride-covered surface of the site can exceed the capacity of the retention areas and can flow rapidly down the steep slopes (A.L. Knight, U.S. Geological Survey, oral commun., May 1984). Rapid flow of large volumes of water on steep slopes can result in rapid erosion and gully formation. Therefore, maintenance of ponds and hillside channels is likely to be a long-term component of site monitoring and maintenance at Maxey Flats.

Buffer Zones

It is unlikely that any shallow land burial system can provide absolute containment of LLW within its trenches for the entire hazardous lifetime of radioactive waste, particularly in those areas where annual precipitation is high. Therefore, near-surface disposal facilities must be

designed with the possibility in mind that there will be some release of LLW from trenches. Because radionuclide decay to nonhazardous waste occurs in predictable time frames, the risks from such releases can be managed. Siting, design, construction, operation (including waste form and packaging), and closure requirements are provided by 10 CFR Part 61 to ensure that releases that may occur are minimized and comply with strict limits to protect public health and safety.

The potential release of contaminants from disposal areas has resulted in an NRC requirement to establish a three-dimensional buffer zone surrounding a disposal area. The buffer zone is a controlled, restricted area that allows for environmental monitoring and facilitates the implementation of mitigative action. It is the zone into which contaminants from trenches might migrate during the contaminants' hazardous lifetime. Buffer zones allow time for radioactive decay to occur and allow dispersion and geochemical processes between the waste and host sediment and rocks to take place. Through these processes, radioactivity of contaminated ground water may be attenuated to within regulatory limits before the ground water migrates to the site boundary.

The natural characteristics of some environments may be less favorable for shallow land burial than others. Nevertheless, a less favorable environment may provide an acceptable shallow land burial site for LLW if the buffer zone surrounding the site is large enough to contain migrating contaminants long enough for decay to reduce radioactivity to safe levels.

The dimensions of the buffer zone depend upon complex, site-specific interrelations of factors, many of which are hydrogeologic. The dimensions can be estimated, in part, through the use of numerical transport models, if the waste can be adequately characterized and if the hydrologic system can be accurately described. Dimensions of the buffer zone may range from tens to hundreds of yards laterally and from tens to hundreds of feet vertically.

OTHER FACTORS

At Sheffield, Ill., and Beatty, Nev., disposal sites for both LLW and nonradioactive hazardous waste are collocated under separate operating licenses. Although problems caused by the proximity of the two types of facilities have not been documented at this time, evidence exists that the mobility of some radionuclides may be increased by interaction with organic compounds present either naturally or in chemical waste. This organic-radionuclide interaction was investigated by Cleveland and Rees (1981) at Maxey Flats. Their work

suggests that, when plutonium occurs in trench leachates as a dissolved species, the plutonium can chemically chelate with some types of waste organic molecules and then become more mobile. Pietrzak, Columbo, Weiss, and others have conducted water-chemistry investigations at LLW burial sites since 1976. Their findings are published in a series of quarterly NRC reports, only one of which is cited here (Pietrzak and others, 1982). Among their many findings, the authors concluded that low concentrations of organic chelating agents may be responsible for keeping radionuclides, particularly cobalt-60, in solution. Investigations conducted at Maxey Flats by Kirby and Toste (1983) support these conclusions. These latter studies were of organic waste buried directly with radioactive waste.

At the Sheffield, Ill., and Beatty, Nev., sites, the two waste types are not buried in direct contact with one another but are collocated at adjacent facilities. This separation precludes mixing of the wastes in the unsaturated zone where vertical water flow dominates but cannot be assumed to do so in the saturated zone where horizontal components of flow can predominate. Because of the possible increase in radionuclide mobility when organic and radioactive leachates mix, the collocation of organic and radioactive waste-disposal sites can result in an increased risk to the environment.

The possible development of an area's natural resources should be considered in the selection of a LLW site. In addition to ground water, such resources include oil, coal, and other mineral resources beneath, and immediately downgradient from, the disposal site. The primary concerns with respect to the presence of exploitable natural resources are (1) the likelihood of inadvertent intrusion by a resource exploiter and (2) the effects of resource development on site performance after the period of institutional control. The relative value of the natural resources should be considered in evaluating the likelihood of exploitation.

Geologic hazards can decrease site integrity and are important factors in site selection. These hazards include volcanic eruption, active faulting, land subsidence, and mass soil and rock movements. Any of these hazards may alter the hydrogeologic system or the physical integrity of a site, can cause releases of radioactive contaminants to the environment, and can complicate predictions of future site performance.

SYSTEMS APPROACH TO SITE EVALUATION

In the site evaluation process, the hydrologic system as a whole should be considered, and a particular site

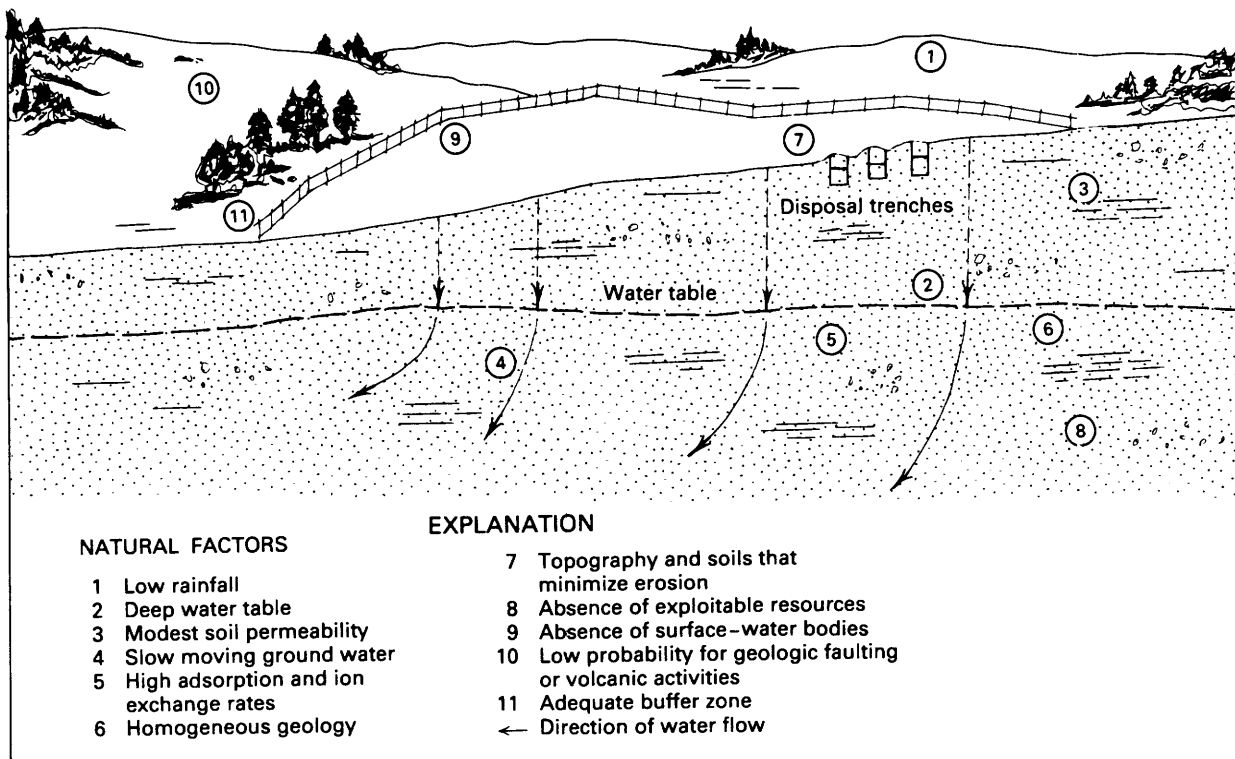


FIGURE 9.—Conceptual view of natural factors related to the suitability of sites for the burial of low-level radioactive waste.

should not be disqualified automatically on the basis of deficiencies in only one or two of the critical parameters. This “systems” approach to site selection is related to the multiple-barrier concept, which utilizes the complementary effects of natural features that inhibit contaminant mobilization and transport. Figure 9 is a conceptual diagram illustrating how the factors discussed in this report combine to form such a natural barrier system. Each factor provides a part of the overall protection system, and the protection provided by a particular factor may vary from site to site. Therefore, assigning acceptable, minimum, or maximum numerical values to particular factors is usually inappropriate. Each factor should be considered as part of the overall barrier system, and the overall system should be evaluated. In its approach to a total system evaluation of potential disposal sites, described in 10 CFR Part 61, NRC includes factors such as waste form and engineering criteria, in addition to the hydrogeologic factors discussed in this report.

In the development of plans for the next generation of LLW disposal facilities, consideration is being given to alternatives to shallow land burial, such as above- and below-ground vaults. If and when such engineered

structures are incorporated into disposal systems, the protection they provide will be considered as another element in the system of barriers to the transport of LLW contaminants. Engineered barriers alone are unlikely to qualify a LLW disposal site that has been previously designated as unsuitable on the basis of hydrogeologic factors. Instead, the total system of protection will be evaluated with the objective of establishing multiple barriers to human exposure.

CONTINUING INVESTIGATIONS AND RESEARCH

The hazards associated with existing LLW sites will persist for at least 300 to 500 years. Most investigations of existing sites have been in progress for less than a decade. This is an inadequate period to assess either all of the environmental factors surrounding such a long-term hazard or the performance of current sites. The information in this report represents the state of our knowledge to date. Although the understanding of LLW fate and transport is not complete at this time, there is considerable knowledge available to form a technical

basis for practical disposal decisions and to incorporate conservatism to counter the uncertainties associated with long-term site performance.

To improve our understanding, the USGS is continuing to conduct research and investigations related to the earth-science aspects of burial of LLW (Dinwiddie and Trask, 1986). The major thrusts of the field investigations and the complementing research program are to (1) develop improved solute transport models, (2) achieve a better understanding of unsaturated flow phenomena, (3) clarify radionuclide geochemistry, and (4) develop techniques to detect the subsurface transport of radionuclides in the gaseous phase.

The USGS LLW investigations are complemented by those of other Federal and State agencies. The NRC, DOE, and EPA are active in supporting investigations of many aspects of the disposal process. The DOE plays a particularly important role in support of the research of investigations of the National Laboratories and as lead agency in assisting State governments in the implementation of provisions of the Low-Level Waste Policy Act (PL 96-573).

SUMMARY AND CONCLUSIONS

Due to weathering and other geomorphologic processes, burial of LLW can be expected to result in the transport of contaminants into the immediate subsurface environment of the burial site. Moreover, because engineered structures, such as above- and below-ground vaults, probably will not maintain their integrity throughout the hazardous life of the waste, the contaminants most likely will be transported from these engineered structures as well. For this reason, it is important that the natural factors at disposal sites provide barriers to transport to achieve the necessary protection of the environment. On the basis of hydrogeologic field investigations at commercial and DOE LLW disposal sites, pertinent natural factors have been identified and confirmed, and insights have been gained into their relation to effective disposal. The most important natural factors are precipitation, site stability, sediment and rock permeability, hydraulic gradient, proximity of surface water, site location in the drainage basin, topography, thickness of the unsaturated zone, native ground-water quality, homogeneity of site hydrogeology, and proximity of geohazards. Careful evaluation and incorporation of these factors into a multiple-barrier concept of environmental protection will increase the probability of identifying effective shallow land burial sites for low-level radioactive waste.

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