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ABSTRACT

ANDREW MORROW BARRON, Geologic and Hydrologic Characteristics of Existing Low-Level Radioactive Waste Disposal Sites in the Eastern United States - Implications for North Carolina

The geologic and hydrologic characteristics of low-level radioactive waste (LLRW) disposal sites in the eastern United States are reviewed in this technical report. Since North Carolina has been designated as the next host for a LLRW faciltiy by the Southeast Compact Commission, this information coupled with the geology/hydrology of North Carolina can be used in the identification of potential siting constraints. In North Carolina, engineered barriers will be incorporated into the selected LLRW technology. In this report concrete degradation mechanisms are reviewed. Based on this information, possible geologic/hydrologic constraints of siting a LLRW disposal facility in North Carolina are discussed.

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CHAPTER 1.

INTRODUCTION

The disposal of low-level radioactive waste (LLRW) in the United States has evolved over the years in response to commercial use of radioactive materials. LLRW is defined in Title 10, Code of Federal Regulations Part 61 (10 CFR Part 61), as all radioactive waste that is not classified as high-level waste, transuranic waste, spent nuclear fuel, or uranium or thorium mine tailings. Since LLRW is defined by exclusion, a small fraction of LLRW can contain fairly high concentrations of radionuclides.

Low-Level Radioactive Waste encompasses a broad range of wastes. Any industry, hospital, medical, educational or research institution, private or government laboratory, or facility involved in the nuclear fuel cycle, that utilizes radioactive materials generates LLRW. Due to the diversity of generating facilities, LLRW is produced in many physical forms and volumes. Table 1. lists radionuclides typically found in LLRW from several types of generating facilities. Specific activities of LLRW can vary from fractions of millicuries per cubic foot (e.g., laboratory wipes) to hundreds of curies per cubic foot (e.g., sealed sources).

The Nuclear Regulatory Commission (NRC) defines LLRW into four classes. The waste classes are differentiated by

TABLE 1. Typical radionuclides in LLRW, by generators (from Lee, 1986).

Reactors	Industry	Government	Medical	Academic
Co-58	P-32	P-32	P-32	C-14
Co-60	C-14	Cr-51	Co-57	Cr-51
Cs-134	Co-60	Co-58	Co-60	H-3
Cs-137	H-3	Co-60	Cr-51	I-125
Mn-54	I-125	H-3	H-3	Ir-197
Sr-90	U-238	Mn-54	S-35	P-32
Zn-65		Ra-226	I-125	S-35
			Tc-99m	Sr-90

concentrations of specific radionuclides within the waste, as set forth in 10 CFR 61.55 of the NRC regulation. Class A, B, and C wastes are generally suitable for near-surface disposal. Waste that exceeds the Class C limit on radionuclide concentrations is not considered suitable for near-surface disposal and was made the responsibility of the federal government by the Low-Level Radioactive Waste Policy Amendments Act of 1985. In general the human toxicity increases from Class A to Class C wastes and this increase is reflected in the more stringent disposal requirements.

Initially commercial LLRW was deposited at off-shore disposal sites approved by the U.S. Atomic Energy Commission (AEC). In response to economic factors and problems associated with monitoring ocean disposal, the AEC determined that land disposal of LLRW was a more practical method. In 1960, two interim disposal sites were designated and began accepting both federal and commercial LLRW. In 1962, the first commercial LLRW disposal facility opened at Beatty, Nevada; later in that same year the Maxey Flats, Kentucky disposal site began operation. Eventually other sites were located at West Valley, New York, Hanford, Washington, Sheffield, Illinois, and Barnwell, South Carolina. All six commercial LLRW disposal facilities employed shallow land burial technology. In this technology, waste containers are placed in an excavated trench which is backfilled with sand or similar material, compacted, and covered with earthen material. Due to problems associated with infiltration of precipitation, leachate accumulation, and radionuclide migration (primarily tritium), three sites have been closed, though the disposal sites at Beatty, Barnwell, and Hanford have continued to accept waste.

Growth in the volume of LLRW and the projected closings of licensed disposal sites have required the development of additional capacity. In 1980, Congress passed the Low-Level Radioactive Waste Policy Act, which established a new framework for LLRW management. The Act placed the responsibility for LLRW disposal on every state, but recommended the use of regional disposal facilities as the most appropriate means for resolving the problem. As a result, most states have formed regional compacts and many are involved in the process of siting a LLRW disposal facility. The Southeast Compact includes Alabama, Georgia, Florida, Mississippi, North Carolina, South Carolina, Tennessee, and Virginia. On September 11, 1986, the Southeast Compact Commission designated North Carolina as the first host state to replace Barnwell and ruled that they must provide a LLRW disposal facility by December 31, 1992.

North Carolina has accepted its host state status; however, in light of the performance history of the six existing LLRW disposal facilities, North Carolina has enacted legislation which affects the type of disposal technology ultimately chosen. In 1987 North Carolina enacted legislation that prohibits shallow land burial, requires engineered barriers, and specifies that the bottom of the LLRW facility must be at least seven feet above the seasonal high water table. These engineered barriers will be designed to complement or improve the performance of a disposal site but are not intended to substitute or compensate for a site deficiency.

Some widely considered alternative methods for near surface disposal include: below-ground vaults, above-ground vaults, earth-mounded concrete bunkers, augered holes, and mined cavities. The technology selected by North Carolina could be any one of these alternatives or a combination of different technologies. These alternatives cover a wide-range of disposal technologies and have been discussed by many authors (Baird et al., 1986; National Low-Level Waste Management Program, 1987; Illinois Department of Nuclear Safety, 1987) in detail. A general description of these disposal alternatives follows:

- Above-Ground Vaults - This disposal technology consists of placing LLRW containers in engineered concrete structures located above the ground surface. This method does not employ an earthen cover but relies on the structure to isolate the LLRW from the biosphere. The material used to construct this facility would likely be reinforced concrete, however, due to the lack of long-term experience with modern concrete it is difficult to project the lifetime of such a facility. It is known that degradation mechanisms exist in the environment which could lead to structural failure. It should be noted that some modifications of this technology involve an earthen cover. This design would be described as being above-grade but below-ground.

- Below-Ground Vaults - This technology places the LLRW in engineered concrete structures located below the natural surface grade. The below-ground vault is covered with an earthen cover similar to covers used in shallow land burial. The structure consists of reinforced concrete floors, walls, and roof. The incorporation of a below-ground vault and an earthen cover restricts water infiltration, prevents human or biological intrusion, and reduces exposure rates from gamma radiation at the land surface.

- Earth-Mounded Concrete Bunker (EMCB) - This disposal technology has been used for France. This method incorporates both above-ground disposal of LLRW (Class A waste) within an earth covered tumulus and below-ground disposal of waste (Class B and C) in a concrete bunker. At the French site, the tumulus is built above the concrete bunker. The bunker uses reinforced concrete in the construction of floors, walls, and roof. The tumulus and cover are constructed of earthen materials. As a hybrid technology involving the integration of trench disposal, vaults, and complex waste packaging, the EMCB is a relatively complex option to implement.

- Modular Concrete Canister Disposal (MCCD) - The disposal of LLRW by this method involves placing individual waste containers in modular concrete canisters which, in turn, are placed below the natural grade of the site. With the exception of the use of concrete canisters, this disposal method resembles shallow land burial and below-ground vault disposal (the concrete canisters provide structural stability). By using both earthen cover and concrete canisters, the isolation of radionuclides from the environment is enhanced.

- Augered Holes (Shaft Disposal) - Augered holes or shaft disposal involves the disposal of radioactive waste in shafts or boreholes that are drilled, bored, or augered by conventional methods. These shafts may be unlined or lined with fiberglass, metal, or concrete. Liners help reduce water infiltration into the disposal unit and improve the structural integrity. Below grade, the upper ten feet of the shaft is sealed with an engineered barrier and the whole unit is covered with a 5 to 10 ft thick engineered barrier.

- Mined Cavities - Mined cavities have been suggested for the disposal of LLRW in the United States and are currently a disposal method used in West Germany. This technology could use an already existing mine or one specially constructed. Mined cavities can be located in salt, coal, granite, or limestone beds. Although mined cavities would not have the surface degradation problems associated with other disposal methods, the requirements stated in 10CFR61 are not satisfied by this method and, therefore it could not be licensed for use in the U.S.

Although these alternative methods briefly summarized above are workable and currently licensable under 10 CFR Part 61 (except mined cavities), the NRC has focused its resources on buried placement technologies and on disposal techniques that incorporate cementitious materials (Baird et al., 1987). The focus on earth-covered technologies is based on the knowledge that an engineered LLRW facility is required to perform on the order of 300 to 500 years. Such a structure will most probably be constructed of Portland cement-type concrete (Baird et al., 1986; Pittiglio and Tokar, 1987; National Low-Level Waste Management Program, 1983). Although Portland cement has been in use only 150 years, cement specialists in general agree that the long-term durability of concrete requires additional protection from acid-rain, freeze/thaw cycles, and erosional processes. An earthen cover would provide protection from environmental degradation and also provide an additional barrier to radionuclide release and intruder protection. The NRC already has substantial experience with earth-covered structures and this knowledge could be used in developing an effective disposal technology. This report focuses on the degradation mechanisms that effect concrete engineered barriers.

Since engineered barriers cannot substitute or compensate for a site deficiency, geological and geohydrological characteristics remain critical factors in preventing the migration of radionuclides through the groundwater. In this technical report the geology and geohydrology of LLRW facilities in the eastern United States will be reviewed. The disposal sites are located at Barnwell, South Carolina; Maxey Flats, Kentucky; Sheffield, Illinois; and West Valley, New York. The geologic and geohydrologic shortcomings that have contributed to radionuclide migration will be discussed. Since environmental conditions exist that promote barrier failure, this report will examine the degradation mechanisms of concrete engineered barriers. Based on this information, the general geology/hydrology of North Carolina, and constraints enacted by North Carolina's legislation, this report will identify possible geologic and geohydrologic conditions in North Carolina that are not suitable for radioactive waste isolation.

CHAPTER 2

MAXEY FLATS, KENTUCKY

Site History

Maxey Flats was opened as a LLRW disposal facility in January 1963 under agreement between Kentucky and Nuclear Engineering Co. (now U.S. Ecology, Inc.). The burial site, which consists of 102 ha (252 acres), is located on a flat top ridge in rural Fleming County, 109 km northwest of Lexington, Kentucky (Fig. 1). The site was operated until problems with radioactive waste migration and leachate accumulation within the burial trenches forced facility closure in December 1977. Maxey Flats is currently in shutdown status, with the required maintenance, monitoring, and evaporation of leachate from burial trenches being performed by Hittman Nuclear Development Corporation.

The burial site consists of 46 closed trenches, one open trench, a number of hot wells, and several special pits. The trenches are generally unlined and vary considerably in size from 46 to 207 m (150 to 680 ft) in length, 3 to 22 m (10 to 75 ft) in width, and 2.7 to 9 m (9 to 30 ft) in depth (Clancy _et al._, 1981). The trench floor slopes one degree toward a sump constructed at the low end for dewatering purposes. The trenches have been backfilled with a minimum of 1 meter of soil to insure that a maximum exposure of

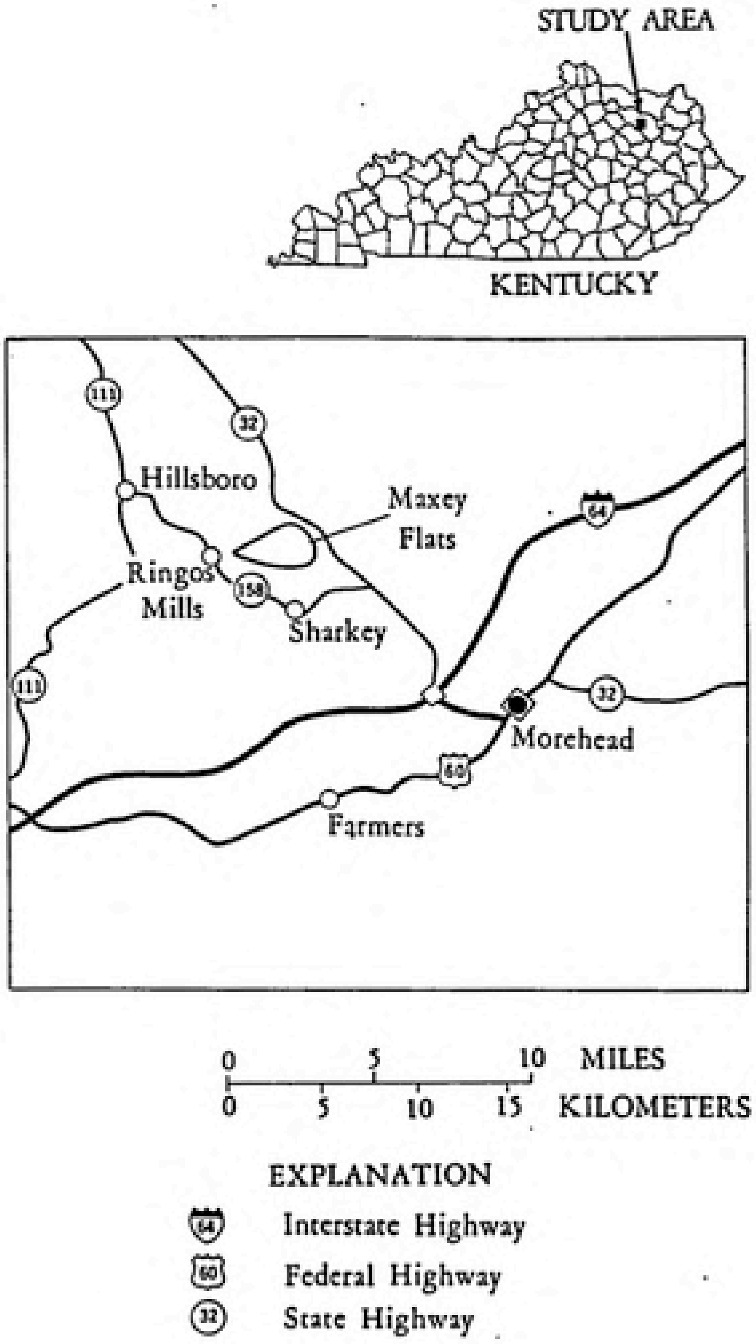


FIGURE 1. Location of Maxey Flats disposal site (from Zehner, 1983).

2 mR/hr at the trench surface is not exceeded. When a trench was filled with waste, a minimum of 1 m (3.3 ft) of clayey soil was backfilled and compacted in layers. To assist in water runoff, a mounded cap was constructed and shallow rooted vegetation planted to impede erosion.

Between 1963 and 1978 approximately 135,089 m^3 of waste was disposed at Maxey Flats. This waste contains approximately 2.4 million curies of by-product material, 431 kg of special nuclear fuel (plutonium, uranium-233, and enriched uranium-235), and 242 x 10^3 kg (533 thousand pounds) of source material (uranium and thorium not included in special nuclear material). The majority of the waste was received in solid form; however 2.2 million liters (58 thousand gallons) of liquid waste was accepted and solidified in urea-formaldehyde before burial.

Geologic Characteristics

The subsurface geology of the disposal site consists of gently dipping sedimentary rocks of Silurian, Devonian, and Mississippian Age. These sedimentary rocks are composed of clayey shales, siltstones, sandstones, and carbonaceous shales. The soils at this site consist of light-brown clay ranging in depth from .3 to 3 m (1 to 10 ft). These clays were formed from the in-situ weathering of the underlying sedimentary rocks. The sedimentary rocks found directly beneath the site in ascending order are: 1) the Upper Crab Orchard (Silurian); 2) the Ohio Shale (Devonian); 3) the Bedford Shale (Devonian to Mississippian); 4) the Sunbury Shale (Mississippian); and 5) the Borden Formation (Mississippian) composed the Henly Bed of the Farmers Member, the Farmers Member, and the Nancy Member. A diagrammatic cross-section of the Maxey Flats site is shown in Figure 2.

The Crab Orchard is predominantly a clayey shale mostly greenish gray to gray. This shale does not have a high fracture density and is relatively impermeable. The Crab Orchard is assumed to be the lower hydraulic boundary, with all groundwater flowing to the side of the hill and eventually discharging into the stream system.

The Ohio Shale averages approximately 56 m (184 ft) beneath the Maxey Flats site and is a dark-gray to black, highly carbonaceous shale. The Ohio Shale forms steep slopes and is well exposed at the burial site. Greenish-gray shale beds up to 3 m (10 ft) thick occur 15 m to 18 m (50 to 60 ft) below the top of this unit.

The Bedford Shale is approximately 8 m (25 ft) thick at the burial site and occurs as a greenish gray to light-olive-gray silty shale. The Bedford Shale has poor fissility (property of splitting easily along closely spaced parallel planes) and weathers to irregularly shaped chips. Locally thin sandstone lenses occur several feet above the base of this unit.

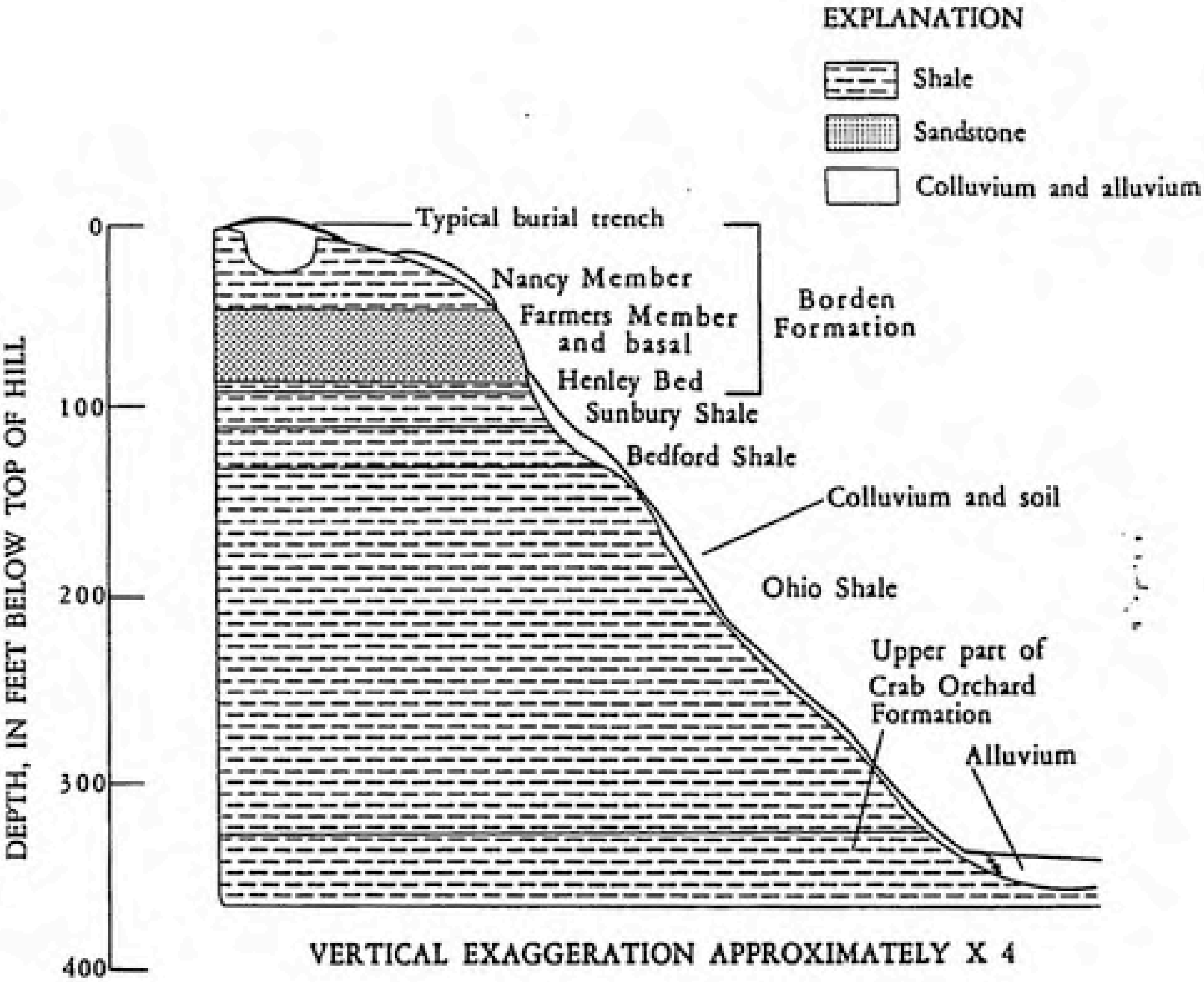


FIGURE 2. Diagrammatic cross-section of the Maxey Flats site (from Zehner, 1983).

The Sunbury Shale is approximately 5 m (18 ft) thick at the burial site and is a dark gray to black carbonate rich rock. This unit is highly fissile and forms steep slopes.

The Borden Formation is composed of the Henly Bed of the Farmer Member, the Farmer Member, and the Nancy Member. The Henly Bed at disposal site is approximately 2 m (6 ft) thick and is greenish shale. The Henly Bed commonly contains a few sandstone lenses .3 to .6 m (1 to 2 ft) thick in its upper section. The Farmer Member is sandstone unit with interbedded shale and is approximately 11 m (36 ft) thick at the site. The sandstone is very-fined grain and occurs in tabular beds up to 1.2 m (4 ft) thick. The interbedded shales are mostly greenish gray and occur in lenses less than .91 m (3 ft) thick. The Nancy Member is predominantly a shale with two distinct marker sandstone beds at the Maxey Flats site. This unit is approximately 14 m (45 ft) thick. The shale is blue to greenish gray and poorly fissle. The marker sandstone lenses are yellowish-brown and occur as two beds up to .6 m (2 ft), near the base of the Nancy Member (McDowell et al., 1971).

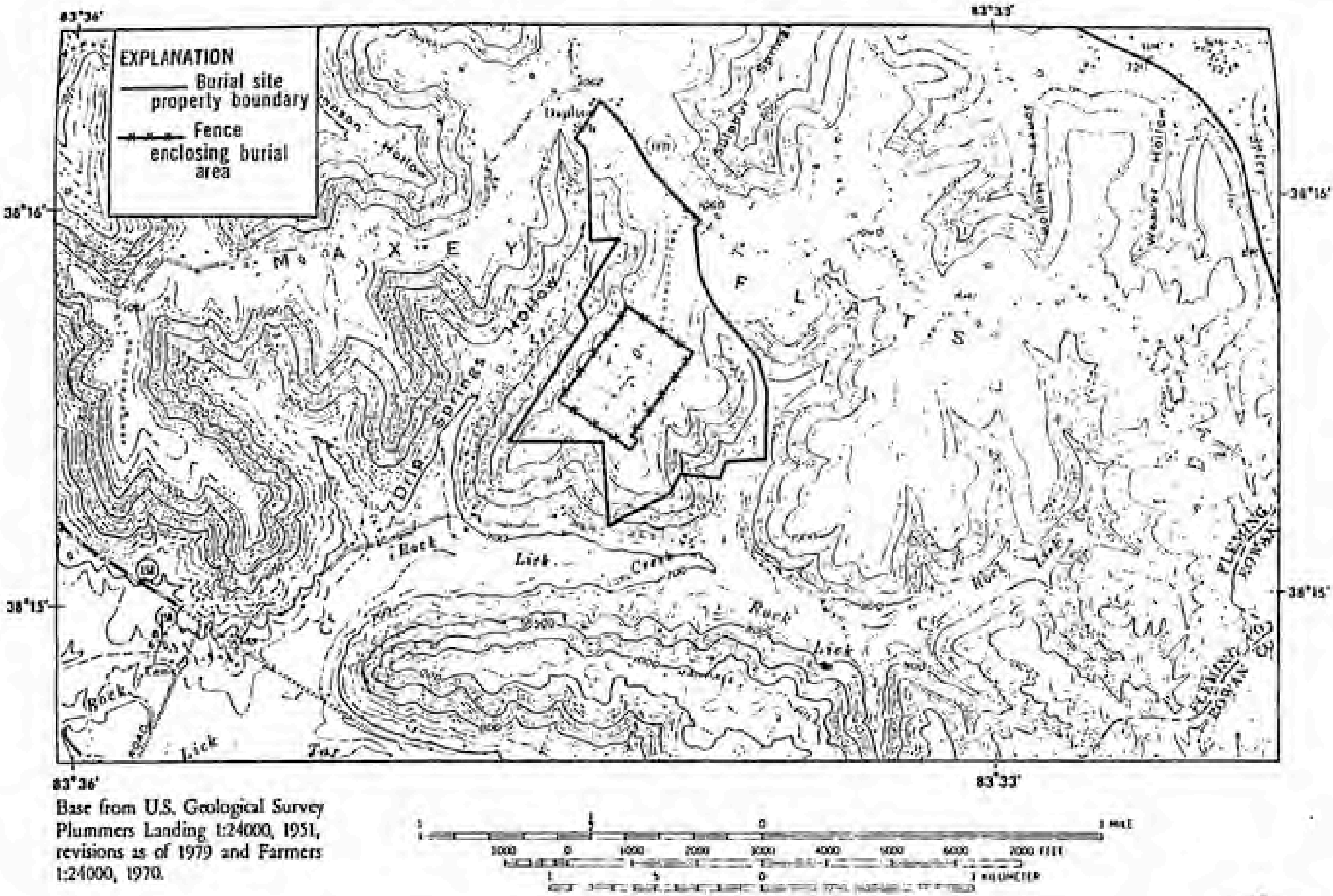
Although the rocks in this region are not presently subjected to regional stresses, all rock units above the Crab Orchard have characteristic fractures. These fractures occur in sets (dips of 80 to 90^0) and were generated by unknown regional stresses. The fractures exhibit iron-oxide alteration bands deposited by groundwater movement (Cahill, 1982). Since the burial trenches are located within the Nancy Member, fractures present may serve as a pathway for radionuclide migration.

Hydrologic Characteristics

Surface Water

Surface water drainage from the LLRW disposal site is by Drip Springs Hollow to the west, Rock Lick Creek to the South, and the unnamed stream to the east (Fig. 3). Surface flow occasionally ceases in all the streams; however pools of water are always present in low areas within the stream bed and indicate subsurface flow. Seventy-five percent of the surface runoff from the burial site flows down a small valley into the unnamed stream. Drainage from these tributaries flows into Fox Creek and then into the Licking River (National Low-Level Radioactive Waste Management Program, 1982).

The climate at Maxey Flats is humid continental, characterized by warm humid summers and cold winters. Mean annual precipitation ranges from 109 to 119 cm (43 to 47 in). The driest months are late summer and autumn; the wettest months are usually during spring and summer (Clancy et al., 1981). Streamflow data from the United States Geological Station at Rock Lick Creek indicates that average discharge is approximately .2 m^3/s (7 ft^3/s) with baseflow



Base from U.S. Geological Survey Plummers Landing 1:24000, 1951, revisions as of 1979 and Farmers 1:24000, 1970.

CONTOUR INTERVAL 20 FEET
National Geodetic Vertical Datum of 1929

Figure 3. Streams, topography, and site boundary (from Zehner, 1983).

accounting for approximately 10 percent of the total discharge.

Ground Water

Hydrologic contacts correspond to stratigraphic contacts below the Farmers Member. Four hydrologic units above the Farmers member which do not correspond to the stratigraphy are: 1) the weathered section (regolith) of the Nancy Member which includes the upper and lower sandstone marker beds, 2) the unweathered section of the Nancy Member, 3) the shale-sandstone sequence at the base of the Nancy Member, and 4) the predominantly sandstone section of the upper Farmers Member (Zehner, 1983).

The stratigraphic section, which includes the regolith and bedrock above the shale-sandstone sequence at the base of the Nancy Member, is of hydrologic importance since this is the strata where the disposal trenches are located. The bottoms of most trenches at Maxey Flats are at the lower sandstone bed in the Nancy Member. Water levels in most trenches do not appear to correspond to a particular horizon, but vary from 315 to 317 m (1033 to 1040 ft) above sea-level. Due to the accumulation of water in the trenches, the upper groundwater system has been altered from its original state. The irregular water table could be due to local groundwater mounds or local depressions from pumping leachate.

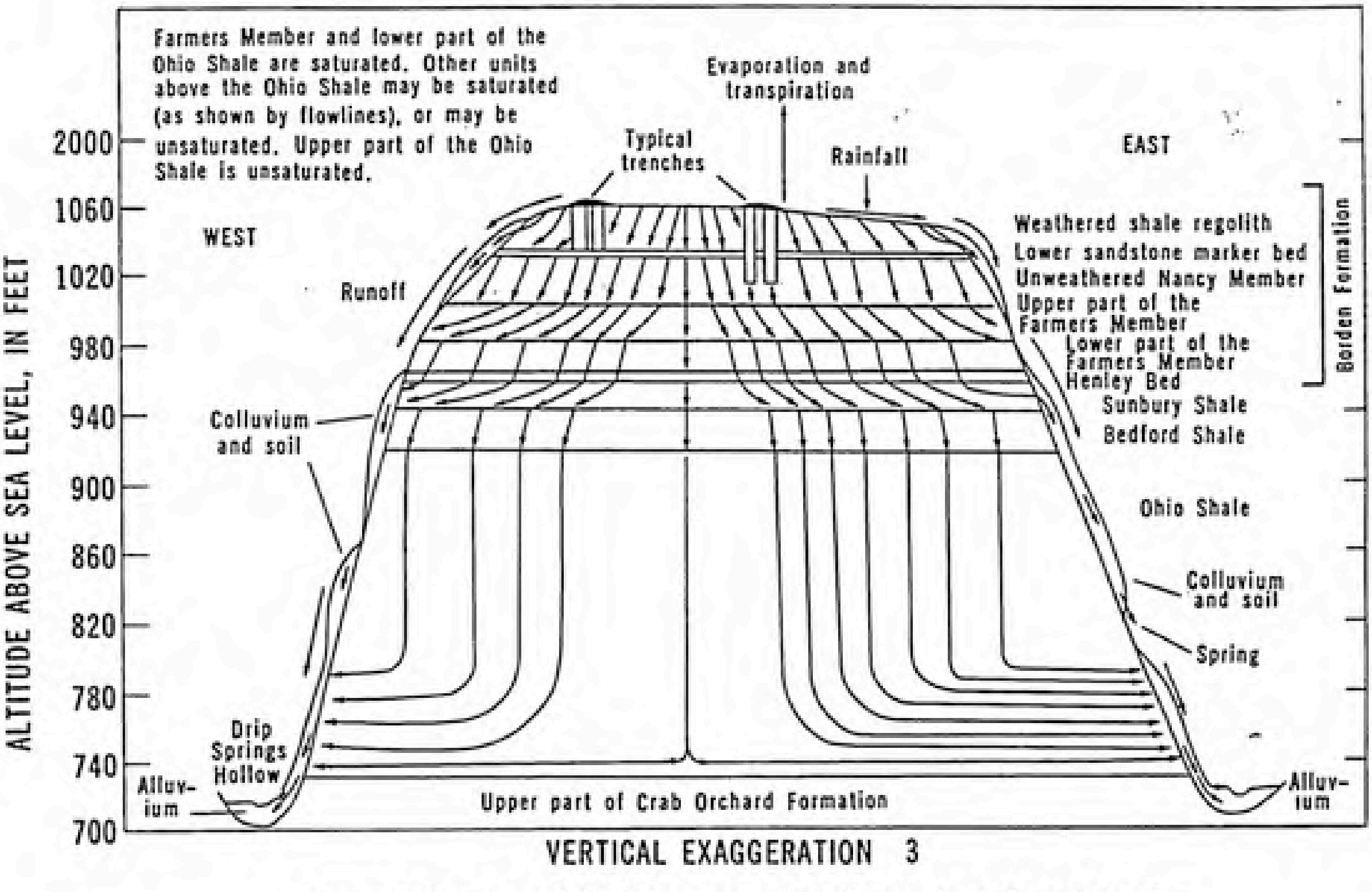
The uppermost water table is located at the base of the regolith in the trench area. Decreasing heads with depth may indicate perched water tables or a vertical gradient in saturated rock. Water table levels and the corresponding rock type are as follows: 1) 304 m to 309 m (997 ft to 1014 ft) above sea-level in the Lower Nancy Formation; 2) 296 m to 297 m (971 ft to 974 ft) above sea-level in the Lower Farmers Member; 3) 286 m to 287 m (938 ft to 942 ft) above sea-level in the Sunbury Shale; and 4) 230 m to 237 m (755 ft to 778 ft) in the Ohio Shale.

The ground-water system at Maxey Flats probably consists of sequences of saturated and unsaturated zones, with more than one sequence in some hydrologic units. The thickness of the unsaturated zones in most rocks is less than 12 m (39 ft) thick and possibly only a few meters thick in some units. The lower sandstone bed of the Nancy Member is saturated at the waste site and the lower shale has variable levels of saturation. Most rocks between the lower part of the Farmers Member and the Ohio Shale are probably saturated, with the possible exception of the upper Sunbury Shale.

Cores taken from wells at Maxey Flats show hydraulic conductivities that range from 10^{-10} to 10^{-8} cm/s (10^{-7} to 10^{-5} ft/d) in the sediments above the bedrock. Hydraulic conductivity is the ability of a porous material to transmit water and depends on a variety of physical factors including: porosity, particle size, particle packing, secondary fractures, specific weight and the dynamic viscosity of the fluid. The secondary conductivity due to joints and fractures has been estimated to be on the order of 10^{-8} cm/s (10^{-5} ft/d). Due to the overall low conductivity of rocks from this site, the primary ground water migration occurs through the secondary permeability (fractures) in the shale units and the interlinking sandstone beds (Clancy et al., 1981).

Ground water entering the surface at the burial site flows vertically downward through the unsaturated zones and has vertical and horizontal flow components in the saturated zones. Flow is predominantly vertical in the unweathered Nancy Member, Henly Bed, and Bedford Shale. Lateral flow occurs in the lower sandstone marker bed of the Nancy Member, the upper part of the Farmers Member, Sunbury Shale, and Ohio Shale. A generalized flow diagram is shown in Figure 4.

Models by Zehner (1983) indicate that 70 percent of the water entering the burial site discharges to the hillside colluvium from rocks above the lower part of the Farmers Member. Twenty percent of the flow discharges from the units between the Ohio Shale and the The upper Farmers Member. The remaining flow discharges by way of the Ohio Shale.



Arrows below ground level represent flowlines. Length and density of flowlines do not indicate velocity or volume of flow.

Figure 4. Diagrammatic hydrogeologic section of the Maxey Flats site (from Zehner, 1983).

Problems Encountered

In the early 1970's, Kentucky became concerned with the accumulation of water in the completed trenches and the increase in the volume and activity of the wastes received for disposal. Water accumulated as result of a high rate of precipitation (112 cm/yr) coupled with the decomposition of waste, creation of new voids, and trench cover subsidence. These conditions have lead to water migration through the cap and the accumulation of contaminated water in the trenches known as the "bathtub effect". In 1973, Kentucky required the site operator, Nuclear Engineering Co., to initiate a water management program. This program involves pumping the contaminated water from trenches to above ground holding tanks, floculating and filtering, evaporating the water (process uses a combustion evaporator), and transferring the evaporator concentrates to a storage tank for later disposal.

Analysis by Weiss and Columbo (1980) showed that leachate is contaminated with a variety of radionuclides, including: ^{3}H ^{60}Co, ^{89}Sr, ^{90}Sr, ^{134}Cs, ^{137}Cs, ^{238}Pu, and ^{239}Pu. Tritium concentrations were the greatest, ranging from 1.1×10^{7} to 2.3×10^{9} pCi/L. Concentrations of radionuclides differ between trenches and are a result of the quantity, waste form, and type of nuclide buried.

Radionuclides have been detected in the major drainage way on-site and in the streams off-site (Montgomery and others, 1977). Radionuclides (maximum concentration in pCi/L) detected in samples from the burial site include: Tritium (45,000 pCi/L), cobalt-60 (5 pCi/L), strontium-90 (90 pCi/L), niobium-95 (.9 pCi/L), zirconium-95 (<.6 pCi/L), ruthenium-106 (<.4 pCi/L), and cesium-137 (.2 pCi/L). Sample locations and concentration of dissolved radionuclides detected outside the burial site were: unnamed stream, tritium (13,000 pCi/L) and strontium-90 (6 pCi/L); Drip Springs Hollow near Rock Lick Creek, tritium (4,700 pCi/L) and strontium-90 (.9 pCi/L); Rock Lick Creek below unnamed valley, tritium (4,700 pCi/L) and strontium-90 (5.8 Ci/L); and Crane Creek, strontium-90 (2 pCi/L). Waste radionuclides in the stream water may have moved from the disposal site by base flow, or by overland runoff carrying contaminates soil from the waste site (Zehner, 1983).

The most significant radionuclide, based on concentration in groundwater, has been tritium. Samples taken from the wells at Maxey Flats vary depending on the well, the location and time of year. Concentrations of tritium vary from less than 200 pCi/L to 6.8 x 10^8 pCi/L (Zehner,1983). In addition to tritium, strontium-90 and plutonium-90 have been found in water samples; however these radionuclides may have been introduced during drilling, well completion, or from surface runoff from contaminated soil and samples from most wells are of limited value in determining the quality of ground water.

Factors contributing to radionuclide releases at Maxey Flats site include the low permeability of near surface soils and poor disposal practices. These factors have resulted in the subsidence of trench covers, increased infiltration of precipitation, accumulation of leachate. At Maxey Flats radionuclides are migrating both through the surface water and the ground water. Due to the small base flow in this area, the principal route for radionuclide release is through surface water runoff. Although radionuclide releases have and continue to occur from the Maxey Flats LLRW facility, studies performed by the NRC and other investigators conclude that there is no significant public health problem associated with the radionuclide releases.

CHAPTER 3

WEST VALLEY, NEW YORK

Site History

The West Valley LLRW facility is located at the Nuclear Service Center, 50 km (31 miles) southeast of Buffalo, in a rural area near West Valley, New York (Fig. 5). The Nuclear Service Center, which is owned by the New York State Energy Research and Development Authority, includes: 1) a nuclear fuel reprocessing center, 2) a spent fuel recovery and storage facility, 3) a heavy liquid storage area, 4) a high level radioactive waste disposal facility, and 5) a LLRW disposal facility. The LLRW site, operated by Nuclear Fuel Services, was opened as a commercial facility in 1963 and accepted LLRW from the northeast and middle Atlantic states. In 1971 water levels began rising in a few of the burial trenches. By 1975 the water level reached the ground surface in trench 4 and broke through the cover of the trench. This radioactive seep had a flow rate of 3.8 L/d (1 gal/d) (National Low-Level Radioactive Waste Management Program, 1982). As a result of this leakage problem, Nuclear Fuel Services terminated commercial operations. Since 1975 the disposal site has been in shutdown condition and pumping of leachate has been performed.

The disposal site consists of 14 trenches located in a northern and southern area (Figure 5). Seven trenches

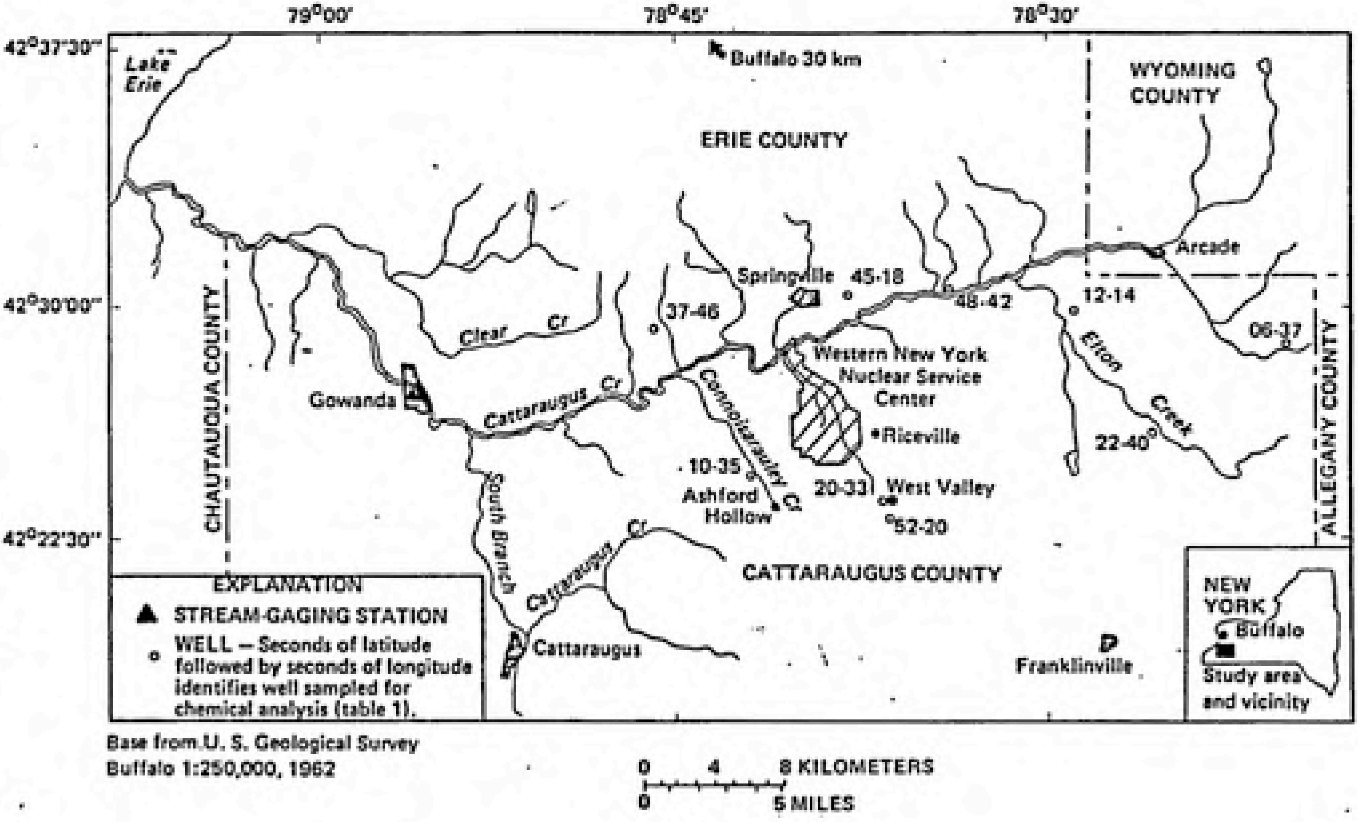


Figure 5. Location of the West Valley site (from Prudic, 1986).

(numbered 1 to 7) are located in the northern area and were used for disposal from 1963 to 1969. Trenches are approximately 240 m (787 ft) in length, 10 m (33 ft) in width, and 6 m (20 ft) in depth. Trench six is actually a series of augered holes for burial of materials requiring immediate shielding. Trench seven is a long and narrow concrete vault used for waste entombment. The seven trenches in the southern area (numbered 8 through 14) were used for LLRW disposal from 1969 to 1975. The dimensions of these trenches are approximately 180 m (590 ft) in length, 10 m (33 ft) in width, and 6 m (20 ft) in depth (Clancy *et al.*, 1981).

Between 1963 and March 1975, approximately 66,837 m^3 of waste was buried at West Valley. This waste contained 704,500 Ci of by-product material, 465,394 Kg of source material, and 56 kg of special nuclear material (including 4 Kg of plutonium). The most abundant radionuclide buried at West Valley based on activity is tritium (106,000 Ci). LLRW is no longer accepted at West Valley and there are no current plans to reopen the facility.

Geologic Characteristics

The West Valley LLRW disposal facility was selected because of the absence of shallow aquifers at the site, the good surface drainage at this site, and the low permeability of the silty till soil. The disposal site is located on a plateau with a surface elevation of about 420 m (1,377 ft) above sea level. The soils are 3 to 3.5 m (10 to 11 ft) thick and consist of weathered till. Underneath the surface soils lies 46 to 89 m (151 to 292 ft) of unweathered till complex which was deposited by two ice sheets of Wisconsian age, 14,000 to 22,000 years before the present (Albanese *et al.*, 1984). The stratigraphy of the sediments is given in Table 2. A geologic cross-section and its location are shown in Figures 6 and 7.

The bedrock, which underlies the Wisconsin till complex, is composed of Devonian Canadaway Group siltstones and shales approximately 300 m (984 ft) thick. These rocks dip southward at 6 to 8 m/km . The bedrock shows no faulting or folding in the upper layers (upper 180 m), but joints or fractures are common. This bedrock later served as parent material for the till complexes deposited during the Wisconsian age glaciation and generally 85 to 95 percent of the pebbles in the till are fragments of the local shales and siltstones (Prudic, 1986).

The till complex includes an upper till, kame deltas, lacustrine sequence, a lower till, and the bottom lacustrine deposit. The sediments in this region were deposited by the advancing ice sheets or the associated meltwater; the shales and siltstones of the Devonian bedrock being the primary source. Temporary glacial lakes formed in the valleys as glaciers blocked the northward drainage of streams, trapping large volumes of silt and clay. Some of

TABLE 2. Stratigraphy of the sediments at the West Valley LLRW site (modified from LaFluer, 1979 and Prudic, 1986).

Unit	Thickness	Lithology
(1)	0.3-1 m	Soft, plastic pebbly silt, found on on slopes. Colluvium formed by soil creep and slumps.
(2)	0.6-2 m	Gravel, pebbles to large cobble and sand. Stream deposits found in valley bottoms
(3)	0.6-2 m	Gravel and silt, underlies terraces along Buttermilk Creek.
(4)	0-6.2 m	Gravel and sand, moderately silty. Alluvial fan deposits.
(5)	5-28 m	Till, predominantly clay and silt. Formed by glacier readvance.
(6)	0-2.5 m	Layered clay or clay-silt rhythmites. Deposited in proglacial lake by advancing ice.
(7)	0-8 m	Gravel and sand deposits. Deposited in deltas or streams.
(8)	0-8 m	Well sorted and stratified sand, interbedded with silt at depth. Deposited in glacial lake by streams.
(9)	6-16 m	Interbedded silt and clay, found in rhythmic layers up to 30 mm thick. Deposited in glacial lake.
(10)	3-10 m	Till, similar to unit 5. Deposited by advancing glacier.
(11)	?	Predominantly clay, clayey silt and and silt in rhythmic layers. Similar to unit 9, formed in glacial lake.
(12)	?	Till, more sandy and stoney than units 5 and 10, found close to bedrock. May be an upland facies of unit 10, or an older till deposit.

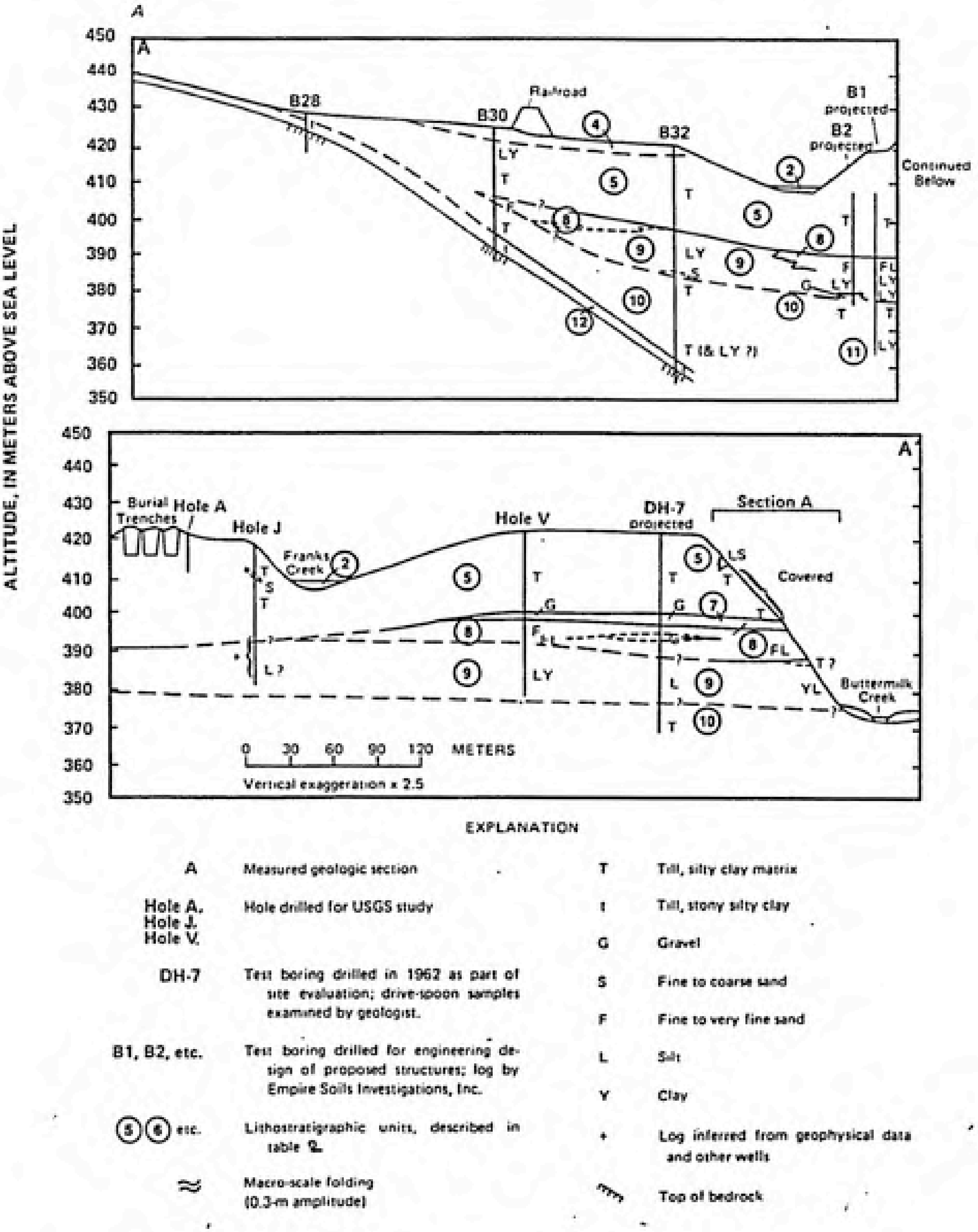
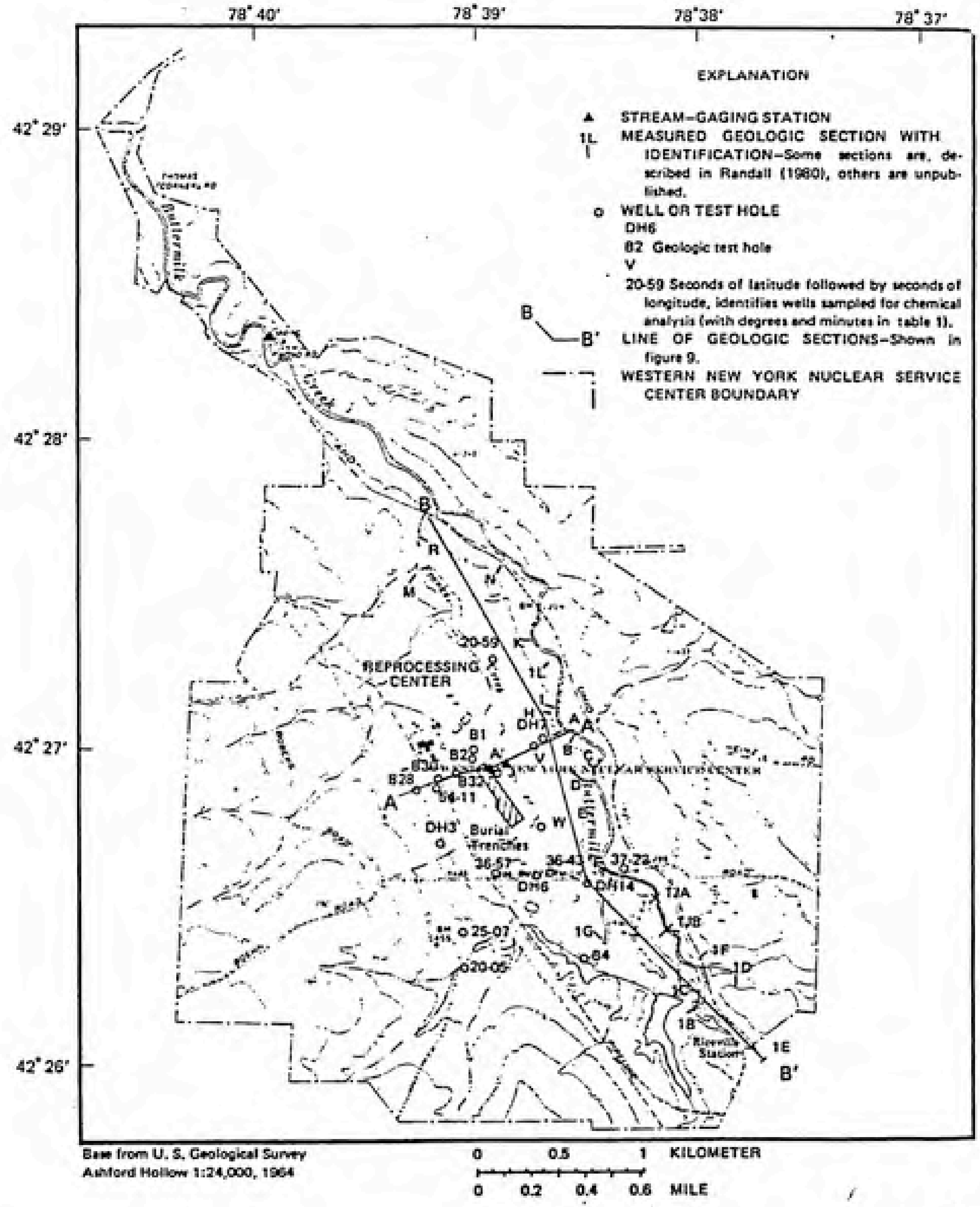


Figure 6. Geologic cross-section at West Valley (from Prudic, 1986).



Base from U. S. Geological Survey
Ashford Hollow 1:24,000, 1964

Figure 7. Location of cross-section, streams, and topography (from Prudic, 1986).

these lacustrine deposits have been preserved while others were eroded as glaciers advanced over them. Sands and gravel were deposited locally, primarily in deltas where streams entered glacial lakes and on alluvial fans of streams that developed during interglacial periods

At the disposal site the trenches are located in the upper till. This till which is approximately 28 m (92 ft) thick, is composed predominantly of clay and slit; cores taken from the burial site contained 50 percent clay, 27 percent silt, 13 percent sand and 10 percent fine gravel on the average. Distributed randomly throughout the till are pods and irregular lenses of stratified sand and gravel and rhythmic silt and clay (Prudic, 1986). This till unit was deposited by a tongue of ice that readvanced as far south as West Valley. Lafleur (1979) has correlated this readvance with the Lavery readvance in Ohio. During this readvance the glacier apparently floated free from the substrate and allowed beds of silt and clay to accumulate.

Beneath the Lavery till, Kame deltas up to 8 m (26 m) thick occur in the burial site vicinity. These units are not continuous and are randomly located. When present, this sequence is composed of pebbles and small cobbles and is absent near the burial site. Deposits east and southeast of the site may have originated as deltas in a declining postglacial lake or as an alluvial fan deposit which spread across the former lake floor (Lafleur, 1979).

The next unit is the lacustrine sequence which has an approximate thickness of 12 m (39 ft) beneath the burial site. The lacustrine deposit consists of interbedded coarse silt, fine silt, and clay in rhythmic layers. This unit is typical of bottom deposits in a glacial lake characterized by icebergs and occasional readvances of a floating or grounded ice tongue. This unit is found in all cores which penetrate the Lavery till and Kame deltas.

The next unit is a till similar to the Lavery till which was deposited during a readvance of a glacier during the Kent readvance. This unit is approximately is approximately 3 to 10 m (10 to 33 ft) thick in the burial site vicinity and is composed predominantly of sand and silt with some deformed slivers of coarse silt interbedded.

Postglacial erosion began during the Holocene (9,900 to 13,000 years ago). Immediately after retreat of the last glacier and the subsequent drainage of postglacial lakes, meltwater from ice to the north and runoff from the hillsides spread gravel over large areas of the Cattaraugus Creek basin, including the Buttermilk Creek valley. The incision by Cattaraugus Creek initiated erosional processes which continue to the present.

Because of this postglacial incision and the fine grained texture that characterizes the till complex, the West Valley area is prone to landslides. Landslides have been observed along the streams bordering the LLRW site. In the long term, larger landslides will eventually encroach on site boundary (Albanese _et al._,1984).

Hydrologic Characteristics

Surface Water

The West Valley Burial site lies entirely within the Buttermilk Creek drainage basin. Franks Creek, a tributary to Buttermilk Creek, drains the east, south and southwest parts of the burial site (Fig 7); an unnamed tributary to Franks Creek drains the north and northwest sections.

The climate at the West Valley burial site is humid continental, with annual precipitation averaging 100 cm (39.4 in). Most of the runoff from the burial site flows into Lake Erie via Franks Creek, Buttermilk Creek, and Cattaraugus Creek or returns to the atmosphere by evapotranspiration.

Ground Water

The stratigraphy of the materials at the LLRW site plays an important role in the movement of ground water. The upper parts of the underlying lacustrine sediments are unsaturated, but the deeper lacustrine sediments are saturated and provide a migration pathway for lateral flow through the coarse sediments, eventually discharging into the bluffs along Buttermilk Creek. The unsaturated conditions in the lacustrine units result from low vertical permeability of the Lavery till and thus, result in low recharge through the till. The lacustrine sequence acts as a drain to the Lavery till and produces downward hydraulic gradients.

Information from a well drilled on the eastern side of the disposal site, shows that the depth to ground water is 31 to 38 m (102 to 125 ft) and is located in lacustrine sediments. Trenches at West Valley were dug to a depth of 6 m (20 ft); the trench bottoms lie from 25 to 32 m (82 to 105 ft) above the water table (Clancy et al., 1981). This aquifer does not yield usable quantities of water. The shattered upper section of the Devonian is the major aquifer in this stratigraphic sequence.

Detailed studies of the LLRW disposal site hydrology have been confined to the Lavery till since the trenches are located in the till. Trench covers were constructed from reworked till, and studies (Prudic, 1986) show that radionuclide migration has not extended through or beyond the Lavery till. The Lavery till is not a homogeneous body, but composed of a weathered section, a unweathered section, and distorted lenses of stratified sand an gravel.

Prudic (1986) examined 28 core samples taken from the unweathered till at West Valley. These samples had an average porosity of 32.4 percent. Analysis of thin sections show no preferred orientation of clay grains and suggests little anisotropy. Field and laboratory tests have measured a hydraulic conductivity that ranges from 2×10^{-8} cm/s (5.67×10^{-5} ft/d) to 6×10^{-8} cm/s (1.7×10^{-4} ft/d) in the unweathered till.

The upper 2 to 3 m (7 to 10 ft) of till is weathered and contains intersecting features. These fractures have firm oxidized borders and extend down approximately 5 m (16 ft) to the unweathered till (Prudic and Randall, 1979). Computer simulations of ground water flow indicate the weathered till is ten times more permeable than the unweathered till.

Randomly distributed lenses or pods of silt, sand, and clay are found in the Lavery till. These distorted lenses of stratified material make up approximately 7 percent of the total mass of sediments. These units are discontinuous, deformed and randomly rotated. Values for hydraulic vertical and hydraulic conductivity vary from 3×10^{-6} cm/s (8.51×10^{-3} ft/d) to 6×10^{-6} cm/s (1.7×10^{-2} ft/d), two orders of magnitude greater than the unweathered till.

The hydraulic gradient in the till surrounding the LLRW site is predominantly downward. In general, ground water flows vertically downward from the trench floors through the till and the unsaturated part of the underlying lacustrine sequence about 23 m below the trench bottom. Ground water then flows laterally northeasterly through saturated lacustrine sediments until discharging along Buttermilk Creek. Figure 8 shows an idealized view of ground water flow in the vicinity of the LLRW disposal site. Computer simulations of possible ground water flow at West Valley suggest that water leaving a trench would take 300 to 2,300 years to travel 23 m (75 ft) to the underlying lacustrine sequence. The shortest distance for surface discharge is 840 m (2,756 ft) and this would require an additional 500 years.

Problems Encountered

Water levels in the trenches have been monitored regularly since 1966 by Nuclear Fuel Services, Inc. Significant increases in water levels in trenches 3 through 5 (north site) was observed in 1971. In March 1975, trench water seeped out through the trench cover along the side of trench 5 and the northern end of trench 4. The burial of commercial LLRW was stopped after the discovery of this seep. From March 1975 through October 1976, approximately 6.4 million liters (1.69 million gal) of leachate was pumped from trenches 3, 4 and 5 (Clancy et al., 1981). Leachate was transferred to the on-site reprocessing plant for decontamination.

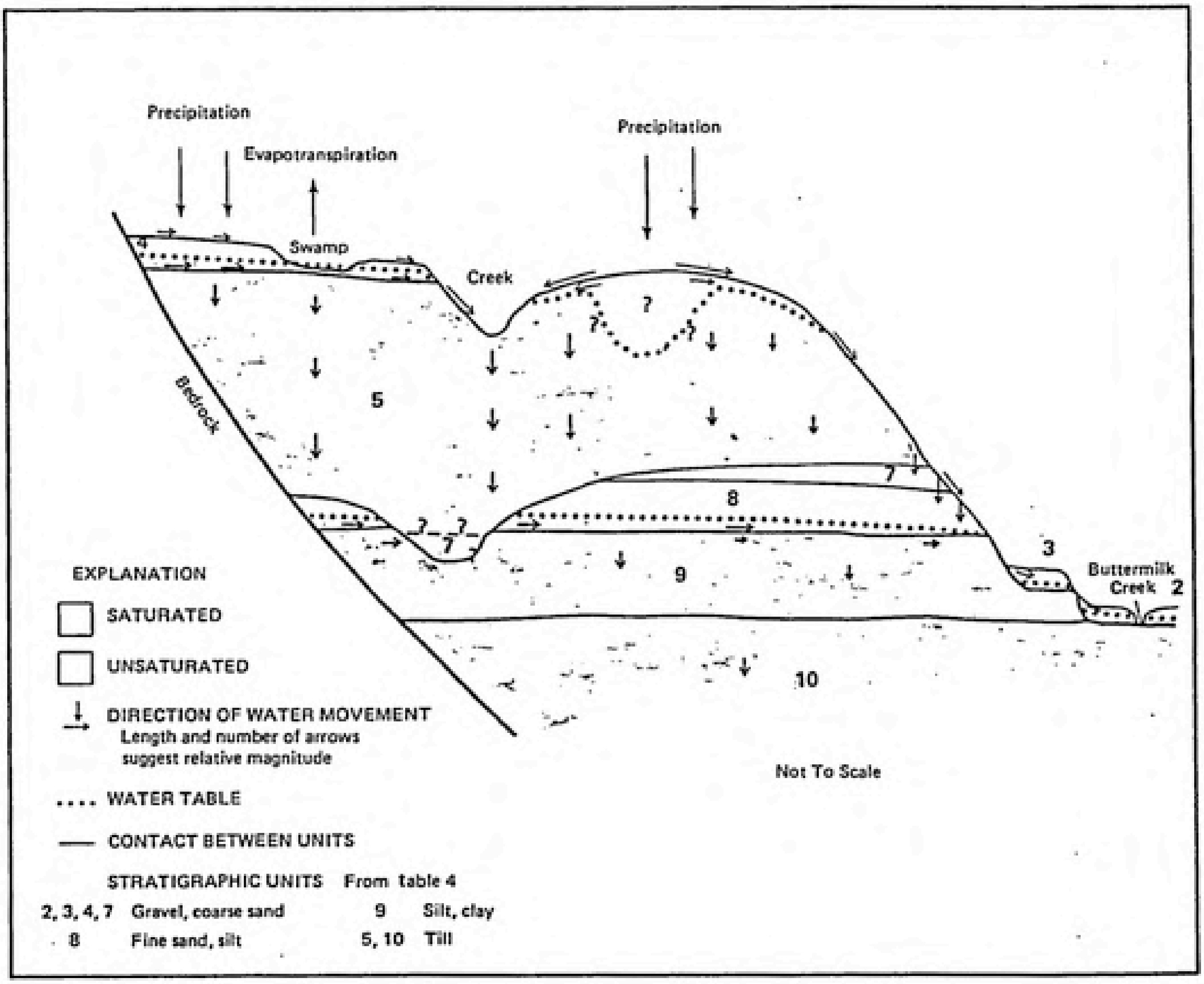


Figure 8. Idealized ground-water flow at West Valley (from Prudic, 1986).

The principal cause of the water accumulation in the trenches at West Valley was the infiltration of precipitation through the trench covers rather than from ground-water seepage from the till. Seasonal drying and subsidence from waste decomposition resulted in cracks forming in the trench covers. These cracks provided efficient pathways for precipitation to the trench. The low permeability of the till coupled with the normal precipitation rate, prohibited rapid migration of the trench water and resulted in the accumulation of large volumes of water.

Radiochemical analysis indicates the trench leachate is contaminated from the buried LLRW. Gross alpha activity ranges from 8.9×10^{-7} to 8.2×10^{-2} uCi/mL. Gross beta activity ranges from 7.6×10^{-6} to 3.1×10^{-2} uCI/mL. The concentration of tritium varies from 3.1×10^{-4} to 4.3 uCi/mL. The major gamma emitting radionuclides found in the leachate are ^{137}Cs, ^{134}Cs, ^{60}Co, and ^{241}Am. The concentration of ^{137}Cs ranges from 4.9×10^{-6} to 1×10^{-3} uCi/mL and ^{134}Cs ranges from 6.4×10^{-8} to 1.3×10^{-5} uCi/mL. The concentration of ^{60}Co varies from 9.9×10^{-7} to 7.0×10^{-5} uCi/mL. The smallest concentrations are for ^{241}Am, this value ranges from 2.1×10^{-8} to 2.0×10^{-7} uCi/mL (Prudic, 1986).

Radionuclide migration is evaluated primarily on information from cores taken alongside and beneath trenches and the radionuclide concentration in trench leachate.

Radionuclide migration can occur both laterally and downward from the LLRW trench sites. At West Valley migration has occurred both outward and downward, but not at significant rates to endanger the public.

Analysis of cores taken from 29 test holes at distances of 2.5 to 5m (8.2 to 16.4 ft) from the burial sites (Prudic and Randall, 1979) indicates that tritium has migrated laterally approximately 2.5 m (8.2 ft) through the unweathered till at two sites. Lack of widespread lateral migration of tritium supports the conclusion that migration is primarily downward at West Valley. Lateral flow from trenches occurs only when water levels in the trench intersect the more permeable weathered till or the reworked till used in constructing the cover.

Cores collected beneath trenches 4, 5, and 8 indicate the downward migration of radionuclides from the trenches at West Valley. The principal radionuclides that have migrated downward at this site are tritium, ^{14}C, and ^{90}Sr; the remaining radionuclides identified in the leachate do not show significant migration. Tritium is the most mobile radionuclide of those buried and has been detected to a depth of 3 m beneath trench 8. Cores taken from trench 5 show that ^{14}C has migrated up to 1 m beneath the trench floor. Strontium-90 was detected beneath trenches in only a few cores and its downward migration varies 0.14 m to 0.70 m (.46 to 2.29 ft) (Prudic, 1986).

Since the movement of ground water and radionuclides at West Valley is primarily downward, Prudic (1986) uses a one dimensional model to determine migration rates for tritium, ^{90}Sr, and ^{14}C. The maximum distance tritium is predicted to migrate after 100 years ranges from 10 to 14 m (33 to 46 ft) depending on model parameters. Due to this slow migration rate, tritium is confined to the weathered till and unlikely to discharge into Buttermilk Creek. Models indicate that the maximum distance that ^{90}Sr can migrate and still be detected is between 3 to 6 m (10 to 20 ft) in 500 years. This migration rate is smaller than the value for tritium and is attributed to the sorption of ^{90}Sr on the till particles and a smaller diffusion coefficient. Carbon-14 would require between 1500 to 20,00 years to travel 23 m (75 ft) to the saturated lacustrine sediments.

Migration of radionuclides at West Valley is severely limited by the geologic and geohydrologic characteristics of the site. The low permeability and thickness of the unweathered till has retarded radionuclide migration. Radionuclides are unlikely to reach the environment through subsurface migration. There has been no significant migration of radionuclides through the ground water and no significant problems with surface contamination. The major problem at West Valley has been the accumulation of leachate within the burial trenches. Cracks in the trench covers facilitate infiltration of precipitation though the low permeability of the till prevents migration from the trench.

CHAPTER 4

SHEFFIELD, ILLINOIS

Site History

The Sheffield LLRW disposal site is located approximately 5 km (3.1 mi) southwest of the town of Sheffield, Illinois (Fig. 9). The facility began accepting commercial LLRW in August 1967 and was operated by California Nuclear, Inc.. In March 1968 the operating license was transferred to Nuclear Engineering Company, Inc. (NECO), presently U.S. Ecology Inc. In 1975, NECO requested a modification to its license that would allow the construction of compacted fill trenches which were intended to increase the capacity and burial lifetime of the facility. The Nuclear Regulatory Commission (NRC) approved construction of compacted fill trenches but withheld approval for waste burial in these new trenches. In 1976, U.S. Ecology filed an application to the NRC and the State of Illinois for expansion of the burial site from 8 ha (20 acres) to 81 ha (180 acres). While this request was under evaluation, U.S. Ecology requested permission to build a new trench (Trench 15) within the original 8 hectare site. In March 1978, the NRC ruled that LLRW could not be buried in Trench 15. The last trench was completely filled on April 18, 1978 and U.S. Ecology ceased burial operations at the

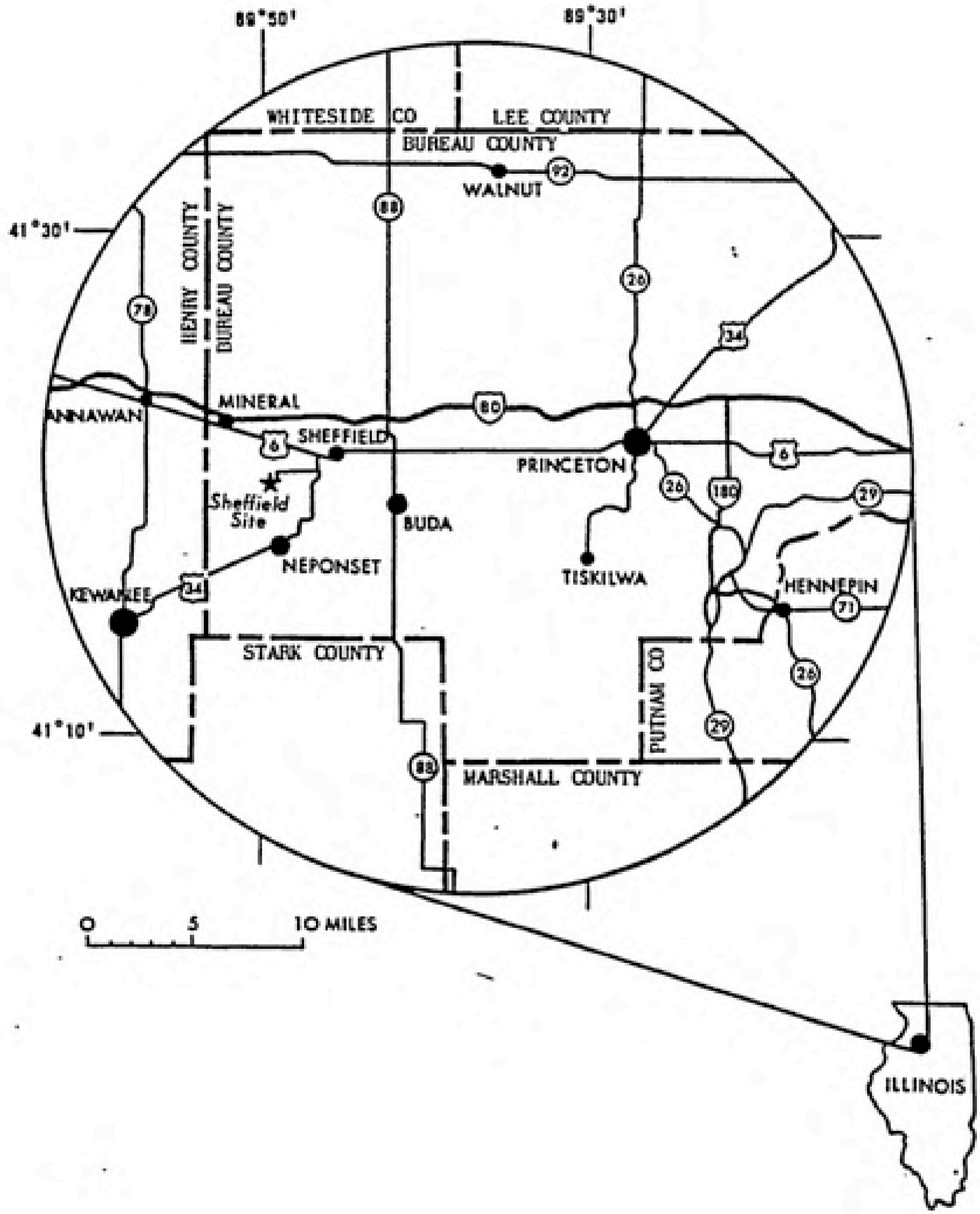


Figure 9. Location of Sheffield disposal site (from Foster et al., 1984).

Sheffield facility (National Low-Level Radioactive Waste Management Program, 1982).

Shallow land burial was the disposal technology used at the Sheffield site. At the time of closure 22 trenches had been constructed and filled with LLRW. Typical trench dimensions range from 40 to 80 m (131 to 262 ft)in length, 12.2 to 24.4 m (40 to 80 ft) in width, and 6.1 to 12.2 m (20 to 40 ft) in depth. Nineteen of the trenches were excavated leaving a minimum of 3 m between the trench bottom and the saturated zone. Two of the trenches were constructed above the existing surface grade by constructing walls of compacted silty-clay (Clancy et al., 1981).

From 1976 until 1978, LLRW was buried in the 21 trenches at the Sheffield facility. During this period, approximately 90,513.1 m^3 (3,196,017 ft^3) of waste was buried. This included 60,205 Ci of by-product material, 54 kg of special nuclear material, and 270,840 kg of source material (Healy et al., 1986). Although disposal has ceased at Sheffield, radionuclide migration and general upkeep of the site continues in this shutdown mode.

Geologic Characteristics

The Sheffield LLRW facility in located in rolling terrain underlain by Pleistocene glacial deposits that average 18 m (59 ft) in thickness. These unconsolidated glacial deposits overlie Pennsylvanian shale approximately 137 m (449 ft) thick (Clancy et al., 1981). A generalized cross-section (Fig. 10) shows the stratigraphic relationship of the various rock units beneath the LLRW site. The location of the cross-section is given in Figure 11.

Beneath the glacial deposits lies a section of the Carbondale Formation of the Pennsylvanian period. This section is composed predominantly of mudstones and fossiliferous shales. Samples of weathered shale range from silty clay to a clayey silt. This thick sequence of shale and mudstone isolates the regional ground-water aquifers from the hydrologic system of the overlying glacial sediments.

The Pleistocene glacial sediments lie unconformably over the Pennsylvanian bedrock. The glacial deposits are composed of Glasford Formation, the Roxana Silt, the Peoria Loess, and fill. The Glasford Formation is further divided into: the Duncan Mills Member, the Hulick Till Member, the Toulon Member, the Randor Till Member, and the Berry Clay Member (Foster et al., 1984).

The oldest glacial sediments are the Duncan Mills Member. These sediments are a thick sequence of lacustrine deposits formed during the Illinoian ice age. The Duncan Mills Member consists of silty clays interbedded with silt, clay and sandy silt layers. This section is found in the bottoms of old valleys and reaches a maximum thickness of 16.7 m (55 ft) (Foster et al., 1984).

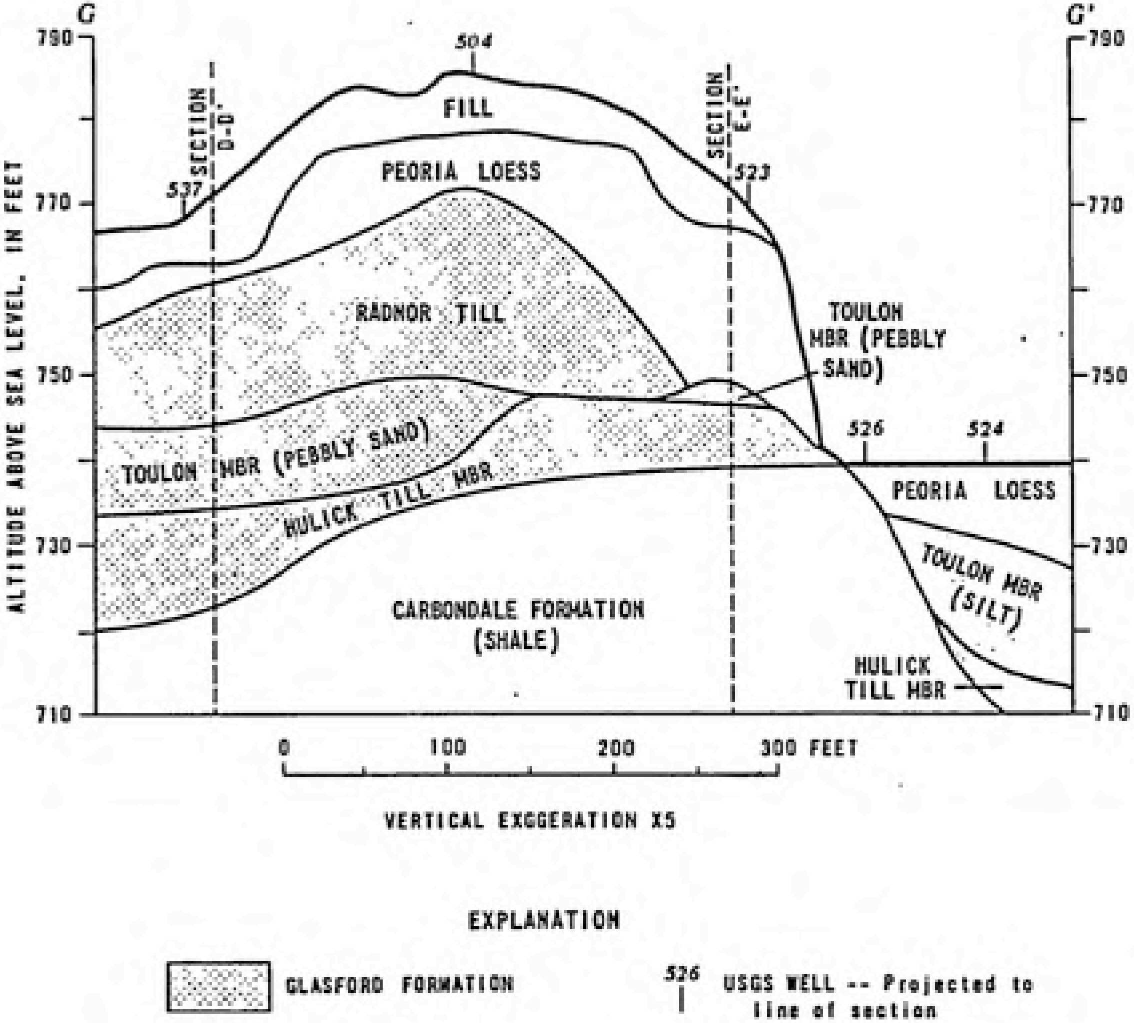


Figure 10. Geologic cross-section of the Sheffield site (from Foster *et al.*, 1984).

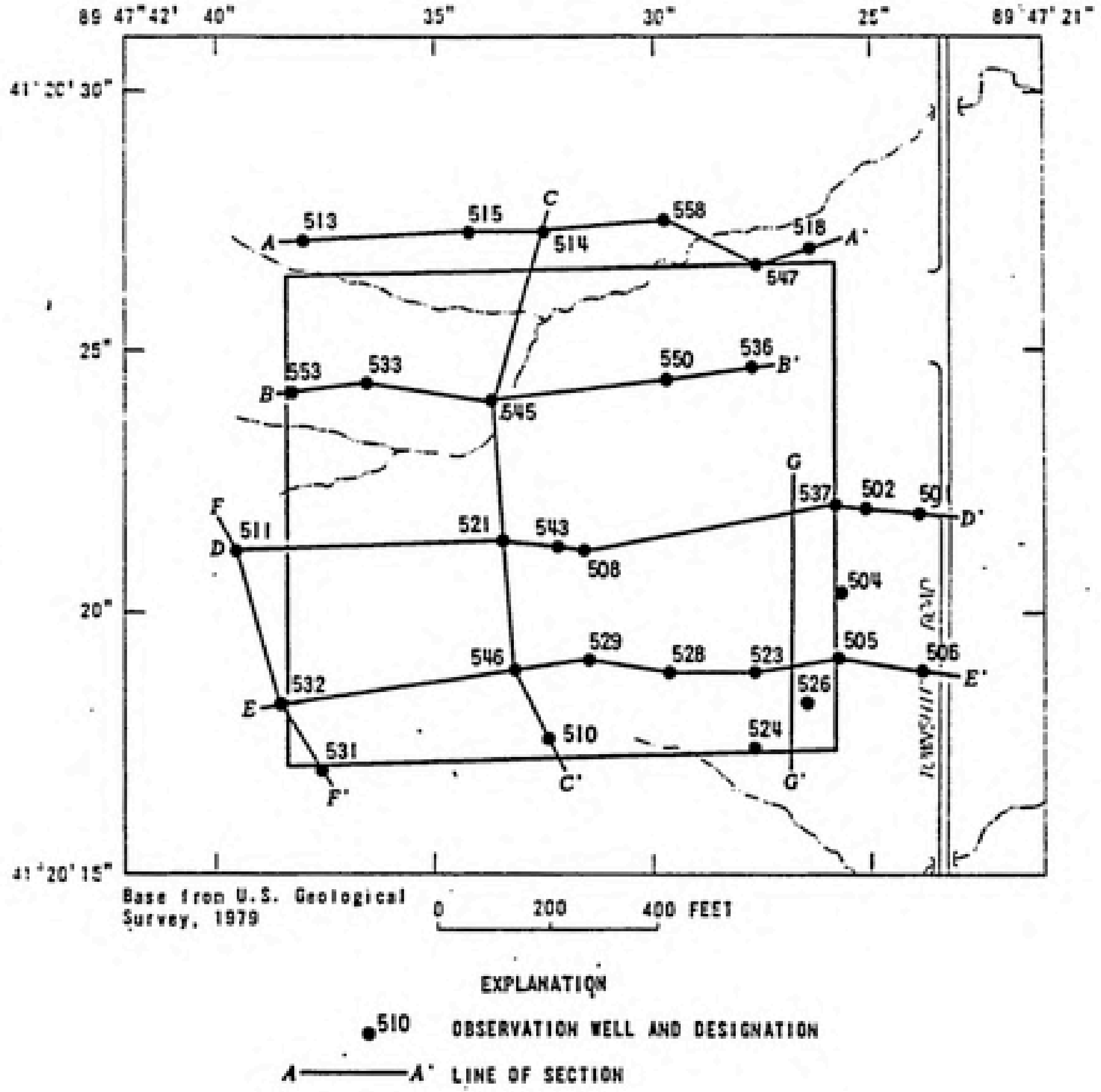


Figure 11. Geologic cross-sections (Foster _et al._, 1984).

The Hulick Till Member overlies the Duncan Mills Member and underlies most of the LLRW site. This unit was deposited during the Illinoian glacial period and is composed of sands, silts, and clays. This unit has an average thickness of 2 m (6.6 ft). In places where the glacier incorporated more lacustrine sediments the Hulick Till has an increased silt content.

The Toulon Member overlies the Hulick Till Member. The Toulon Member is an outwash plain deposit of the Illinoian glacial period. These outwash sediments grade from moderately-sorted pebbly-silty sands at the western site area to well-sorted pebbly sands in the eastern area. The Toulon Member is approximately 5 m (16.4 ft) thick and is absent in the southwest and northwest sections of the LLRW site.

During the final stages of the Illinoian glacial period, The Randor Till Member was deposited. This unit overlies the Toulon and is approximately 3 m (9.8 ft) thick when present. This till unit consists of interbedded clayey-silts and non-continuous sand-silt lenses. The Randor Till Member is distinguished from the Hulick Till Member by its higher clay content, 72 percent to 56 percent (Foster et al., 1983).

Overlying the Randor Till Member in the upland areas of the site is the Berry Clay Member. The Berry Clay Member was formed during the Sangamonian Stage after the Illinoian glaciers had retreated. The Berry Clay Member is gley soil formed by the in-situ weathering of the Randor Till Member (Willman and Frey, 1970).

During the Wisconsian Stage, continental ice sheets did not cover this area of Illinois and, therefore, the characteristic till and lacustrine sediments are absent. Aeolian sands and silts were deposited at this time and are represented at the Sheffield site by the Roxana Silt and the Peoria Loess. The source material for these units was the lake deposits along the Mississippi River and the outwash plains. The Roxana Silt is composed of Lower Wisconsian Silts and ranges from .4 to 2.2 m (1.3 to 6.6 ft) in thickness. The overlying Peoria Loess, Middle to Upper Wisconsian, covers the entire site and ranges in thickness from .6 to 9.1 m (1.9 to 29.8 ft) (William and Frey, 1970).

The present soil is from the weathering of the Peoria Loess. This soil is predominantly a clayey silt and, when present, varies in thickness from 0.6 to 2.7 m (2 to 9 ft). In the construction of the burial trenches, the soil has been removed or covered by fill. The fill is the youngest unit at the LLRW site and consists of clayey silt to silt. This material was used in trench cap construction and in the filling of low areas. Thickness of the fill varies from 0.6 to 7.1 m (2 to 23.3 ft) depending on the site area (Foster et al., 1984).

Hydrologic Characteristics

Surface Water

The Sheffield LLRW facility lies within the headwater tributaries of Lawson Creek, which at its nearest point is 1.6 km (.99 mi) east of the site. Surface water drains from the site by three streams which discharge into Lawson Creek. Flow from the Lawson Creek eventually reaches the Mississippi River.

Northwest Illinois's climate is humid continental, with warm summers and cold winters. Precipitation averages 89.1 cm/yr (35 in/yr) (Healy et al., 1985). This value is broken down into recharge to the saturated zone (6.2 cm), surface runoff (22.9 cm), and evapotranspiration (60 cm).

Ground Water

The variable lithology of the glacial sediments that overlie the Pennsylvanian bedrock provides a complex hydrologic system at Sheffield. The site hydrologic system is composed of glacial sediments from the ground surface to the bedrock. The unsaturated zone and the shallow saturated zone are contained within the glacial sediments. The deeper regional aquifers are isolated from possible radionuclide migration by the Pennsylvanian bedrock (Healy et al., 1985). Recharge of the hydrologic system is from precipitation since no significant underflow is present.

At Sheffield the unsaturated zone averages 12 m (39 ft) in thickness. With the exception of the Duncan Member which is always saturated, the unsaturated zone may include, depending on site location, the Peoria Loess, Roxana Silt, The Berry Clay Member, the Randor Till Member, the Toulon Member, and the Hulick Till. The glacial sediments found in the unsaturated zone have a range of textures and, therefore, a wide range of permeabilities. The Peoria Silt is a significant unit at this LLRW and has a an average vertical hydraulic conductivity of 1.1 x 10^{-5} cm/s (3.1 x 10^{-2} ft/d) and an average horizontal conductivity of 8.8 x 10^{-6} cm/s (2.5 x 10^{-2} ft/d). Burial trenches were placed in the unsaturated zone (with the exception of trench 18) and rely on the sorption characteristics of this zone to impede radionuclide flow.

In general, the glacial sediments at Sheffield have average vertical and horizontal conductivities on the order of 10^{-8} to 10^{-6} cm/s (10^{-5} to 10^{-3} ft/d). The pebbly sand of the Toulon Member is an exception, however, with horizontal conductivity of 5.5 x 10^{-2} cm/s (1.6 x 10^{2} ft/d) (Foster _et al._, 1983). Burial trenches were placed in the unsaturated zone at Sheffield (with the exception of trench 18) to take advantage of the low conductivities of the sediments to impede radionuclide flow.

Ground water that moves through the soil flows vertically downward through the Peoria Loess to the saturated zone. In addition to this flow, water is

apparently moving laterally in the unsaturated zone in subsurface areas where the Peoria Loess contacts the pebbly-sand unit of the Toulon Member and at the basal contact of the Toulon Member with the Hulick Till.
This lateral movement of water in the unsaturated zone may account for the rapid tritium migration at the southeastern area of the site.

The saturated zone includes all glacial sediments between the water surface and the bedrock. The saturated zone averages 6 m (20 ft) in thickness and the water table ranges from 6 to 15 m (20 to 49 ft) below the ground surface (Clancy et al., 1981). Most sediments have low permeability with the exception of the course pebbly-sand sediments. Depending on site, the saturated zone may include the Duncan Mills Member, the Hulick Till Member, the Toulon Member, and the Peoria Loess.

The Duncan Mills Member is fully saturated beneath the waste site and overlies the Pennsylvanian bedrock. The average vertical hydraulic conductivity is 6.7×10^{-7} cm/s (1.9×10^{-3} ft/d).

The Hulick Till Member acts as a semi-impermeable barrier to vertical flow in the saturated zone. This unit overlies the Duncan Mills Member in the valleys, and overlies bedrock in topographically higher regions. The average vertical hydraulic conductivity is 1.5×10^{-6} cm/s (4.3×10^{-3} ft/d) and the average horizontal conductivity is 5.5×10^{-7} cm/s (1.6×10^{-3} ft/d)(Foster et al., 1983).

The Toulon Member underlies 5.7 ha (14 acres) of the LLRW site, 4 ha (10 acres) are partially to completely saturated. The hydraulic conductivity of this unit varies with its lithology and ranges from 2.2 x 10^{-5} to 5.5 x 10^{-2} cm/s (6.2 x 10^{-2} to 1.6 x 10^{2} ft/d) (Foster et al., 1983). The difference in these values is a function of the amount of silt present in the pebble units. The pebbly-sand unit of the Toulon Member has the highest measured conductivity and is the controlling factor in the migration of water into, through, and across the LLRW site.

The Peoria Loess is predominantly in the unsaturated zone; however in a few locations it extends into the saturated zone as much as 3.6 m (11.8 ft). The average vertical hydraulic conductivity is 8.8 x 10^{-8} cm/s (2.49 x 10^{-4} ft/d) and the average horizontal conductivity is 1.1 x 10^{-5} cm/s (3.1 x 10^{-2} ft/d).

In this complex hydrologic environment, water will move faster in the lithologic units with the higher hydraulic conductivities. At the Sheffield LLRW site ground water flows from the west to the east and mimics the surface drainage pattern. There are two principal flow paths for this site. The primary flow path, extending from offsite to northeast of the site, is through the saturated pebbly-sand unit of the Toulon Member. The secondary flow path is through the silt of the Peoria Loess. Discrepancies in the calculated and observed migration rates suggests that ground water is moving along the interface of the Peoria Loess and the Toulon Member (Foster et al., 1984). Possible flow paths are shown in Figure 12.

Problems Encountered

The performance of the Sheffield LLRW site has shown some of the same problems as Maxey Flats, West Valley, and Barnwell. Three major problems have been encountered at the Sheffield LLRW disposal site: erosion, trench cap subsidence, and radionuclide migration from some trenches. These problems are discussed in the following sections.

Surface erosion from precipitation has resulted in the formation of gullies and rills in the drainage ways between those trenches on slopes which were created by the building up of trench walls. Surface runoff is concentrated in the small drainage ways between caps. This channeling of water has resulted in deeply incised gullies. In some locations these gullies have exceeded 2.1 m (6.9 ft) in width and 3 m (10 ft) in length. Interbranch gullies can be eliminated by grading the surfaces to a more gentler slope. Gentle slopes would allow sheet flow over trench surfaces and thus eliminate flow in narrow channels between caps. This erosion process can lead to damage to the caps and loss of cap integrity (Kahle and Rowlands, 1981).

Trench subsidence has occurred at the Sheffield LLRW site and is dependent on the amount of surface water

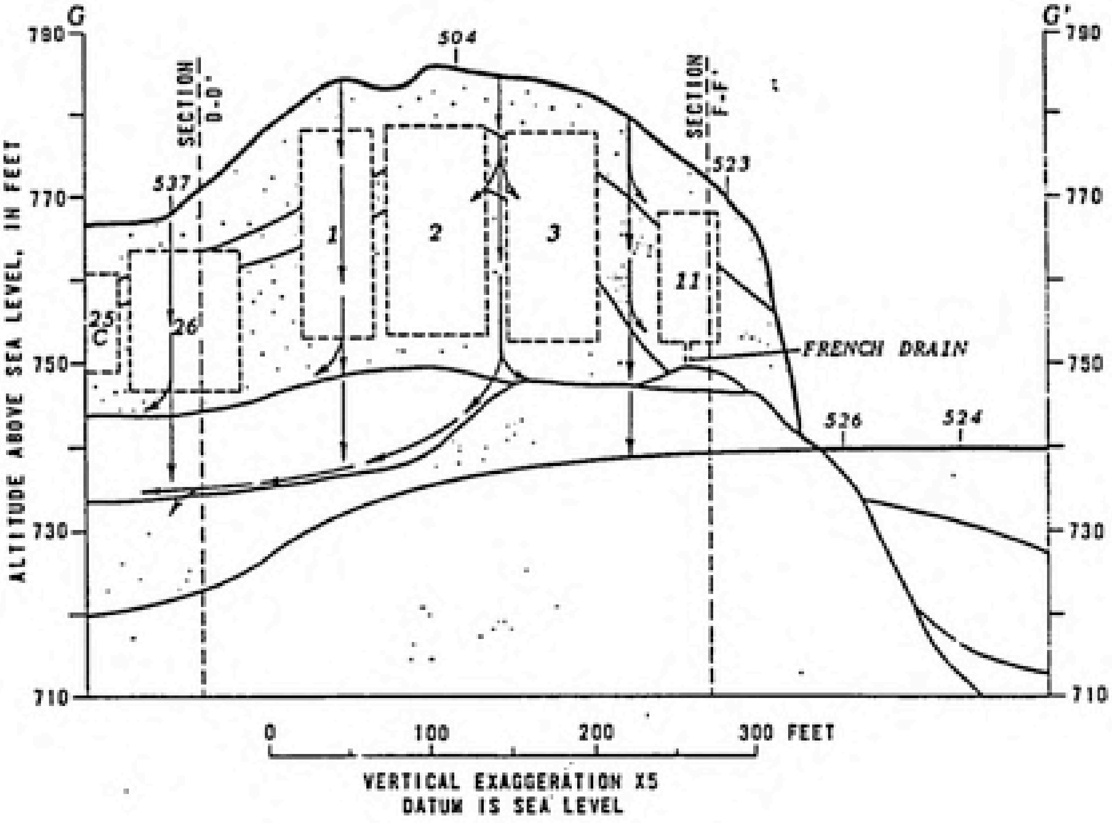


Figure 12. Possible ground-water flow through the unsaturated zone (from Foster <u>et al.</u>,1984).

infiltrating the trench cap. Trenches at this site have the potential for subsidence due to soil consolidation, piping, and waste decomposition. Holes occasionally form in the trench cap when voids develop below the trench cap. These collapsed holes vary in size from .6 to 4.0 m (1.9 to 13.1 ft) across and 1.2 to 3.0 m (3.9 to 10.0 ft) in depth (Foster et al., 1983). This situation leads to increased infiltration of trench caps by precipitation and a greater potential for radionuclide migration through the groundwater. In contrast to the problem of leachate accumulation at Maxey Flats and West Valley, water has not accumulated in the trenches at Sheffield due to the more permeable soils at the burial site.

As a result of erosion and trench subsidence, precipitation has been able to infiltrate the trenches and interact with the LLRW at Sheffield. Analysis of trench water (Foster et al., 1983) has detected ^{3}H, ^{60}Co, ^{22}Na, ^{137}Cs, ^{134}Cs, ^{90}Sr, ^{89}Sr, ^{54}Mn. Tritium was the most abundant radionuclide detected with values ranging from 157 nCi/l (trench 18) to 620 nCi/L (trench 14a). The maximum rate of tritium migration is greater than 7.6 m per year and has occurred at the southeast corner of the disposal site from trench 11.

CHAPTER 5

BARNWELL, SOUTH CAROLINA

Site History

The Barnwell LLRW site is located near the eastern boundary of the Savannah River Plant, approximately 8 km (5 mi) west of Barnwell, South Carolina (Fig. 13). The site was opened for commercial disposal in 1971 by Chem-Nuclear Systems, Inc. under a lease arrangement with South Carolina. The Barnwell facility was originally licensed for above ground storage of radioactive wastes in 1969, however, the license was amended to allow LLRW disposal in 1971 (National Low-Level Radioactive Waste Management Program, 1983). Barnwell has accepted LLRW from nuclear power plants and commercial institutions and will continue to operate until December 31, 1992. At this time, North Carolina becomes the next operating LLRW disposal facility for the Southeast Compact.

The Barnwell site employs shallow land burial using standard or "slit" trenches. The standard trenches are used for the bulk of the LLRW though the dimensions have increased from the initial 15 m (49 ft) in width by 152 m (499 ft) in length to 30 m (98 ft) in width by 305 m (1000 ft) in length. Trenches are usually 6.7 m (22 ft) in depth. Slit trenches are used for high activity waste (non-fuel bearing reactor core components) and have dimensions .9 m

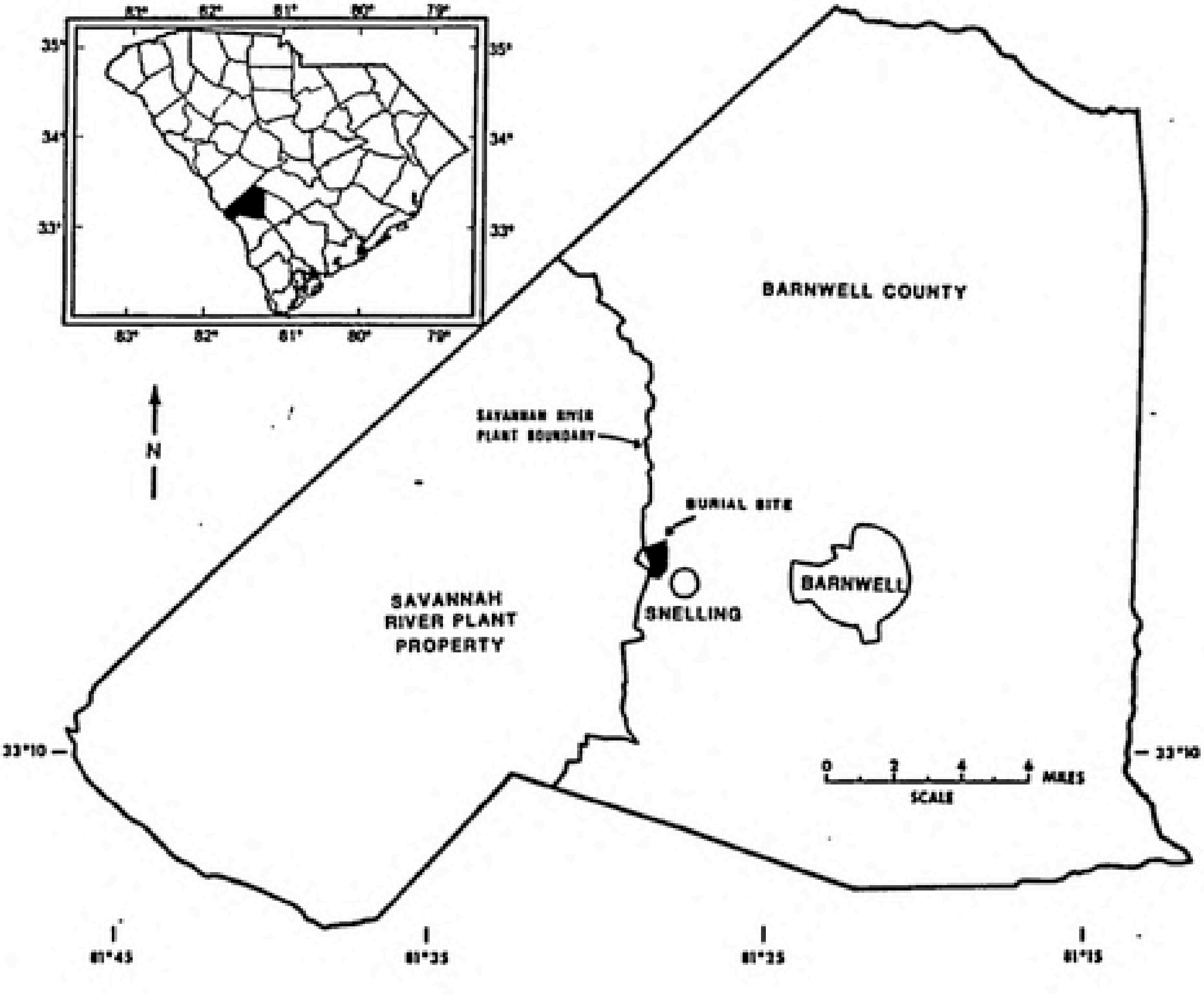


Figure 13. Location of the Barnwell LLRW disposal site (from McDonald, 1984).

(3 ft) in width, 152 m (499 ft) in length, and 6 m (20 ft) in depth (Clancy et al., 1981). Slit trenches reduce occupational exposure during offloading of waste.

Through 1987, 559,643 m^3 (19,760,989 ft^3) of LLRW has been buried. This waste contains 3,696,797 Ci of by-product material, 2,402 Kg (5,308 lb) of special nuclear fuel, and 9,456,600 kg (20,851,898 lbs) of source material (Autry, 1988).

Geologic Characteristics

Barnwell is located in the Atlantic Coastal Plain geologic province and approximately 72 km (45 mi) southeast of the Fall Line which separates the Piedmont from the Coastal Plain provinces. Subsurface geology consists of unconsolidated sediments (305 m thick) ranging from upper Cretaceous to Quaternary Period (approximately 98 million years ago to present). These unconsolidated sediments dip 1.8 to 6.1 m/km (6 to 20/ft/mi) and rest upon older Triassic (208 to 245 million years old) rocks. The stratigraphic column is shown in Figure 14.

The Triassic sedimentary rocks occur in the Dunbarton Basin. This Triassic basin was formed during the opening of the Atlantic ocean. The rapid accumulation of sediments within this basin produced tightly-cemented red claystone, siltstone, fine grained sandstone, breccia, and

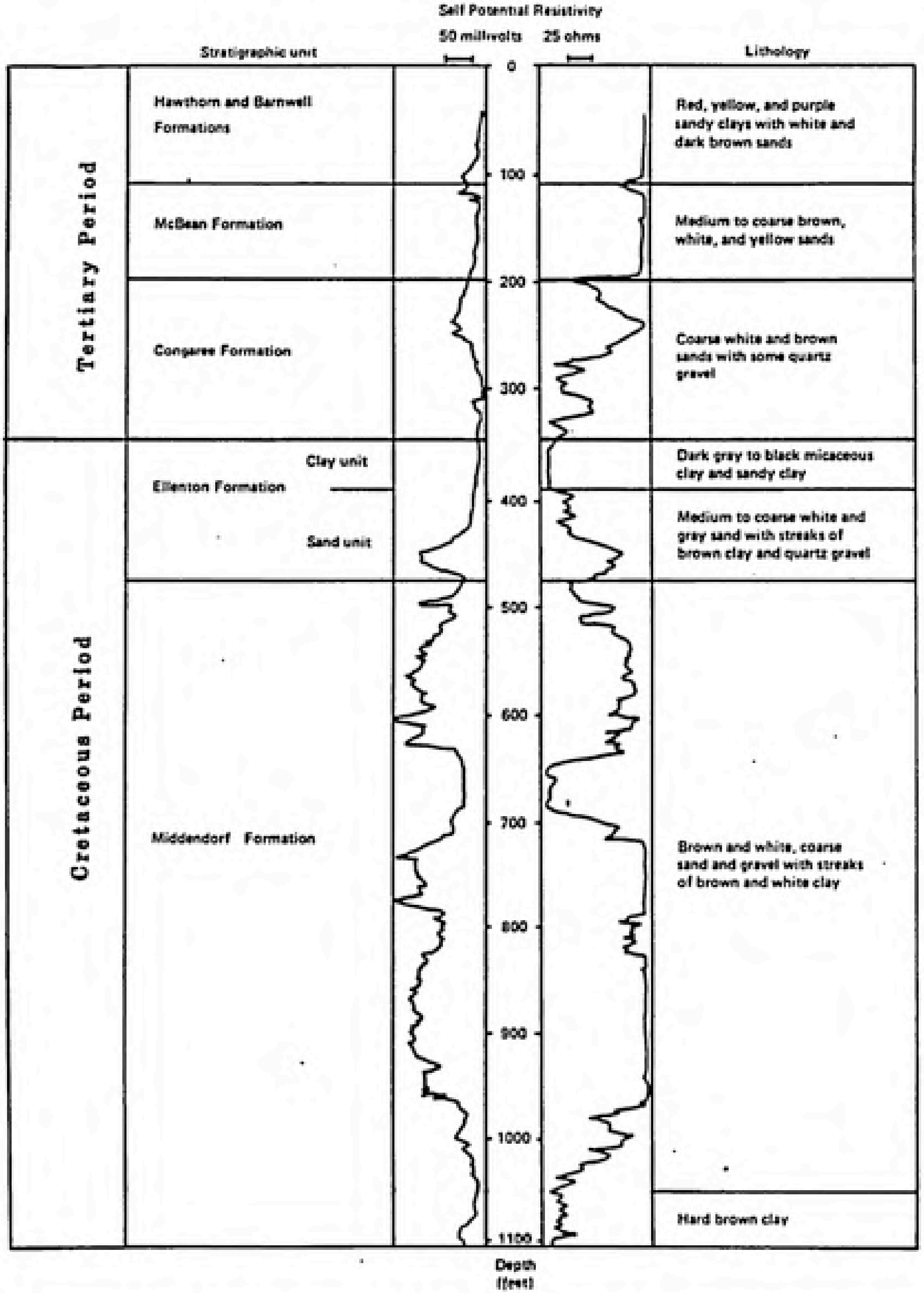


Figure 14. Stratigraphy and lithology of the Barnwell LLRW site (from Cahill, 1982).

conglomerate. Near the upper surface of the basin the rocks are weathered to less consolidated clays, silts, and sands.

The Cretaceous system consist of the non-marine Middendorf formation and the marine Ellenton formation. The Middendorf formation consists of crossbedded micaceous quartzite and estuarine deposits of coarse sand and gravel interbedded with clay beds or lenses. This formation rests on top of the Triassic rocks.

The contact between the sands of the Middendorf and Ellenton can be determined by mineralogic changes. Although the two sands are similar, the Ellenton contains an abundance of glauconite, pyrite, lignite, and selenite (McDonald, 1984). The Ellenton predominantly consists of dark gray to black micaceous clay interbedded with quartz sands. This micaceous unit, 12 to 15 m (40 to 50 ft) thick, is located in the upper section of the Ellenton and hydraulically separates the lower sediments from the overlying Tertiary sediments.

The Tertiary system is composed of the Congaree, McBean, Barnwell Formations of Eocene age, and the Hawthorne formation of Miocene age. Most of the permeable zones are sands and occur in the Congaree and McBean formations. The Hawthorne and Barnwell formations contain clays.

The Congaree Formation is recognizable at the contact with the Ellenton by the contrast between the dark clays of the latter with the sandy gravel of the former.

The McBean Formation consists of white to tan clays interbedded with quartz sands. The contact between the McBean and Congaree occurs at approximately 58 m (190 ft) below the surface, where purple clays lenses are interbedded with sands of the McBean Formation.

Above the McBean is the Barnwell Formation, this unit consists of red to brown clayey sand which grades into yellow sand at the McBean contact. The Barnwell sediments usually occur below the water table and contain sand lenses interbedded with silts and clays.

Hydrologic Characteristics

Surface Water

Barnwell is located within the Lower Three Runs Creek (LTRC) watershed. About 98% of the drainage flows toward the Savannah River (Fig. 14). The topography of the site is gently rolling hills varying from 73 to 80 m (240 to 260 ft) above sea-level. LTRC is 4.6 km (3.8 mi) south of the facility and, as a result of the low surface relief, the LTRC is a relatively slow flowing stream which has an average width of 9.8 m (32 ft). The closet tributary of LTRC is Marys Creek that originates from a spring .9 km (.56 mi) south of the Barnwell site.

Precipitation averages 119 cm (47 in) per year. Most surface runoff is directed by gravity flow away from the disposal trenches to holding ponds along the western margin of the site. The highest amount of precipitation is recorded in the summer, while the highest streamflow occurs during the winter. This seasonal difference is due to the increased rate of evapotranspiration during the summer. Approximately thirty-five percent of the rainfall percolates downward and recharges the Shallow aquifers. These aquifers then discharge into the LTRC and Marys Creek and, therefore, are possible pathways for radionuclide migration.

Ground Water

Due to its relatively simple geology, ground water characteristics are fairly well understood at the Barnwell site. The ground water system is composed of the unsaturated zone and four major water bearing zones (Fig. 15). Ground water at Barnwell occurs under water table, semi-confined, and artesian conditions. The upper 91 m (300 ft) of sediments exhibit water table or semi-confined conditions; below 137 m (450 ft), artesian conditions prevail. Under water table conditions, the water surface is free to rise and fall. In the artesian aquifer, the aquifer is overlain by a less permeable formation that acts as a confining bed.

The unsaturated zone consists of aeolian sands and the upper portion of the Hawthorn Formation, which is mainly fine-grained sands mixed with clays and silt. The

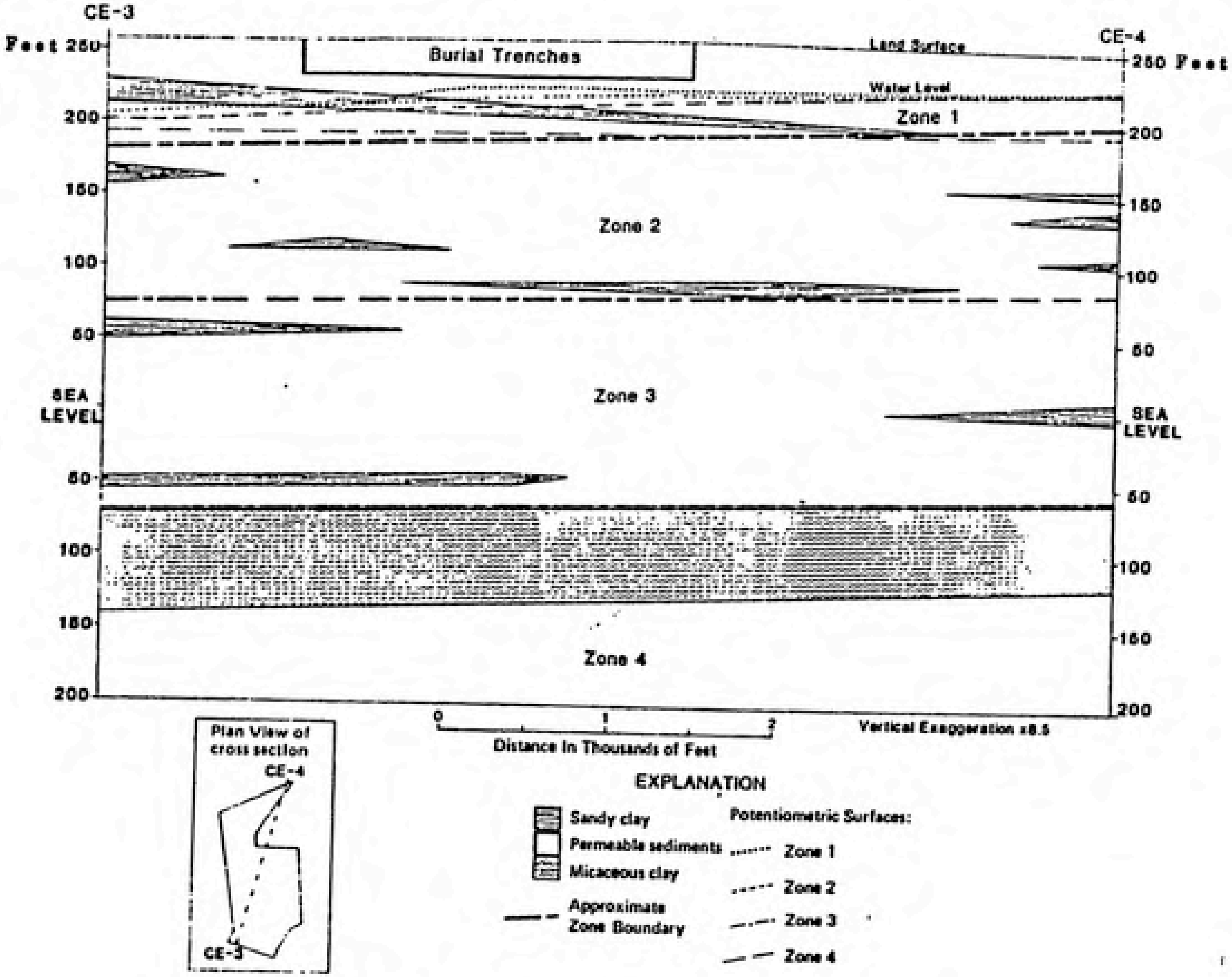


Figure 15. Geologic cross-section showing the ground-water system at Barnwell (from McDonald, 1984).

unsaturated zone is that part of the sedimentary column in which void spaces are not completely filled with water. The unsaturated zone extends from the land surface to just above the water table. All wastes at Barnwell are buried in the Hawthorn formation, 10 to 20 m (32 to 66 ft) above the water table.

Because of the gentle slope and the absorptive sand cover, surface water occurs only after heavy rainfall. Approximately 38 cm (15 inches) of the annual precipitation infiltrates to recharge the ground water. The water that migrates downward is controlled by the hydraulic conductivity and percent saturation of the unsaturated zone. Porosity varies from 30 to 40 percent in the sediments at Barnwell, but the hydraulic conductivity is generally low due to the presence of silts and clays in pore space fillings. Hydraulic measurements performed on sediment cores from the bottom of trench 23 (Cahill, 1982) show that sediments which are 50 percent saturated have a hydraulic conductivity of less than 3.5×10^{-11} cm/s (1×10^{-7} ft/d).

Zone 1 is composed of the lower Hawthorn Formation and the upper Barnwell Formation. These sediments are mostly sands interbedded with silt and clay which form a water table aquifer. This zone extends from the water table to approximately 21 m (70 ft) below land surface. The saturated zone thickness varies seasonally from 6.7 m (22 ft) at the northern boundary to 9.7 m (32 ft) at the southern boundary.

Water flow in zone 1 is southerly and discharges into Marys Branch Creek. Vertical hydraulic conductivity varies from 1.9×10^{-8} to 1.6×10^{-3} cm/s (average 7.1×10^{-6} cm/s,.02 ft/d). Horizontal hydraulic conductivities 2.0×10^{-8} to 2.8×10^{-3} cm/s (average 5.3×10^{-4} cm/s, 1.5 ft/d). Water in zone 1 migrates primarily horizontally, however, some water moves downward into Zone 2.

Zone 2 is composed of predominantly sands of the lower Barnwell Formation and the upper part of McBean Formation. Zone 1 is separated from Zone 1 by a silty-clay unit of the Barnwell Formation. Discontinuous clay lenses in this zone range from inches to a few feet in thickness. The top of this aquifer is approximately 21 m (70 ft) below the surface and is approximately 30.5 m (100 ft) thick. This aquifer is the main water source in the Barnwell area and can produce up to 757 L/min (200 gal/min). Water percolates at the burial site from Zone 1 to Zone 2. Horizontal water movement in this zone is southerly and most of the recharge entering this aquifer will discharge into Mary's Branch Creek. Vertical hydraulic conductivity varies from 9.9×10^{-11} to 5.3×10^{-3} cm/s (2.8×10^{-7} to 1.5×10^{1} ft/d). Horizontal hydraulic conductivity varies from 2.1×10^{-7} to 4.2×10^{-3} cm/s (6.0×10^{-4} ft/d to 1.2×10^{1} ft/d), the average is 3.5×10^{-3} cm/s (9.92 ft/d) (Cahill, 1982).

Zone 3 consists of fine to medium grained sands in the lower McBean Formation and the upper Congaree Formation. The sands in this aquifer are generally subrounded quartz beach sands. Interbedded clay lenses and limestone units occur within this aquifer. Zone 3 is located from 52 to 107 m (171 ft to 351 ft) below the surface. Silt and clay beds separate zone 3 from zone 2 and the bottom is delineated by the Ellenton Formation. Wells penetrating this artesian aquifer yield 757 to 2,460 L/min (200 to 650 gal/min).

The city of Barnwell obtains its water from this aquifer; however, the wells are not in the flow path of groundwater from the LLRW site. This zone primarily discharges into the Lower Three Runs Creek. Vertical hydraulic conductivities vary from 8.8×10^{-9} to 7.8×10^{-3} cm/s. Horizontal hydraulic conductivities vary from 5.3×10^{-7} to 6.7×10^{-3} cm/s, average 6.0×10^{-3} cm/s (Cahill, 1982).

Zone 4 consists of 137 m (450 ft) of the Middendorf Formation between the silty clay base of the Ellenton and the top of the Dunbarton Triassic Basin. This aquifer consists of medium to coarse sand and gravel beds interbedded with clays.

This aquifer is the most productive and wells drilled have yielded 7,575 L/min (2,000 gal/min) for 1,075 hours. Siple (1967) prepared a potentiometric surface of this aquifer and showed that most of the water discharges into the Savannah River.

The upper three aquifers and the streams in the Barnwell site vicinity are interrelated. Water enters the area through precipitation and recharges the aquifers and ultimately is discharged into the streams. Zones 1 and 2 include local recharge and discharge into Marys Branch Creek. Zone 3 does not receive significant recharge from Zones 1 and 2 and discharges into Lower Three Runs Creek. Zone 4 is hydrologically isolated and discharges into the Savannah River.

Problems Encountered

Although no significant problems have occurred at the Barnwell Disposal site, some limited radionuclide migration has occurred from the trenches. Analysis of trench leachate, moisture in sediment cores, and water samples indicate tritium levels higher than background levels (1×10^3 to 3×10^3 pCi/L). This migration has progressed at least 10 feet from the older trenches at this site (Cahill, 1982).

Brookhaven National Laboratories analyzed leachate from trenches 5, 6, 7, 8, 13, and 22. The results from these studies (Colombo et al., 1978) show that all trench leachate had detectable levels of tritium. Trench 7 had the highest tritium activity, approximately 6.4×10^8 pCi/L.

In addition, water samples from wells WW5, WW6, WW7, CN-1E, CN-3N, CN-4W were taken from Zone 1. Analysis of these samples indicate that lateral tritium migration was detectable only in water samples from CN-4W, which is located 3 m (10 ft) from trench 8. Water from this well has values of tritium activity that range from 1 x 10^5 to 2 x 10^5 pCi/L. This indicates that tritium has migrated at least 3 m (10 ft) from trench 8. Samples taken from the Zone 2 aquifer indicate that tritium has not migrated into this unit (Colombo et al., 1978).

Sediments cores were taken from selected wells (CN-1 through 7) for analysis of gamma-emitters and tritium. Analysis of the moisture content in cores shows the greatest tritium activity near the land surface adjacent to burial trenches. The greatest tritium value, 1.8 x 10^6 pCi/L, was measured from a core taken from well CN-4 at approximately 3 m below the surface. The occurrence of high tritium values in the unsaturated zone suggests that tritium migrates upward either as a vapor or with soil moisture evaporation. Sediment cores have been collected beneath trenches 2,5 7, and 8 to a depth of 3 m (10 ft) above the water table. All core samples had detectable tritium activity with the highest value, approximately 1 x 10^9 pCi/L, beneath the west end of trench 7. In addition, analysis of cores beneath trench 2 showed the presence of ^{60}Co. This isotope was detected in the unsaturated zone to a depth of 1.8 m beneath the trench but is considered statistically insignificant (Autry, 1988).

The time required for radionuclides to migrate to the nearest stream (Marys Branch Creek) is difficult to estimate. Cahill (1982) has modeled the area and calculated stream discharge from the aquifers and the water velocity within the major aquifers. Zone 1 has an average horizontal velocity of 1.4×10^{-5} cm/s (.04 ft/d) and an average vertical velocity of 2.5×10^{-6} cm/s (.007 ft/d). Tritiated water will take approximately 10 years to travel to zone 2. The average horizontal velocity in zone 2 is about 8.8×10^{-5} cm/s (.25 ft/d). The minimum travel time for tritiated water to migrate from the disposal site to Marys Branch Stream is approximately 50 years, based on vertical ground flow through zone 1 and horizontal flow through zone 2. Assuming an initial activity of 2×10^5 pCi/L of tritium, the eventual discharge over 50 years will approach background levels (1×10^3 to 3×10^3 pCi/L) due to radioactive decay, dispersion, and dilution.

CHAPTER 6
General Geology And Hydrology of North Carolina

North Carolina lies in three physiographic provinces of the United States (Figure 16): the Blue Ridge, the Piedmont, and the Coastal Plain. Each province has its own distinctive history which reflects its geologic/hydrologic characteristics. A study of this variation in geology/hydrology will be helpful in locating a site with the best overall characteristics.

Blue Ridge

The Blue Ridge province in western North Carolina is characterized by steep slopes dissected by narrow stream valleys. This province is bounded on the west in Tennessee by the Valley and Ridge province; the Piedmont bounds the eastern edge of the Blue Ridge. The Blue Ridge is underlain by metamorphosed igneous and sedimentary rocks, collectively referred to as bedrock. Exposed bedrock is found in road cuts, valleys and river beds. Typically the bedrock is covered by saprolite, varying from a less than 1 m (3.3 ft) to 30 m (98 ft) thick. Saprolite is an unconsolidated material formed from the weathering of bedrock (Heath, 1980).

The Blue Ridge is a region that underwent severe deformation during metamorphic and orogenic events. Faults and shear zones are common in this province and reflect the complex geologic history. The Blue Ridge is bordered on

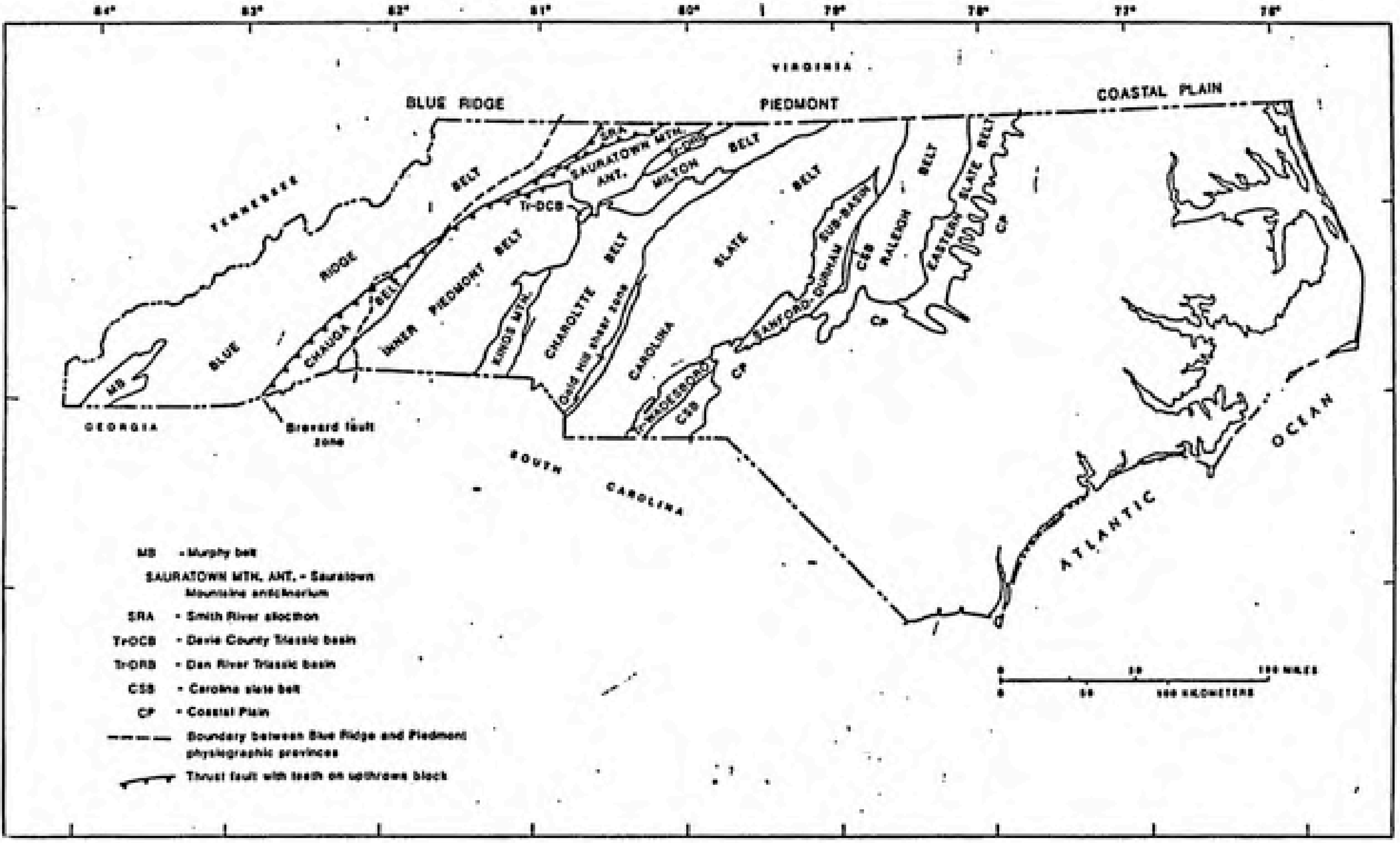


Figure 16. Physiographic provinces of North Carolina. Also shown are geologic belts and faults (from Daniel, 1987).

both sides by major faults: the Blue Ridge to the west and the Brevard fault on the east (Hatcher and Zietz, 1980).

The ground water system (Fig.17) in the Blue Ridge is composed of two parts: (1) the saprolite which underlies the surface and (2) the crystalline bedrock with its fracture system (LeGrand, 1984). Pore spaces in the saprolite serve as reservoirs for ground water. Bedrock does not have primary porosity and ground water is stored in the numerous fractures of the bedrock. Most fractures appear to be non water-bearing below a depth of 91 to 122 m (299 to 400 ft) (Heath, 1980).

Analysis of 507 wells in the Blue Ridge by Daniels (1986) gives an average depth of 11.3 m (37.1 ft) to the water table in the unconfined aquifer (Table 3). The influence of topography on the depth to the water table is apparent. The effect of the higher relief and more rugged topography in the Blue Ridge is reflected by the greater depths to the water table than in similar topographic settings in the Piedmont. Seasonal fluctuations for the index well of the Blue Ridge, monitored by the U.S. Geological Survey (Ragland *et al.*, 1987), is shown in Figure 18. The ground water system in the Blue Ridge is recharged by precipitation on the interstream areas; average precipitation for the Blue Ridge is 13.56 cm (53.39 inches) (Davis, 1988).

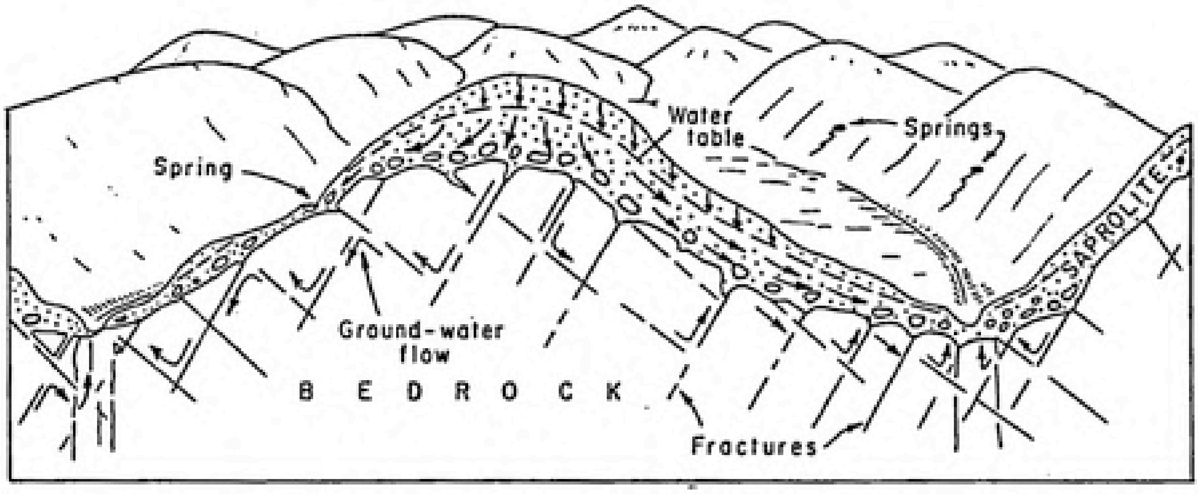
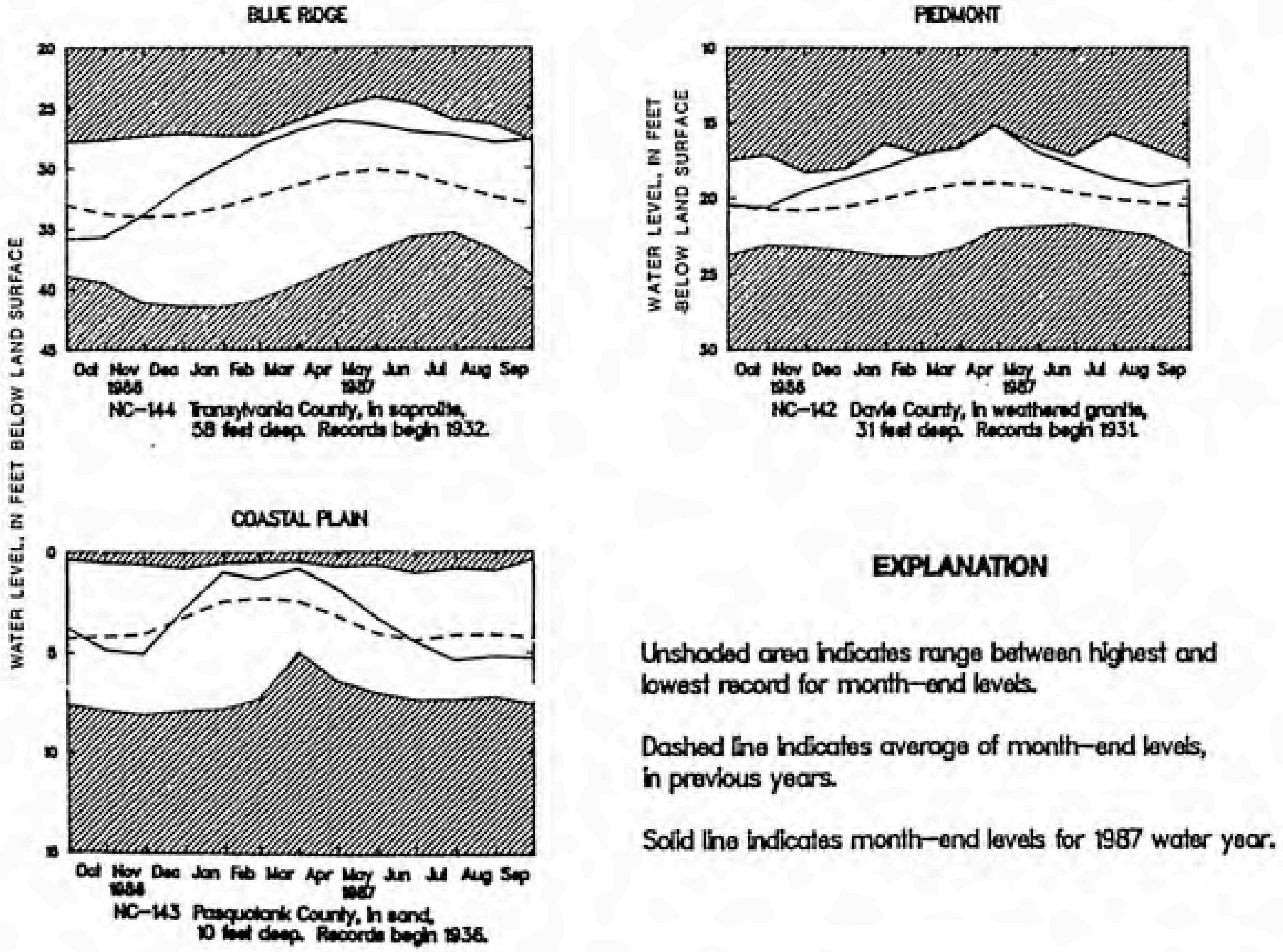


Figure 17. Ground-water situation in the Blue Ridge and Piedmont (from Heath, 1980).

Well characteristic	Blue Ridge					Piedmont					Coastal Plain 1/	
	Draws and valleys	Slopes and flats	Hills and ridges	All wells	Number of wells	Draws and valleys	Slopes and flats	Hills and ridges	All wells	Number of wells	All wells	Number of wells
Average water level (feet below land surface)	23.4	37.5	62.9	37.1	507	22.1	29.3	36.8	31.3	2,326	18.8	145
Median water level (feet below land surface)	18	35	50	30	507	20	25	32	27	2,326	15	145
Average casing (feet)	50.1	57.7	66.6	56.8	698	52.7	53.2	50.0	52.0	2,685	71.7	293
Median casing (feet)	43	55	60	53.5	698	45	46	41	44	2,685	63	293
Average saturated thickness of regolith (feet)	32.2	27.6	20.8	28.0	422	33.6	24.6	20.4	24.0	1,749	47.7	112
Median saturated thickness of regolith (feet)	28	20	10	20	422	28	15	9	13	1,749	44.5	112

1/ Topography of bedrock surface cannot be determined. Influence of topography on well yield in Coastal Plain is unknown.

Table 3. Summary statistics for wells in the Blue Ridge, Piedmont, and Coastal Plain (Coastal Plain wells are along the western edge) (from Daniel, 1987).



NC–144 Transylvania County, in saprolite, 58 feet deep. Records begin 1932.

NC–142 Davie County, in weathered granite, 31 feet deep. Records begin 1931.

NC–143 Pasquotank County, in sand, 10 feet deep. Records begin 1936.

EXPLANATION

Unshaded area indicates range between highest and lowest record for month–end levels.

Dashed line indicates average of month–end levels, in previous years.

Solid line indicates month–end levels for 1987 water year.

Figure 18. Water levels at three long-term wells during the 1987 water year in North Carolina (from Ragland *et al.*, 1987).

Piedmont

The Piedmont province encompasses approximately forty percent of the land area in the state of North Carolina. The elevation of the land varies from 152.2 m above sea-level along the Coastal Plain to 610 m along the Blue Ridge boundary. The Piedmont contains igneous, metamorphic and sedimentary rocks that range in age from Precambrian to Triassic. As in the Blue Ridge, the Piedmont contains faults and zones of deformation. The Piedmont can be divided into a number of northeast trending geologic belts. Areally, the most significant are the Charlotte, Carolina Slate, and Raleigh belts.

As in the Blue Ridge, the bedrock may outcrop along steep hillsides, stream channels, and roadcuts. In other areas, the bedrock is overlain by unconsolidated material (saprolite) which ranges in thickness from less than 1 m (3.3 ft) up to 30m (98 ft). Soil is present as a thin mantle on top of the saprolite and is also derived from the bedrock.

The ground water system of the Piedmont province is similar to that of the Blue Ridge (Fig 17). The system consists of two parts: (1) the saprolite which underlies the land surface and (2) the crystalline bedrock. In the saprolite, ground water is stored in pore spaces between rock particles (typical porosity 20 to 30 percent). Because bedrock does not have primary porosity, the water is contained in the fractures, a common feature of Piedmont rocks. Most fractures are non-water bearing below a depth of 91 (299 ft) to 122 m (400 ft). Analysis of 2,326 wells in the Piedmont (Daniels 1986) gives the average depth to the water table of 9.5 m (31.3 ft) below the land surface (Table 3). As in the Blue Ridge, the effect of topography on the depth to water table is apparent. In addition, an index well monitored by USGS in the Piedmont shows seasonal fluctuations (Figure 18). Ground water recharge in the Piedmont is through precipitation on the interstream divides; average precipitation in the Piedmont is 10.93 m (43.03 inches) (Davis, 1988).

Coastal Plain

The Coastal Plain includes approximately fifty percent of the land area of state and extends from the Fall Line to the Atlantic Ocean. The formations of the Coastal Plain are different from the predominantly crystalline rocks of the Piedmont and Blue Ridge. The Coastal Plain is composed of a sequence of sedimentary rocks that overlie the basement complex (part of the Piedmont). These sedimentary rocks are composed primarily of interbedded layers of sand, silt, clay, shale, and limestone that range in age from Late Jurassic to Recent. These sedimentary rocks form a wedge-shaped mass that thickens eastward (dip approximately 15 ft/mi); the sediment thickness at Cape Hatteras is approximately 3,048 m (10,000 ft) (Lloyd *et al*., 1985).

The Coastal Plain is underlain by a sequence of aquifers. Ground water occurs in permeable sands, silty sands, and limestone. Aquifers are confined and unconfined. The confining beds are composed of clay and silt, with estimated range of hydraulic conductivity from 3.5×10^{-7} to 3.5×10^{-9} cm/s (1×10^{-3} to 1×10^{-5} ft/d) (Lloyd *et al.*, 1985). LeGrand (1984) depicts the ground water in three general zones: the zone of unconfined water at shallow depth, 2) the zone of fresh artesian water, and 3) the zone salty artesian water (Figure 19). The depth to the water table decreases coastward and is at surface in the swampy areas. Analysis of 145 wells in the western Coastal Plain by Daniels (1986) gives an average depth of 5.7 m (18.8 ft) to the water table (Table 3). Measurements taken by the USGS (index well NC-143 Pasquotank County) indicates that average month-end levels are within 1.5 m (5 ft) of the land surface (Figure 17). Recharge of the ground-water system is from precipitation and averages 128.25 cm (50.49 in) (Davis,1988).

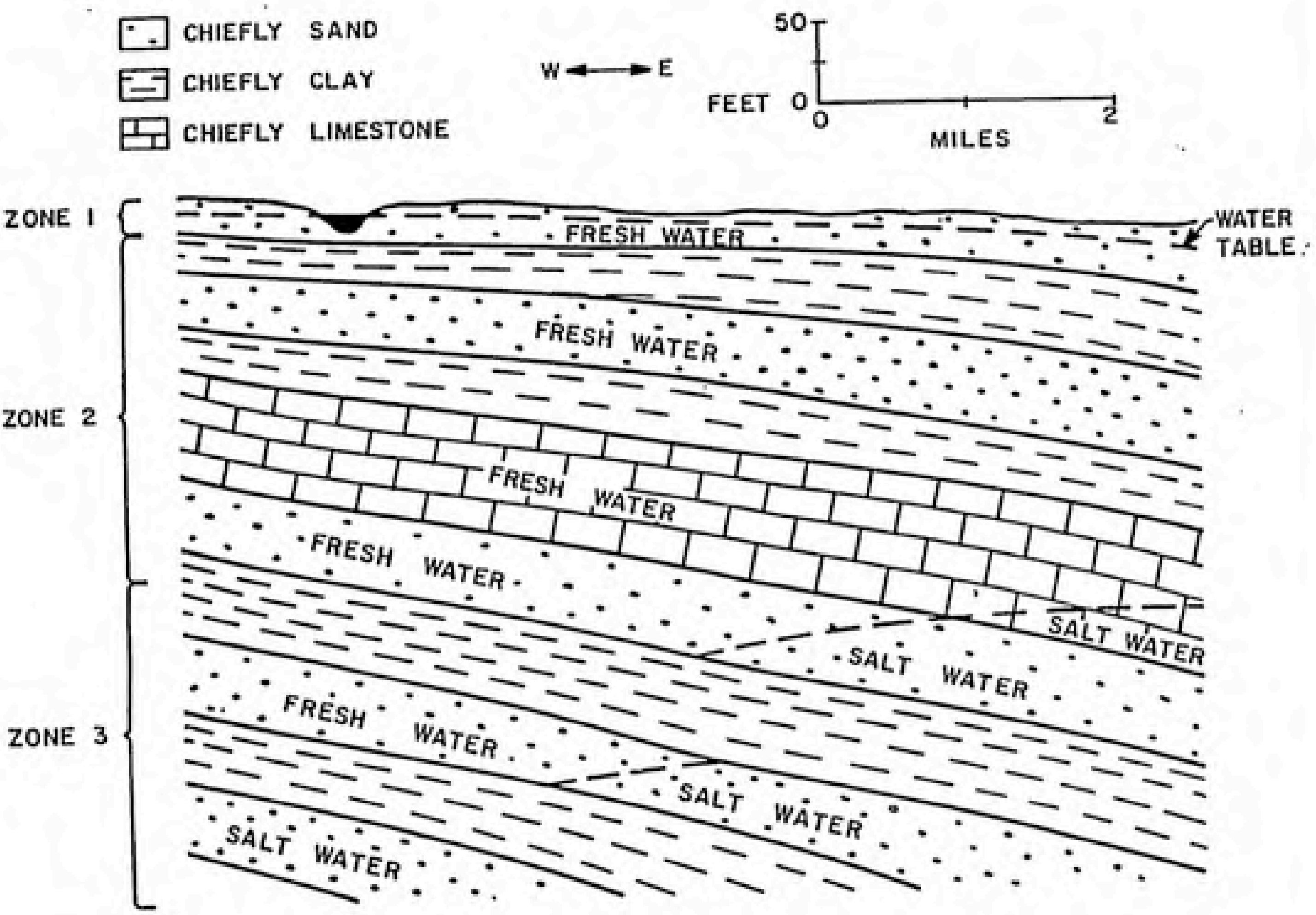


Figure 19. Generalized occurrence of ground water in the Coastal Plain, sequence of rocks and beds are diagrammatic (from LeGrand, 1984).

CHAPTER 7

ENGINEERED BARRIERS

The alternative technologies proposed for LLRW disposal incorporate a variety of engineered barriers. An engineered barrier is a man-made structure or device that is intended to improve the land disposal facility's ability to meet the performance objectives of 10 CFR 61 in Subpart C (Table 4). In these regulations, NRC requires that Class C waste be placed beneath at least 5 meters of cover or behind intruder barriers that must remain effective for at least 500 years. This 500 year time frame can be applied to concrete used in the construction of a LLRW disposal facility, not just intruder barriers. Although engineered barriers may differ in design, materials, and construction, they share the common goal of meeting these performance objectives. Five common engineered components of various LLRW technologies are as follows:

- Cover - An earthen cap designed to meet 10 CFR 61 requirements for mitigating erosion, water infiltration, and intrusion.

- Structure - A stabilized enclosure, sealed against water infiltration and providing long term structural stability.

Performance Objectives (10 CFR 61 Subpart C)	Disposal System Functions (Failure Analysis)
61.42 Protection of the general population from releases of radioactivity	
Concentrations 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 releases of radioactivity in effluents to the general environment as low as is reasonably achievable.	• Prevention of radionuclide release to the atmosphere • Prevention of radionuclide release to surface water • Prevention of radionuclide release to ground water
61.42 Protection of individuals from inadvertent intrusion.	
Design, operation, and closure of the land disposal facility must ensure protection of any individual inadvertently intruding into the disposal site and occupying the site or contacting the waste at any time after active institutional controls over the disposal site are removed.	• Prevention of inadvertent intrusion during the post closure period
61.43 Protection of individuals during operations.	
Operations at the land disposal facility must be conducted in compliance with the standard for radiation protection set out in Part 20 of this chapter, except for releases of radioactivity in effluents from the land disposal facility, which shall be governed by 61.41 of this part. Every reasonable effort shall be made to maintain radiation exposures as low as is reasonably achievable.	• Minimization of radiation dose to workers during the operational period
61.44 Stability of the disposal site after closure.	
The disposal facility must be sited, designed, used, operated, and closed to achieve long-term stability of the disposal site and to eliminate, to the extent practicable, the need for ongoing active maintenance of the disposal site following closure so that only surveillance, monitoring, or minor custodial care are required.	• Maintenance of stability of disposal site

Table 4. Performance objectives for LLRW disposal facilities and disposal system functions (from Otis, 1986).

- Fill - Materials placed in the voids between waste containers. Fill (grout, sand, gravel etc.) prevents the movement of water and provides structural stability in preventing trench cap subsidence.

- Container - Modular receptacle designed to provide additional structural stability and resistance to corrosion by leachate.

- Waste Form - Waste form acts as a direct safety feature by controlling the release rate of the radionuclides in any infiltrating water. Materials such as concrete or bitumen are commonly used to bind wastes in a solid matrix.

Otis (1986) performed in depth functional analyses of engineered components and determined that earthen covers and structural barriers (vaults, roofs, floors, walls) are the most important engineered barriers for LLRW disposal systems. The principal material used in structural barriers is reinforced concrete. Because most designs for the disposal of LLRW use reinforced concrete structures, the degradation of concrete is critical to facility performance. Since a variety of mechanisms can lead to engineered barrier failure and potential radionuclide migration, it is essential to identify site-specific degradation mechanisms.

Properties of Concrete

Concrete is composed of two main components: aggregates and cement. Aggregates are sands and gravels, or crushed rock. Aggregates can be divided into fine (particle size less than 1/4 inch) and coarse (particle size greater than 1/4 inch) categories. Most cements used currently are based on Portland Cement which was patented in 1834 by an English bricklayer after he burned limestone and clay together in his kitchen. When mixed with water, cement powder acquires mud like consistency. Concrete hardens by hydration, a chemical process in which the chemical compounds in cement incorporate water into their structure.

The most important reaction occurs when water and tricalcium silicate combine to form calcium hydroxide and calcium silicate hydrate. Calcium silicate hydrate is a gelatinous material that coats cement grains and bridges them together. This interwoven network of hydrated cement grains, unreacted cement grains and the aggregates (sand and gravel) is primarily responsible for concretes strength (Weisburd, 1988).

Concrete has high compressive strength but the tensile strength is only 8-10 percent of the compressive strength. In order to provide added tensile strength, steel or welded iron mesh can be combined with concrete. Reinforced concrete is a common material and provides the necessary stability for structures such as engineered barriers.

Concrete Aggregates

Aggregates generally occupy 60 to 75 percent of the volume of concrete. Sand, gravel, crushed stone and air-cooled blast furnace slag are commonly used aggregates which produce concrete weighing approximately 145 lbs per cubic foot. The properties of the aggregate vary with the source of materials and must be considered in choosing the proper concrete.

The composition of an aggregate can have a significant effect on concrete performance. Certain siliceous reactive aggregates undergo expansive reaction with alkali compounds (K_2O and Na_2O) to form alkali silicates. These reactions are deleterious to concrete's performance and lead to abnormal expansion, cracking, and loss of strength. The grading and maximum size of the aggregate affect the relative aggregate proportion and water requirements, porosity, permeability and shrinkage of the concrete. Absorptive aggregates are prohibited from use when concrete is subjected to freezing and thawing.

Portland Cement Types

The performance of concrete is dependent on the composition of the cement paste used in construction. Assuming the use of appropriate water/cement ratios, as well as proper aggregates and construction procedures, strong and durable concrete can be produced.

Five types of Portland Cement have been identified by the American Society For Testing and Materials. The cement selected for a LLRW repository depends on the site environmental conditions and structural requirements. Table 5 indicates the major components of Portland Cement and the corresponding type as specified by industry.

The proportion of compounds used in Portland Cement determines its type. Tricalcium silicate (C_3S) provides early strength to the concrete; however, in the curing process, C_3S releases a considerable amount of calcium hydroxide. Calcium hydroxide protects reinforcing steel from corrosion but increase the susceptibility of sulfate attack. Dicalcium silicate (C_2S) cures slowly and is not suitable for structures requiring early strength. Due to its slow hydration rate, the rate of heat generation is small and cracking due to thermal expansion is minimized. Tricalcium aluminate (C_3A) reacts rapidly and has a rate of heat liberation approximately twice that of C_3S. C_3A provides high early strength and accounts for much of the shrinkage in cement. Tetracalcium aluminate-ferrite (C_4AF) provides little strength, heat liberation and volume change. C_4AF is much more resistant to sulfate attack.

Type I cement (Table 5) is a general purpose cement. This cement is used when concrete is not subject to sulfate attack or to an excessive temperature rise due to the heat generated by hydration.

	Type of Cement				
	I	II	III	IV	V
Compound*	Standard	Moderate Heat	High Early Strength	Low Heat	Sulfate Resisting
Tricalcium Silicate (C_3S)	45	44	53	28	38
Dicalcium Silicate (C_2S)	27	31	19	49	43
Tricalcium Aluminate (C_3A)	11	5	11	4	4
Tetracalcium Aluminate-Ferrite (C_4AF)	8	13	9	12	9
Miscellaneous	9	7	8	7	6

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* A represents Al_2O_3

C represents CaO

F represents Fe_2O_3

S represents S_iO_2

C_3S represents $(CaO)_3S_iO_2$

Table 5. Different types of Portland Cement, values in percent (from Illinois Department of Nuclear Safety, 1987).

Type II cement is used where there is moderate exposure to sulfate attack or where moderate heat of hydration is permissible. The strength of this cement exceeds Type I strength after 90 days.

Type III cement provides high strength earlier than Type I and Type II . Due to the pronounced expansion and contraction while setting, cracking of the concrete is typically a problem.

Type IV cement contains smaller proportions of C_3S and C_3A and as a result, is weak at 28 days, but exceeds the strength of Type I after 90 days. Type IV cement has a low heat of hydration and was developed for massive concrete applications such as dams.

Type V cement cannot contain more than five percent by weight of C_3A. Type V cement is used where concrete is exposed to severe sulfate attack from the soil or ground water with high sulfate content.

Small quantities of air-entraining material can be added to any of the five types of cement described above. Air entrainment improves the workability of concrete, reduces water to cement ratio and in proper amounts produces a low-permeability concrete. Deliberate entrainment of air can produce a paste that is resistant to freeze-thaw cycling provided sufficient hydration has occurred before the cement is allowed to freeze while saturated. Slag and pozzolan are common used air-entraining materials. Air-entrained Type I, II, and V cements are suitable materials for the construction of LLRW facilities.

Concrete Composition

The quality, strength, and expected performance of concrete is determined by the proportion of water, cement, and aggregate. For high strength concrete, the water/cement ratio should be less than 0.4 or as low as 0.3 (Mackenzie *et al.*, 1986). In addition, the aggregate/cement paste ratio is equally important. In order to obtain a dense concrete, the void space left unfilled must be kept as low as possible. In general, the fine aggregate (sand) is approximately 35-40% by volume of the total aggregate when the maximum size of the coarse aggregate is 3/4 inch. The proportion of cement used is generally 15% of the aggregate (by weight or volume). In general, concrete strength is not greatly improved by using a higher proportion of cement; however, decreasing the amount can have adverse consequences since the aggregates will begin to touch each other instead of being surrounded by cement paste.

Hydraulic Properties

The porosity and permeability of concrete are important considerations. These properties affect water or radionuclide migration, degradation mechanisms, and the durability of concrete. Most concrete likely to be used in LLRW disposal facilities would be air-intrained. This type of concrete provides workability and protection from freeze-thaw.

The porosity of air-entrained concrete ranges from 11 percent to 17 percent. Adding too much water to the concrete mix causes bleeding and increased porosity. In newly mixed concrete the porosity may vary from 30 to 40 percent. Effective diffusion coefficients for contaminant migration in concrete pores range from 10^{-10} to 10^{-5} cm^2/sec (Shuman et al., 1988), depending on the porosity, pore-size distribution and free water content.

The permeability of a material measures the ability of a gas or liquid to move through it under a pressure gradient. Excluding construction defects, the permeability of concrete is a function of the permeability of the cement paste and the aggregate and their bond. A common value for concrete permeability is 10^{-11} cm/s.

The permeability of concrete is a major factor affecting the corrosion of reinforcing steel that is embedded in the concrete matrix. A low water to cement ratio, along with well-graded coarse and fine aggregates, produces a concrete which is less-permeable and more resistant to degradation processes. In LLRW facilities where the concrete may contact more than moderate chloride concentrations in the soil or water, the water/cement ratio should be less than or equal to 0.4.

Concrete Degradation Mechanisms

In order to address the various degradation mechanisms of engineered barriers, a well formulated definition of failure is needed. An explicit definition of failure for the disposal facility is given in 10 CFR 61, however, several choices of engineered barriers may meet the needs. Suitability of a particular type of engineered barrier depends on site specific characteristics, however, the choice may be influenced by available data. Based on this rationale, Otis and Cerven (1987) define barrier failure in context of structural and radionuclide containment failure. The two definitions are as follows:

- An engineered barrier has failed if its structural component has lost 50% of its original strength within the desired lifetime of the unit.
- An engineered barrier has failed if it no longer provides resistance to the movement of radioactive material greater than that of the surrounding geologic medium alone.

The durability of concrete and corrosion of steel reinforcement have been studied for many years. Those factors that reduce the long-term integrity of concrete are reasonably well understood. There is, however, little information to help predict the durability of concrete for a period of 500 years, since Portland cement-type concrete has only been in use for about a third of that time. This lack of long-term detailed and quantitative experience with concrete structures makes it difficult to project performance with any degree of certainty beyond a period of about fifty years (National Low-Level Waste Management Program, 1987).

Failure of concrete results in the increased likelihood of infiltration by precipitation and, ultimately, migration of radionuclides away from the waste site. Once the concrete begins to crack or spall, further degradation can accelerate rapidly. Reinforced concrete can be degraded by physical or chemical causes or a combination of both. A concrete failure tree is shown in Figure 20. The major degradation mechanisms of reinforced concrete are:

- EROSION - Wind and water action can cause surface wear in reinforced concrete. Ultimately this erosion could result in reduced structural strength and increase the stresses in concrete. Wind and water action could pose a problem with LLRW disposal technologies that have above-ground components.
- Freeze-Thaw - Frost damage occurs as a result of the expansion of water as its freezes in the void spaces. Alternate freezing and thawing cycles can generate stress-induced cracking or cement paste structural disruption. Frost damage does not occur in dry

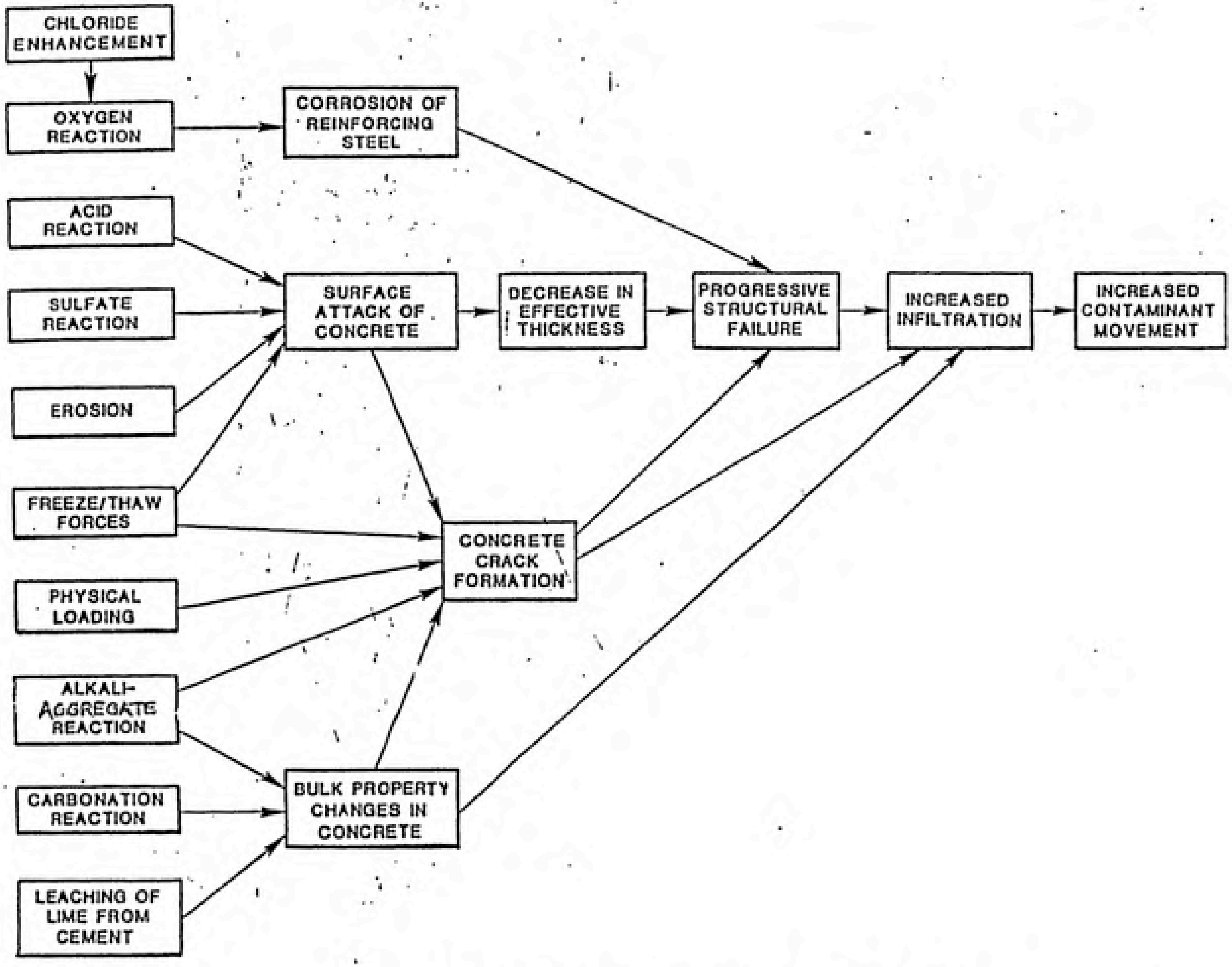

Figure 20. Reinforced concrete failure tree

(from Illinois Department of Nuclear Safety, 1987).

concrete. Resistance to frost damage is achieved by a high density concrete and low permeability of the concrete formulation, which reduces the amount of freezable water in the pore spaces (MacKenzie et al., 1986). Long term resistance to frost damage will be a concern for above-ground LLRW structures. Covered or subsurface structures may require resistance to freeze/thaw during the operation period.

- Physical Loading- Concrete has high compressive strength but very low tensile strength. If the forces due to physical loading are greater than the strength of concrete, the concrete will crack. Physical loads include combinations of live load (e.g.,snow, ice, the LLRW itself), dead load (weight of the structure), wind load, seismic load (acceleration forces generated by earthquakes), thermal load, and impact loads.
- Sulfate Attack - Water-soluble salts can erode concrete by reacting with constituents in the hardened cement paste. Concrete composed of cements with a high $C_3A(3CaO.Al_2O^3)$ content are susceptible to sulfate attack. Magnesium, calcium, and sodium sulfates are the most aggressive in attacking concrete. The degradation mechanism involves reaction with lime and with hydrated calcium aluminate in the cement paste. The reaction results in the production of calcium sulfate and calcium aluminosulfate. These products have greater volume than the cement and generate

stress-induced cracking of the concrete. This degradation mechanism is primarily a problem in the western U.S. where reactive sulfates are found in the alkali soils. Portland Type II and Type V cements are resistant to sulfate attack.

- Alkali-Aggregate Reaction - Certain siliceous reactive aggregates undergo expansive reaction with alkalies (K_2O and Na_2O) to form alkali-silicates. These reactions are deleterious to concrete performance and can lead to abnormal expansion, cracking, and ultimately failure. Another form of the alkali reaction is that between the hydroxyl ions associated with the dissolution of the alkalies and carbonate rock aggregates (often argillaceous dolomitic limestones). This reaction is known as the "carbonation reaction" and results in the formation magnesium hydroxide which leads to expansion, concrete cracking and aggregate degradation.
- Acid Attack - Concrete is chemically basic as result of the hydration reactions of Portland cement and is subject to acid attack. Acid attack occurs by the chemical reaction between acid and calcium hydroxide in the hydrated cement. This reaction produces water soluble calcium compounds which are typically leached away. Ultimately this process destroys the binding ability of the cement paste and weakens the concrete. Acid attack generally occurs if the pH is less than 5.

A dense concrete with a low water-to-cement ratio and high cement content affords reasonable protection against mildly acidic conditions of pH 4 to 5 (Illinois Department of Nuclear Safety, 1987). A pH of less than 5 is typical of soils in the eastern United States. If the acid content is high, nonreacting aggregates are recommended for the concrete. This degradation mechanism can occur both above and below ground components of the disposal facility.

- Chloride Attack - Chloride attack is a major degradation mechanism for concrete structures exposed to seawater or for roads or runways where chloride salts are used as deicers. The degradation of plain or reinforced concrete by chloride attack can be accelerated by the presence of freeze-thaw mechanisms and/or wet-dry cycling (MacKenzie et al., 1986). Dense concrete with low-porosity should be used in environments where seawater comes in contact with the structure. For reinforced concrete, the thickness of concrete covering the bars should be increased. Chloride attack is a major problem with exposure seawater but less important in common soils. If chlorides are present at a site, concrete with a high density and low permeability will protect against chloride attack.
- Calcium hydroxide leaching - When concrete is exposed to infiltrating water, the calcium hydroxide in the

cement paste can be leached out. The leaching of calcium hydroxide depends on the water flow rate, concrete permeability, and the head differential across the concrete member. After the free $Ca(OH)_2$ is removed, further exposure to water dissolves the calcium from $CaO-SiO_2-H_2O$ (tobermite) gel. A one and one-half percent loss of strength occurs for every one percent loss of calcium hydroxide (Illinois Department of Nuclear Safety, 1987). This process weakens the structural integrity of the concrete and the structure ultimately collapses. For failure to occur from Ca(OH)2 leaching, the structure must be in continuous contact with water (e.g. dams and reservoirs). Given the requirements for LLRW disposal, this degradation mechanism will not be a factor.

- Corrosion of Reinforced Steel in Concrete- Corrosion of embedded steel results in the expansion, cracking and eventual spalling of a layer of concrete between the rebar and surface of the concrete member. In addition to loss of cover, this degradation process can result in structural failure of the reinforced unit. The rate of corrosion of reinforcing steel depends on the rate at which oxygen and chloride ions diffuse through the concrete. To insure a service life of 500 years, a concrete cover of 4.6 inches is needed to delay the corrosion of steel (MacKenzie et al., 1986).

- Other Mechanisms- Non-corrosion degradation mechanisms can also have catastrophic consequences. For example flooding, windstorms, and earthquakes can have highly damaging effects and can result in the structural failure of the disposal facility. These discrete natural phenomena pose a problem mainly for above ground disposal facilities.

All of the concrete degradation mechanisms have to be assessed for each specific site and technologies under consideration. These considerations are essential for selecting the optimal technology to meet the performance objectives of 10 CFR 61. Performance data on concrete engineered barriers, either actual or modeled, are generally lacking for the time frame of interest (500 years). It is clearly evident that more information about concrete is required; in particular, data is needed concerning long-term degradation and ultimate containment abilities. Based on the current information, earth-covered LLRW disposal technologies are favored by the NRC over above-ground structures (Pittiglio and Tokar, 1987). Earthen covers lessen the effects of concrete degradation mechanisms (freeze thaw-cycles, acid attack, and erosion) and provide an added barrier from the standpoint of intruder protection as well as radionuclide release.

CHAPTER 8

IMPLICATIONS FOR NORTH CAROLINA

Although no significant exposure to the public has resulted from the performance of the disposal sites discussed in the previous sections, the occurrence of trench cap subsidence and erosion, leachate accumulation, and radionuclide migration has prompted interest in alternate technologies for the disposal of low-level radioactive waste. North Carolina has adopted legislation which prohibits shallow land burial, requires the incorporation of engineered barriers into the burial facility, and specifies that the bottom of the LLRW disposal facility must be at least seven feet (2.13 m) above the seasonal high water table. These legislated constraints increase the complexity of the siting process and necessitate a rigorous environmental assessment of potential sites in North Carolina. Regardless of the disposal technology ultimately chosen, the geologic/hydrologic site characteristics will play important roles in retarding radionuclide migration and minimizing the degradation of engineered barriers. If North Carolina is to be successful in selecting a suitable LLRW site, the characterization process is of extreme importance and demands the most rigorous effort.

POSSIBLE CONSTRAINTS

North Carolina has begun the process to pick possible sites for the construction of LLRW facility. The geologic/hydrologic constraints of the state's environment coupled with site characteristics of the older LLRW sites will be useful in the screening process. North Carolina lies in three physiographic provinces of the United States: the Blue Ridge, the Piedmont and the Coastal Plain provinces. Each province has its own geologic and hydrologic characteristics and, therefore, each may impose unique constraints to siting a LLRW repository. Although the legislation governing LLRW disposal facilities is stringent, a suitable location could be found in each region. In the following sections some possible geologic/hydrologic constraints and degradation mechanisms significant to each province will be discussed.

Blue Ridge

The Blue Ridge is a region that underwent severe deformation during metamorphic and mountain building events. Faults and shear zones are common and reflect its complex history. The topography of the Blue Ridge is rugged and is characterized by steep slopes and narrow stream valleys. As a result of this topography, erosion of the steep slopes is a problem. Finding a level site which is not close to surface water and not subject to erosional forces are important considerations in the Blue Ridge.

The ground-water system in the Blue Ridge is composed of two parts: (1) the saprolite and (2) the crystalline bedrock. Analysis by Daniels (1986), indicates an average depth of 11.3 m (37.1 ft) to the water table. Fractures are very common in the crystalline rocks of the Blue Ridge and provide secondary porosity.

These fractures, faults and shear zones are potential radionuclide pathways and pose a serious problem to siting a facility in the Blue Ridge. Given the difficulty of mapping and locating these features at a particular site, the required geologic characterization and hydrologic modelling of potential sites would be difficult, if not impossible, given the time constraints of North Carolina's selection process.

In addition to these geologic/hydrologic constraints, a disposal facility located in the Blue Ridge would be subjected to degradation mechanisms. Possible significant degradation mechanisms include: freeze/thaw cycles, acid attack, erosion and physical loading. These mechanisms pose a possible threat to the durability of engineered barriers. Given the severe winter conditions in western North Carolina, freeze/thaw cycling would be a significant degradation mechanism for above-ground structures.

Piedmont

The Piedmont contains igneous, metamorphic, and sedimentary rocks. As in the Blue Ridge, the Piedmont has been subjected to periods of severe deformation; faults and shear zones are common features of the region. Typically the crystalline bedrock is overlain by unconsolidated material (saprolite) which ranges in thickness from 1 m (3.3 ft) up to 30 m (98 ft). Soil is typically present in a thin mantle on top of the saprolite. Although the geology is similar to the Blue Ridge, the topography of the Piedmont is less rugged and therefore offers more suitable land for possible LLRW sites.

The ground water system of the Piedmont province is similar to the Blue Ridge and consists of two parts: (1) the saprolite which underlies the land surface and (2) the crystalline bedrock. Analysis of 2,326 wells in the Piedmont (Daniels, 1986) indicates an average depth to the water table of 9.5 m (31.3 ft). Compared to the Blue Ridge, the water table is closer to the land surface in the Piedmont, but generally not within seven feet of the land surface.

The occurrence of faults, fractures and shear zones are potential pathways for radionuclide migration and pose potential problems for a suitable site. Extensive geologic characterization and hydrologic modelling is required in order to determine the suitability. In order to overcome these difficulties, potential sites in areas with thick saprolite should be evaluated. Based on geologic/hydrologic characteristics, the Piedmont is apparently better suited for siting a LLRW facility than the Blue Ridge.

In addition to geologic/hydrologic problems, potential degradation mechanisms for concrete barriers exist in the Piedmont. The principal degradation mechanisms include: acid attack, freeze/thaw (western Piedmont) and erosion.

Coastal Plain

The Coastal Plain is underlain by a sequence of unconsolidated sedimentary rocks which thicken eastward. These sedimentary rocks are composed primarily of interbedded layers of sand, silt, clay, shale, and limestone. The geologic history of the Costal Plain is less complex and sedimentary rocks have not been subjected to the intense deformation processes of the Blue Ridge and Piedmont. Sections of the Coastal Plain have similar geologic characteristics to the Barnwell disposal site and offer possible suitable site locations.

The water table occurs at shallower depths in the coastward direction and is at the land surface in swampy areas. Analysis of wells in the western coastal plain by Daniels (1986) gives an average depth of 5.7 m (18.8 ft) to the water table. Measurements taken by the USGS in Pasquotank County (Index well NC-143) indicate an average depth of 1.5 m (5 ft) to the water table. This shallow water table presents a problem given North Carolina's legislation which mandates that the disposal facility must be separated by at least seven feet from the seasonal high water table.

Given the geology/hydrology and climate of the Coastal Plain, possible degradation mechanisms include acid attack, erosion, and physical loading. Soil pH on the Coastal Plain varies from 3.6 to 8.5, therefore, the possibility exists for severe corrosion of concrete and steel.

SUMMARY

In reviewing the performance history of the four LLRW disposal facilities in the eastern United States, evidence suggests that most, if not all, containment failures are a result of either: 1) an inadequate identification and characterization of geologic materials, or 2) the failure to consider geologic/hydrologic criteria during the siting process. At Maxey Flats and West Valley, a lack of a complete understanding of the geologic/hydrologic system contributed directly to trench subsidence, leachate accumulation and radionuclide migration. At Sheffield, the inadequate characterization and groundwater modelling of the glacial sediments resulted in designs which were susceptible to trench cap erosion and eventual radionuclide migration. Only the Barnwell facility has avoided the problems encountered at Maxey Flats, Sheffield, and West Valley. This is a result of a relatively simple geology/hydrology system coupled with improved trench cap design.

Although North Carolina will employ engineered barriers in the disposal technology, such barriers cannot fully compensate for the geology/hydrology of the site. Since the durability of engineered barriers is not known for the period of 300 to 500 years, the geology/hydrology of the site are vitally important factors for insuring that public exposure does not occur from radionuclide migration.

Based on the overall geology/hydrology of North Carolina, the geologic/hydrologic shortcomings of the eastern LLRW disposal sites, and potential external degradation mechanisms at all three provinces, this report has identified possible constraints in the siting of a LLRW facility. The Blue Ridge and Piedmont shortcomings are due to the complex geology and hydrology. Although the water table is deep, it would be difficult to accurately model the site characteristics. In order to site a facility in these regions, the potential site should have a thick layer of saprolite over the bedrock.

In contrast, the Coastal Plain is blessed with a simple geologic/hydrologic system; its major shortcoming is the shallow water table. The western Coastal Plain apparently offers the most suitable sites for the technologies currently considered. It is important to note, however, that the siting decision is based on a number of factors, not solely the geology or hydrology.

The information contained in this report can be used in the regional studies to exclude those areas which are not suitable for a LLRW facility. Given the wide variety of alternative technologies and the geohydrologic variation of North Carolina, only general constraints have been discussed in this paper. Geologic/hydrologic characterization and ground water modelling must be performed for each possible site; only with that type of analysis can a complete assessment on the suitability of a potential site be made.

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