Study Plan for a Field Experiment to Investigate the Effects of Low-Level Radioactive-Waste Burial on Flow of Water through a Saturated, Clayey Till at West Valley, New York

By Richard M. Yager

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
micrometer (µm)	.00394	inch
millimeter (mm)	0.0394	inch
centimeter (cm)	0.3939	inch
meter (m)	3.281	foot
kilometer (km)	0.621	mile
	Area	
square meter (m^2)	10.76	square foot
square kilometer (km^2)	0.386	square mile
hectare (ha)	2.47	acre
	Volume	
milliliter (ml)	2.65×10^{-4}	gallon
cubic meter (m^3)	35.31	cubic foot
liter (L)	0.264	gallon
liter (L)	3.53×10^{-2}	cubic foot
	Hydraulic conductivity	
meters per second (m/s)	2.835×10^5	feet per day
	Pressure	
kilopascal (kPa)	0.145	pounds per square inch
kilopascal (kPa)	0.3345	feet of water
	Chemical concentration	
milligrams per liter (mg/L)	1	parts per million[1]
micrograms per liter (µg/L)	1	parts per billion
	Temperature	
degree Celsius (°C)	(9/5 °C) + 32	degree Fahrenheit (°F)

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

[1] Milligrams per liter approximately equal parts per million when dissolved-solids concentration is less than about 7,000 milligrams per liter.

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ABSTRACT

Burial of low-level radioactive waste below the zone of weathering in saturated, fine-grained sediments has been considered as a disposal option for humid areas, where the abundance of precipitation precludes burial in the unsaturated zone. The use of this disposal option in the United States requires a diffusion-dominated flow system to allow sufficient time (500 years) for the principal radionuclides in the waste to decay to harmless levels. Little information is available, however, to predict whether this disposal method could allow fractures to develop within the host material or the grout that seals the excavation; such fractures could provide pathways for advective transport from the waste to land surface. In the proposed study, a hollow steel cylinder (monitoring caisson) would be placed within an augered hole in clayey till near West Valley, N.Y., to simulate a full-scale disposal container, so that the effects of excavation, burial, and sealing on the movement of water through the saturated, fine-grained host material can be investigated.

The host material is a thick, clayey till at a site that has been well documented by previous studies. The till is unweathered at depths below 5 meters (m) and has a hydraulic conductivity of 2 to 6 x 10^{-10} meters per second. The hydraulic conductivity is an order of magnitude higher near land surface, where the till is weathered and contains oxidized fractures. Flow through the unweathered till is downward and is estimated to range from 3 to 23 millimeters per year.

Physical and hydraulic properties of the till will be determined, and zones dominated by advection or diffusion will be delineated. The depth of advective transport, assumed to correspond to the depth of fracturing, will be measured (1) through direct observation of fractures in excavations, (2) from concentration gradients of tracer dyes along vertical profiles, and (3) seasonal fluctuations in pore pressure. Core samples obtained during drilling of horizontal boreholes at selected depths in a research trench will be analyzed for tritium to identify recent (post-1960) recharge, which would indicate the presence of high-angle fractures. The diffusion-dominated part of the flow system will be identified from the age of pore water, which will be estimated through a comparison of oxygen-18 and deuterium concentration gradients measured in the till with those computed by the advection-dispersion equation.

The monitoring caisson will be 1.8 m in diameter and 20 m high and will contain moveable steel platforms to provide access to all depths within the caisson. The annular space surrounding the monitoring caisson will be sealed with layers of three different grout mixtures selected on the basis of laboratory studies. Both cement and bentonite grouts will be used to determine the most effective sealing properties for the installation. Instruments placed in the grout surrounding the caisson will record changes in stress that result from hydration of the grout during curing and upon infiltration of pore water from the adjacent till.

Hydraulic conductivity of the till/grout interface will be estimated from constant-head injection tests in sand layers within each grout layer; large flow rates will indicate flow along the interface. A tracer solution containing an electrically conductive solute and dye will be injected into the sand layers to delineate preferential flow paths along the interface. Leak sensors triggered by the presence of a conductive fluid will be monitored to locate flow paths, and a coring tube will be driven through the area of suspected flow to obtain a sample of the till/grout interface for inspection and chemical analysis. Pore water will be extracted from this sample to determine the aqueous chemistry of the till and grout within the interface region, and thin slices of the sample will be analyzed to determine the mineralogy of the solid phases.

INTRODUCTION

The Low-level Radioactive Waste Policy Amendments Act of 1986 requires that the low-level radioactive waste generated within each State be disposed of either within the borders of that State or in a host State under an interstate compact. Current methods of low-level radioactive-waste disposal in the United States typically use shallow burial trenches. Although the best locations for these disposal sites are in dry environments, where the lack of precipitation and the thick unsaturated zone minimize the movement of water through the waste materials, disposal sites probably will become necessary in humid regions as well.

Previous disposal practices in humid regions have included trenches that were excavated in deposits of fine-grained, relatively impermeable sediments (Prudic, 1986). Such trenches at many sites were excavated within the upper, weathered zone of the deposit, but precipitation that infiltrated some of the earthen trench covers could saturate the waste materials, then flow out of the trenches through the backfill and along fractures in the weathered sediments, carrying radionuclides with it toward nearby creeks.

An alternative waste-disposal option for humid regions is burial below the zone of weathering in deeper, saturated, fine-grained sediments with sufficiently low permeability that the only mechanism by which radionuclides can migrate is diffusion. This option requires that diffusion remain the dominant mechanism for 500 years to prevent migration of radionuclides before they decay to harmless levels (U.S. Nuclear Regulatory Commission, 1986). Three conditions must be met to ensure that radionuclides do not migrate from the site before decaying sufficiently:

1. The host material must (a) be sufficiently impermeable to prevent advective transport (leaving diffusion as the dominant transport mechanism), and sufficiently thick to provide long ground-water traveltimes, and (b) contain no fractures or other paths for advective transport between the waste and land surface.
2. The waste must be encapsulated in a suitable grout to prevent infiltration of ground water and leaching of radionuclides from the waste.
3. The disturbance caused by excavating the host material and sealing the disposal container must not alter the properties of the host material nor allow pathways for advective flow to form between the waste and land surface.

Three studies have characterized deposits of unweathered, fine-grained clayey sediment in Saskatchewan, Ontario, and New York; at all three sites, diffusion appears to be the dominant transport process, and permeability is less than 10^{-9} m/s, which results in ground-water-flow rates of only a few millimeters per year (Keller and others, 1988; Desaulniers and others, 1981; Prudic, 1986). Little information is available, however, to indicate whether the disturbance resulting from proposed burial procedures could cause the host material or the grout used to seal the excavation to develop fractures that would serve as pathways for advective transport from the waste to land surface.

Objectives of Study

The objective of this study is to evaluate the effects of burying and grouting a 1.8-m-diameter, 20-m-high waste container on the movement of pore water through the host material and the grout within a clayey till deposit 28 m thick. The study will (1) record changes in the ground-water-flow patterns that result from the excavation and sealing of a subsurface monitoring container similar to one currently used for storage of radioactive waste in Ontario, and (2) investigate the resulting physical and chemical changes in the host material and grout that could alter the natural flow system.

Approach

Previous studies by the U.S. Geological Survey (USGS) indicate that the thick, clayey till near West Valley, N.Y., 40 km south of Buffalo, in Cattaraugus County (fig. 1), would provide a suitable location for a field experiment to investigate the potential effects of waste burial on the movement of water through saturated, fine-grained sediments and the grout used to seal the excavation (Prudic, 1990). An empty 1.8- x-20-m steel cylinder (monitoring caisson) will be placed within an augered hole in the till to simulate a full-scale disposal container, and the annular space surrounding the caisson will be sealed with layers of differing grout materials for comparison of their sealing properties. Field experiments will be conducted from inside the caisson and from the walls of a nearby excavated trench to define the hydraulic and fracture characteristics of the host medium.

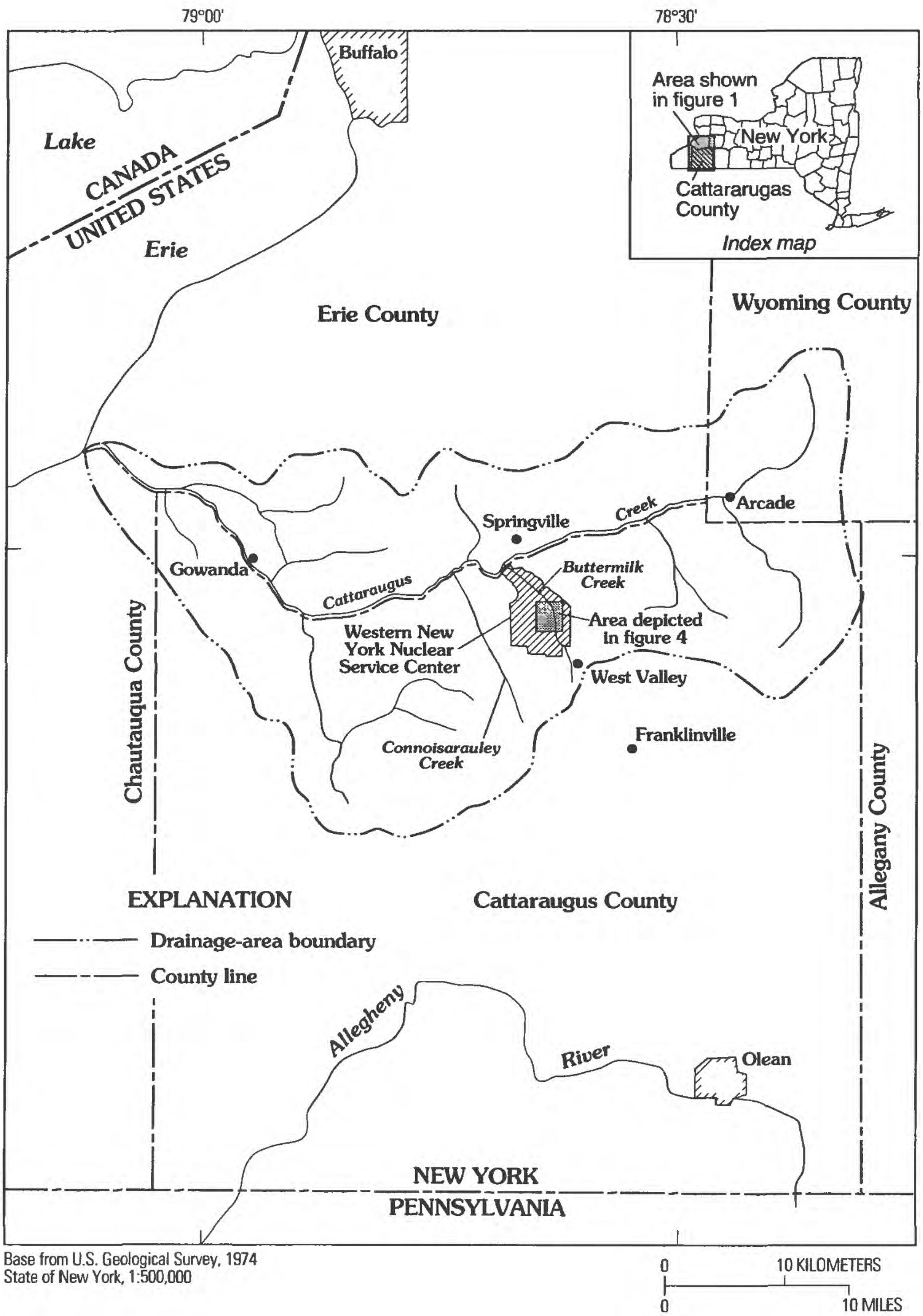


Figure 1. Location of study site at Western New York Nuclear Service Center near West Valley, Cattaraugus County, N.Y. (Modified from Bergeron and others, 1987, fig. 1.)

The proposed study will be a 5-year effort that entails the following :

1. Site characterization to document the hydrology and estimate the depth of advective transport in the flow system;
2. Emplacement and operation of the steel caisson to simulate waste burial and subsequent monitoring to investigate its effects on the integrity of the host material and on movement of pore water; and
3. Restoration of the site upon completion of the study.

Purpose and Scope

This report presents the plan of study for the field experiment to simulate the emplacement of a full-size disposal container in saturated, fine-grained sediments. It also:

1. Describes methods of low-level radioactive waste disposal that have been considered for humid areas such as the northeastern United States;
2. Summarizes the history and geohydrologic characteristics of the study site;
3. Discusses the study components; and
4. Explains the field procedures and experiments designed to (a) determine the depth of advective transport in the till, and (b) ascertain the effects of subsurface disposal on the integrity of the surrounding till and on the movement of pore water through disturbed till and grout materials.

Acknowledgments

This study plan was developed through the Nuclear Hydrology Program of the USGS. Thanks are extended to the following people, who reviewed plans for the proposed study and provided substantive comments: Lawrence McKay and other researchers at the University of Waterloo, Ont., who suggested methods of characterizing the till at West Valley; Richard Heystee of Ontario Hydro, who provided information on (1) facilities used to store low- and intermediate-level wastes in Canada, and (2) studies that have been conducted to evaluate their performance; John Stormont of Sandia Laboratories, N.M., and J.J.K. Daemen of the University of Nevada at Reno, who discussed the results of laboratory and field studies to measure the performance of various grout materials in sealing boreholes; and John Boa, Lillian Wakeley, Samuel Wong, and John Peters of the U.S. Army Corps of Engineers at the Waterways Experiment Station, Miss., who provided information on the design and testing of cement grout and the processes that could affect its performance in a subsurface environment.

LOW-LEVEL RADIOACTIVE-WASTE BURIAL

Radioactive waste results from processes that use radioactive materials and is generally categorized by the intensity of radiation emitted by radionuclides in the waste material. In the United States, high-level radioactive waste refers to (a) spent and reprocessed fuel waste that is generated during operation of nuclear powerplants, (b) transuranic waste, and (c) uranium-mill tailings; low-level radioactive wastes include other radioactive waste generated by nuclear powerplants and by nondefense-related commercial and institutional activities. Most low-level waste is not highly radioactive, except for certain types, such as highly irradiated reactor components.

Low-level radioactive waste is usually characterized by its volume and activity. The activity is the rate at which radiation is emitted by radionuclides and is characterized by the number of atomic nuclei that disintegrate per second. The activity of radioactive material decreases with time as the material is transformed to stable form through radioactive decay.

Sources and Types of Waste

A total of 3,124 m^3 of low-level radioactive waste with an activity of 103,140 Ci (curies) was shipped from sources in New York State in 1991 for disposal (New York State Energy Research and Development Authority, 1992). Nuclear powerplants accounted for 74 percent of the volume and 99 percent of the radioactivity (fig. 2). Nearly all of the remaining radioactivity was in waste generated by a manufacturer of radionuclides and radiopharmaceuticals. Nuclear powerplants are expected to account for about 75 percent of the volume and 98 percent of the activity of low-level radioactive waste during the next 60 years as powerplants are decommissioned and dismantled (Mayo and others, 1989).

The types of low-level radioactive wastes typically disposed of in New York State are listed in table 1. The wastes include solid and liquid materials and mixed refuse containing chemically hazardous materials. Solid materials in the waste include

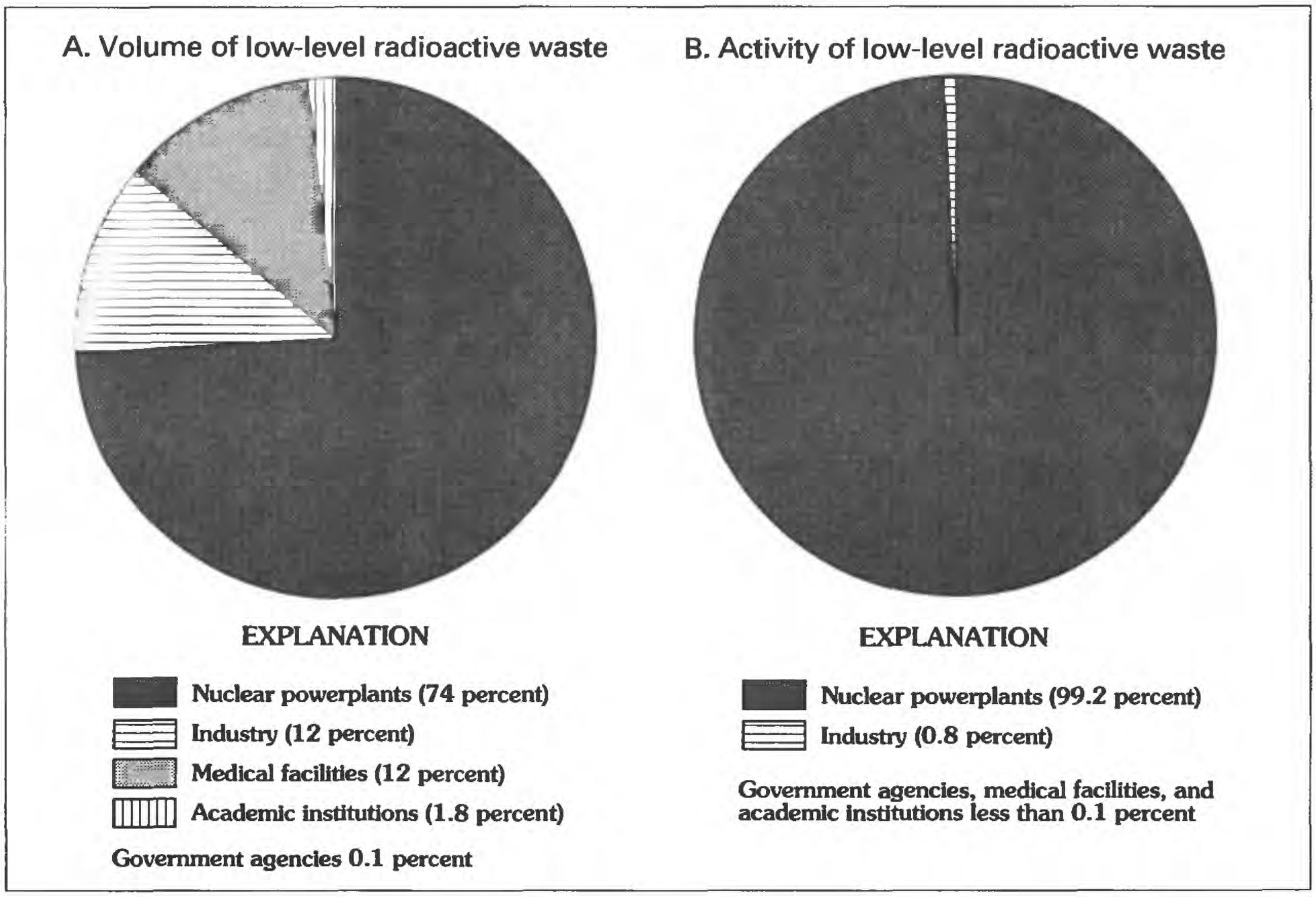


Figure 2. Volume and activity of low-level radioactive waste shipped in from major sources New York State in 1991: A. By volume. B. By activity. (Modified from New York State Energy Research and Development Authority, 1992, figs. 1-1 and 1-2.)

Table 1. Types of low-level radioactive waste generated in New York State
[Data from New York State Energy Research and Development Authority, 1992, p. 14.]

Medical facilities	**Industry**
compacted trash or solids	depleted uranium
laboratory or biological waste	compacted trash or solids
absorbed liquids	contaminated plant hardware
sealed sources	absorbed liquids
	sealed sources
Academic institutions	liquid scintillation waste
compacted trash or solids	
laboratory or biological waste	**Nuclear powerplants**
absorbed liquids	spent ion-exchange resins
animal carcasses	evaporator bottom and concentrated liquid waste
	filter sludge
Government agencies	dry compressible waste
Compacted trash or solids	irradiated reactor components
contaminated plant hardware	contaminated plant hardware
absorbed liquids	

clothing, paper, plastic, glass, metal and concrete. Liquid materials must be stabilized before disposal; and this entails dewatering, then solidification in concrete or asphalt, or absorbtion into solid materials. Radioactive gases have been identified at low-level radioactive waste repositories (Striegl, 1990); the principal gases identified were end products of biological decomposition and include carbon dioxide, water vapor, and methane.

The radionuclides of concern in a low-level radioactive waste repository will change with time as radionuclides with short half-lives are transformed to stable end products. Radioactive isotopes of cobalt (^{60}Co), cesium (^{137}Cs), and iron (^{55}Fe) are expected to account for most of the radioactivity in the first 100 years after disposal of the repository (Mayo and others, 1989). After 500 years, radioactive isotopes of carbon (^{14}C) and nickel (^{59}Ni and ^{63}Ni) will account for most of the radioactivity; the rest will be radionuclides with long half-lives such as americium (^{241}Am), niobium (^{94}Nb), and plutonium (^{239}Pu).

Proposed Types of Subsurface Disposal

Three commercially operated subsurface repositories are currently accepting low-level radioactive waste in the United States–Barnwell, S.C., Richland, Wash., and Beatty, Nev.; several new repositories that comply with the requirements of the Federal Low-Level Radioactive Waste Policy Amendments Act are planned. The selected sites must meet site-suitability requirements of the U.S. Nuclear Regulatory Commission (USNRC) (1986) and the host States (such as those defined by New York State Department of Environmental Conservation, 1987). Most repository designs also include engineered barriers or structural components to improve the sealing performance of the repository. Three types of subsurface disposal have been suggested for low-level radioactive waste: improved shallow burial, augered holes, and mined cavities (Schwarz, 1990). The first entails placement above the zone of water-table fluctuation, whereas the latter two can be used within the saturated zone.

Improved Shallow Burial

Trench excavations used in improved shallow burial facilities (fig. 3A) differ from those in current facilities in that they incorporate concrete liners or vaults as engineered barriers. The concrete liner or vault serves as a foundation that holds waste containers stacked in stable arrangements. The void space between the waste containers is backfilled to provide the additional stability and strength needed to support the trench cover. The trench cover may consist of multiple layers of materials to provide an intrusion barrier and reduce infiltration of water from land surface. A drain underlying the trench conducts infiltrating water away from the facility.

Augered holes

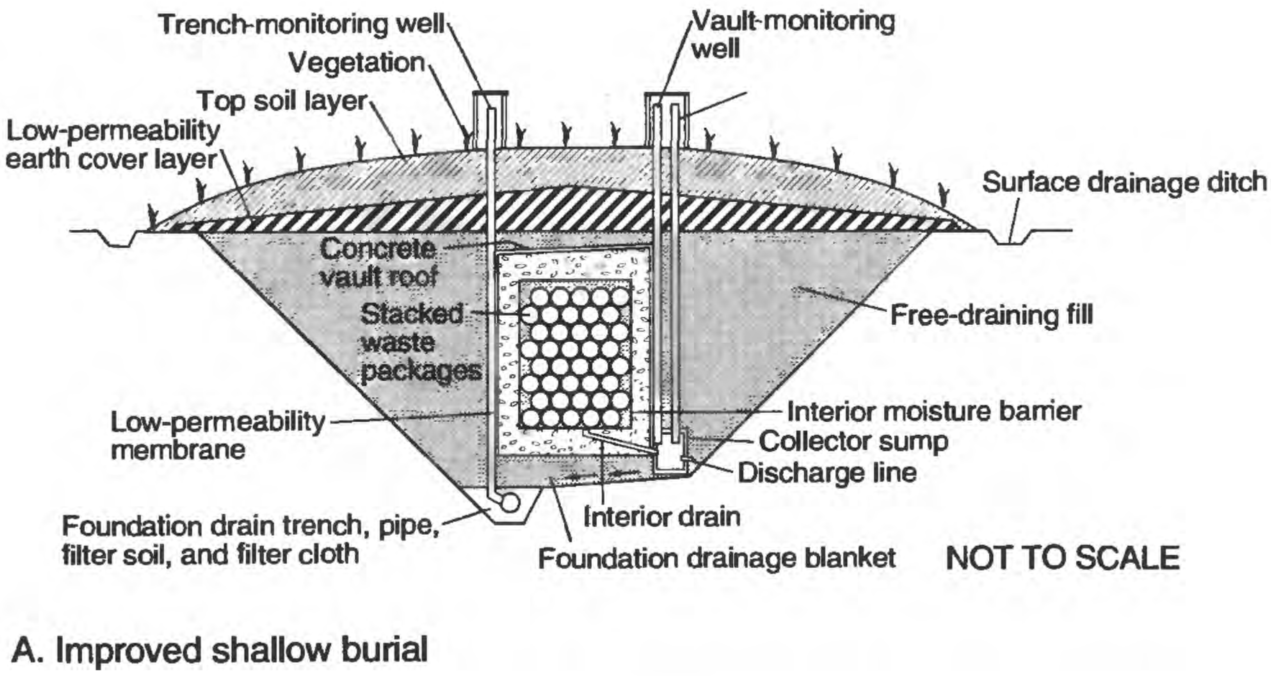
In this type of disposal, large-diameter holes are augered into host material of relatively low permeability. A detailed sketch is shown in figure 3B. Waste containers are stacked coaxially within the holes or are placed within a steel cylinder that is put in the hole. The space between the borehole wall and the waste containers or steel cylinder is then backfilled with grout to provide structural stability and seal the waste. A concrete slab or plug at the top of the hole provides a barrier against intrusion.

Mined Cavity

This type of disposal uses cavities previously excavated for removal of natural resources, for example, salt mines, or tunnels bored specifically for disposal of low-level radioactive waste. Waste containers are stacked in separate underground rooms or within the tunnels. The space between the waste containers and the cavity wall is grouted to seal the waste. The access shaft or ramp connecting the excavation with the land surface is backfilled after the cavity has been filled with waste.

Type Selected for Study

Burial of waste in saturated sediments below the zone of weathering in augered holes or tunnels has been suggested as a disposal option for humid areas (Bechai and Heystee, 1989; Cherry and others, 1979; Prudic, 1990). Although tunnels are technically and economically feasible for disposal of large volumes of waste, the costs and difficulties of construction make this option unsuitable for the proposed field experiment. The augered-hole type of facility was selected for this study because it allows construction and emplacement of a full-size container, and the results of field tests can be compared directly with those from an actual facility of this type that is currently used by Ontario Hydro to store low- and



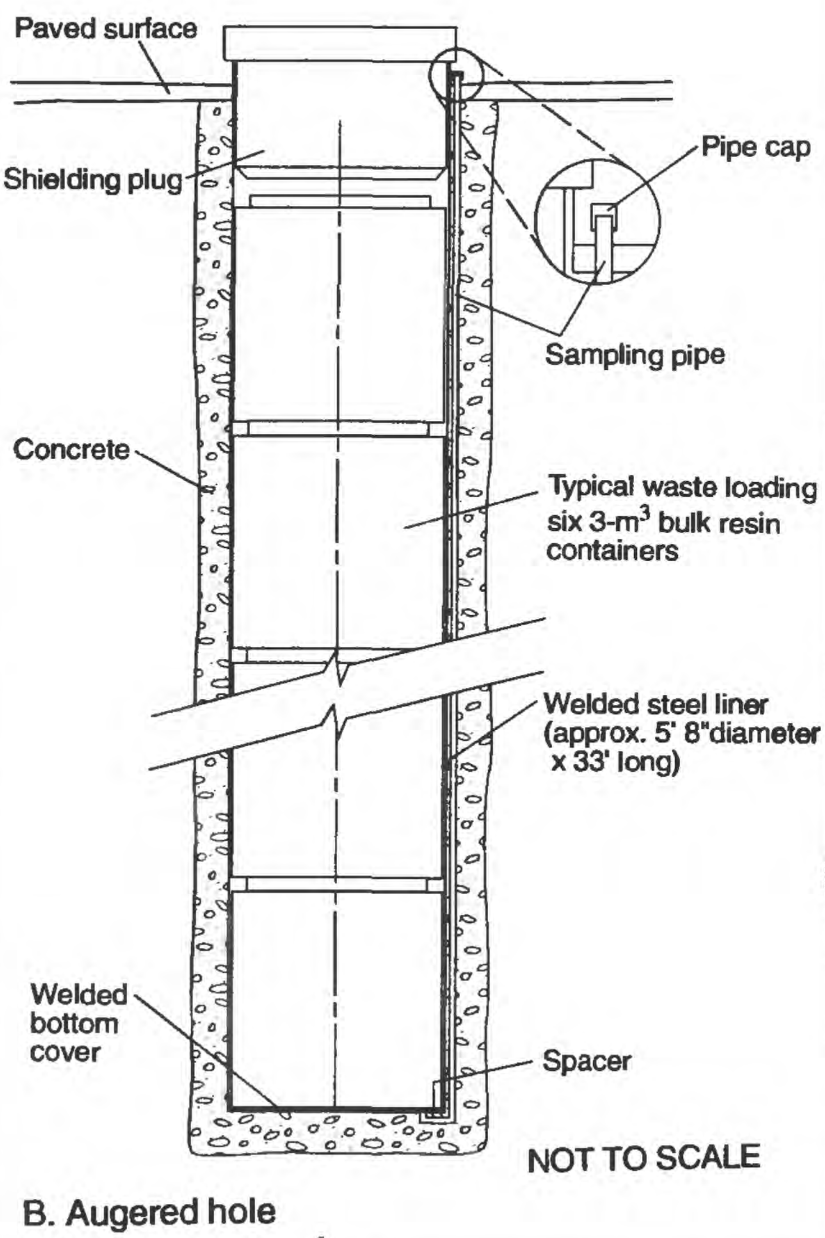


Figure 3. Two types of low-level radioactive-waste disposal in vertical section: (A) Improved shallow burial. (From Denson and others, 1987, fig. 1-1.) (B) Augered hole. (From Ontario Hydro, 1985, fig. 4-3.)

intermediate-level radioactive waste (R.J. Heystee, Ontario Hydro, oral commun., 1992).

The Ontario Hydro facility, which the proposed study would replicate in part, consists of rows of augered holes containing 1.7-m-diameter steel cylinders 12 m in length. The steel cylinders are coated with coal-tar epoxy, and the 0.2-m-wide annular space between the cylinder and the borehole wall is sealed with concrete. A concrete plug 1 m thick seals the top of each cylinder. The waste is placed directly in the cylinder or within 0.5-m-diameter steel liners that fit inside the larger cylinder. The smaller cylinders are retrievable, and as many as seven can be placed within a single hole. The land surface surrounding the augered holes is paved with asphalt to facilitate drilling and backfilling of the holes.

SITE LOCATION AND DESCRIPTION

The proposed research site occupies 1 ha on the west side of the Buttermilk Creek Valley at the Western New York Nuclear Service Center (WNYNSC) (fig. 4), where a sequence of glacial and postglacial deposits form a fairly level plateau at an altitude 50 m above Buttermilk Creek. The plateau is bordered on the east by a steep embankment that drops 50 m to Buttermilk Creek and on the west by Franks Creek, a tributary valley eroded 10 m into the plateau. The proposed research site is about 300 m east of the waste-disposal areas at the WNYNSC.

History of Operation

In 1961, the New York State Office of Atomic and Space Development acquired 1,350 ha of undeveloped land near the village of West Valley (fig. 1) for the development of a nuclear-fuels-reprocessing plant. The land was subsequently named the Western New York Nuclear Service Center (WNYNSC). In 1963, the U.S. Atomic Energy Commission issued a permit to a private operator authorizing development of about 100 ha of the site for construction of a reprocessing plant and supporting facilities (fig. 4). The

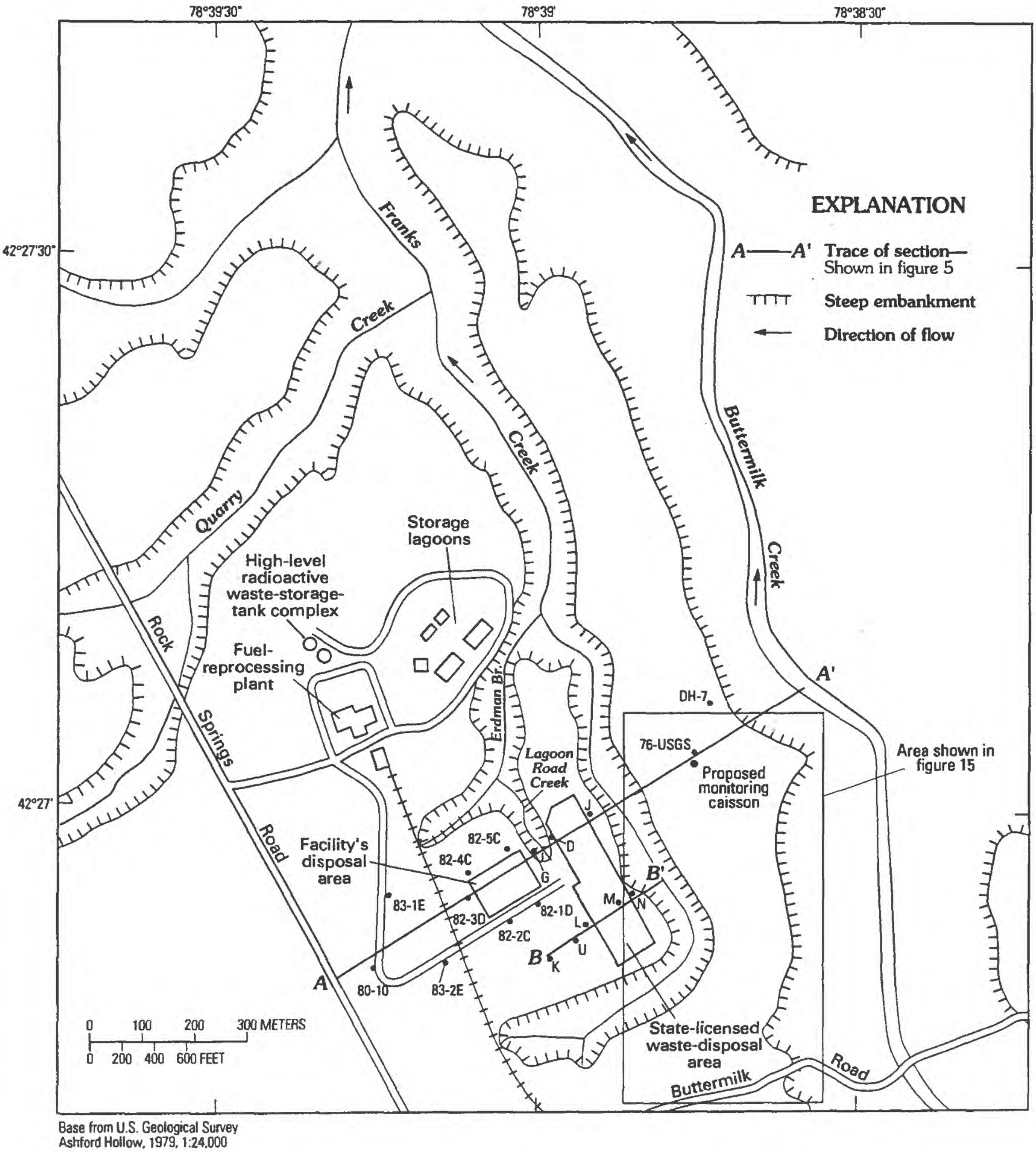


Figure 4. Location of proposed research site at the Western New York Nuclear Service Center. (Modified from Bergeron and others, 1987, fig. 3. Location is shown in fig. 1.)

supporting facilities included a structure for receiving and storing irradiated fuel before reprocessing, an underground storage-tank complex for liquid, high-level radioactive wastes generated by reprocessing, and a low-level radioactive-wastewater treatment plant. The site also includes two separate disposal areas for shallow burial of solid radioactive wastes—a 4-ha area licensed by the State of New York for burial of commercial low-level radioactive waste (not operating at present), and a 2.2-ha area licensed by the USNRC for wastes with higher radioactivity generated onsite.

The reprocessing plant received spent fuel-rod assemblies from nuclear reactors and processed the fuel elements to recover uranium and plutonium from 1966 until it was closed in 1972. The facility continued to receive and store fuel-rod assemblies until 1975. In 1982, the reprocessing plant was turned over to the U.S. Department of Energy, which contracted the operation of the facility to a private operator to decommission the reprocessing facilities and to solidify the high-level radioactive liquid waste stored at the site for future disposal at a high-level-waste repository.

In 1992, the site contained spent fuel-rod assemblies that had not been reprocessed, as well as high-level radioactive liquid wastes generated by the recovery process and a variety of low-level radioactive solid wastes generated by the reprocessing facility and received from offsite commercial installations. Additional low- and intermediate-level radioactive wastes generated by the decontamination and solidification activities have been buried at the USNRC-licensed disposal area and stored in an above-ground facility. The New York State Energy Research and Development Authority currently administers the remainder of the center outside the former plant site.

Hydrogeology

The proposed research site is underlain by glacial deposits as much as 150 m thick that are the product of repeated glaciations in the late Wisconsinan in the Buttermilk Creek Valley. The sediments were deposited in a former valley that had been carved into the shales, siltstones and sandstones of the Upper Devonian Canadaway and Conneaut Groups that underlie the area. Much of the sediment deposited by the ice sheets or associated meltwater consists of silt and clay derived from these rocks.

Glacial Deposits

The oldest sediments in the Buttermilk Creek Valley are deposits of till deposited during advances of the ice sheets. During the recessional stages between glaciations, temporary lakes formed in the valley as the glaciers blocked the northward drainage of meltwater; silt and clay deposits formed on the lake bottoms, and sand and gravel deltas formed where streams entered the lakes. Subsequent readvances of the ice sheet overrode these early deposits and transported and redeposited the sediment as more recent till deposits. Streams that formed after the last glaciation deposited alluvial fans of sand and gravel atop the glacial sediments in some parts of the valley and eroded the glacial sediments in others. The Buttermilk Creek Valley of today is deeply incised into the surrounding plateau.

The proposed research site (fig. 4) is underlain by a sequence of glacial deposits composed of till and lacustrine, deltaic and fluvial sediments (fig. 5). The uppermost deposit is the Lavery Till, a clayey till 2 to 28 m thick with a clay content of about 50 percent that serves as the host material for waste-disposal areas at the WNYNSC (LaFleur, 1979). The upper 2 to 3 m of the Lavery Till is weathered and contains oxidized fractures that provide secondary permeability near land surface. The maximum depth of oxidized fractures observed in walls of a research trench excavated near the proposed research site was 5 m (Prudic, 1986). The Lavery Till contains scattered stratified deposits that appear to be discontinuous; the deposits include pods up to 1 m thick and 2 m long and lenses up to 2 m thick and more than 30 m long (Edwards and Moncreiff, 1987).

Beneath the Lavery Till is a sequence of recessional lacustrine and kame-delta deposits 20 m thick that consist of laminated silt and clay grading upward into fine to coarse sand and silt. In borehole 76-USGSV (table 2), adjacent to the proposed research site (fig. 5), the upper, sandy part of the unit is capped by fluvial gravel. The lacustrine sequence is underlain by the Kent Till, a silt-rich till that is exposed in Buttermilk Creek (LaFleur, 1979).

Precipitation and Ground-Water Movement

The climate of western New York is classified as moist continental, with an average annual temperature of 7°C and average annual precipitation of 100 cm (Prudic, 1986). Monthly temperatures range

Table 2. Log of observation well 76-USGSV

[From Bergeron, 1985, table 3. Location shown in fig. 4. %, percent. ft, feet. cm, centimeters. diam, diameter. mm, millimeter]

76-USGSV. Drilled October 14-28, 1976. Latitude 42°27'01", longitude 78°38'47", altitude, 1,385.90 ft. Log from U.S. Geological Survey study of low-level radioactive-waste burial trenches.

0-44 ft	Till: predominantly silt and clay, with a little randomly distributed coarse sand to pebbles (est. 10-15% of core, 0 to 15 ft, 5% or less at 15 to 35 ft, 10-15% at 35 to 43 ft); oxidized at 0 to 9 ft, grading at 9 to 16 ft to unoxidized, relatively clayey at 40 to 44 ft with minor wisps or partings of coarse silt.
44-49	Lacustrine material: layers of coarse silt, clay with rare silt partings and pebbles, rhythmic-laminated dark gray clay and light gray silt, and probably fine to coarse sand.
49-69	Till: relatively clayey; includes occasional lenses of rhythmic clay and silt, and silt partings; coarse sand to pebbles est. about 5% of core at 49 to 53 ft, generally greater below.
69-83	Till: predominantly silt and clay; randomly distributed coarse sand to pebbles generally forming about 10% of core, but some relatively pebbly till may be at 75 to 78 ft; unoxidized; possibly unsaturated at 81.5 to 83 ft.
83-94	Gravel: probably mostly small pebbles and granules, with very coarse to very fine sand, traces of silt; poorly sorted; oxidized; unsaturated; pebble counts at 85 and 90 ft show 18% and 21% exotic lithologies, respectively, among broken or rounded stones 1 to 3 cm diam.
94-99	Sand: fine to very fine, with 20-50% medium to very coarse; traces of silt; rare granules; rare thin layers of grayish-red clay with embedded very coarse sand; oxidized, unsaturated.
99-99.5	Gravel: fine pebbles and granules.
99.5-103.5	Sand: very fine to fine, layered; a few thin layers and partings of silt; oxidized, unsaturated; small gray concretions.
103.5-107	Lacustrine material: upper part mostly silt and (or) clay, no samples; lower part dark clay with numerous partings of unoxidized silt, a few layers of oxidized very fine sand to silt, and occasional round blebs or augen as large as 5 mm of grayish red silty sand and rarely of gray silt or silty sand; unoxidized except very fine sand as noted.
107-118	Lacustrine material: silt; chiefly as rhythmic layers of coarse silt 1/2 to 3 mm thick alternating with generally thinner layers or partings of dark-gray fine clayey silt; some thicker layers of coarse silt; one layer of very fine sand at 111.6 to 111.7 ft; silt and sand weakly oxidized, generally pale yellowish-brown (10YR-5Y 6/2); unsaturated; a few layers with partings of red clay near base.
118-129	Disturbed lacustrine material: fine or clayey silt, gray to olive gray, regular fine beds 1 to 3 mm thick, with a few beds of brownish-gray clay (5YR 5/1) as much as 5 mm thick, and a few partings or very thin beds of coarse silt, which together constitute 50% or more of core; interbedded with layers of disturbed material ranging from severely contorted rhythmic thin layers to irregular mottled blebs of fine to coarse silt, commonly with scattered grains of coarse sand to granules and with scattered blebs or aligned blebs of grayish red (10R 4/2) to light brown (5YR 5/5) silt to sandy silt and one bleb of brown layered clay and silt; at 124 ft, disturbed material includes three layers, each 2 to 3 cm thick, of structureless clayey silt with randomly distributed pebbles to coarse sand, gray (N5-5GY 6/1) mottled with dark gray (N4), grayish red (10R 4/2), and (or) pale yellowish brown, more stony than the till above 83 ft.
129-150	Lacustrine material: silt, medium to fine, generally in regular beds 1 to 20 mm thick with slight contrast in grain size between beds, but with partings of coarse silt below 138 ft and beds of coarse silt 1-6 cm thick below 149 ft; olive-gray, barely plastic, graded silt beds at 134 ft; a few zones of folded, disturbed beds; rare clay beds up to 7 mm thick; rare scattered coarse sand above 135 ft have zero or negative (unsaturated) pressure head.

from -6°C in January and February to 20°C in July. Monthly precipitation ranges from 7 cm in the winter to 9 cm in the spring. A continuous snow cover can be expected from mid-December through mid-March; maximum depths usually occur in February.

Most precipitation that falls in areas underlain by the Lavery Till runs off into nearby streams or is lost through evapotranspiration; the remainder infiltrates through silty clay soil into a shallow, subsurface flow system in the weathered part of the Lavery Till. Most of this water flows laterally through fractures and animal burrows (such as mole runs) toward depressions and gullies, but a small amount infiltrates downward into the unweathered part of the till.

Head measurements in piezometers installed near the WNYNSC waste-disposal areas 300 m southwest of the proposed research site indicate that ground water flows vertically downward through the unweathered till (fig. 6) at a rate of 3 to 23 mm/yr, as estimated from numerical simulations by Prudic (1986). From there it enters the underlying lacustrine sequence, but at a rate insufficient to saturate the upper part of the sequence (Bergeron and others, 1987). Most of the water in the lower, saturated part of the lacustrine sequence flows laterally and discharges to the edge of the plateau above Buttermilk Creek; a small amount could enter the underlying Kent Till (fig. 5).

The weathered Lavery Till probably is saturated for part of the year but could become partly saturated as evapotranspiration increases in the summer. The underlying unweathered Lavery Till probably is saturated year-round, although neutron-moisture profiles indicate it to be unsaturated in some areas (Bergeron and others, 1987). The degree of saturation in the lacustrine sequence increases downward.

Hydraulic Properties of Lavery Till

The horizontal hydraulic conductivity of the unweathered part of the Lavery Till, as estimated from falling-head permeameter tests on core samples obtained during test-hole drilling and slug tests in

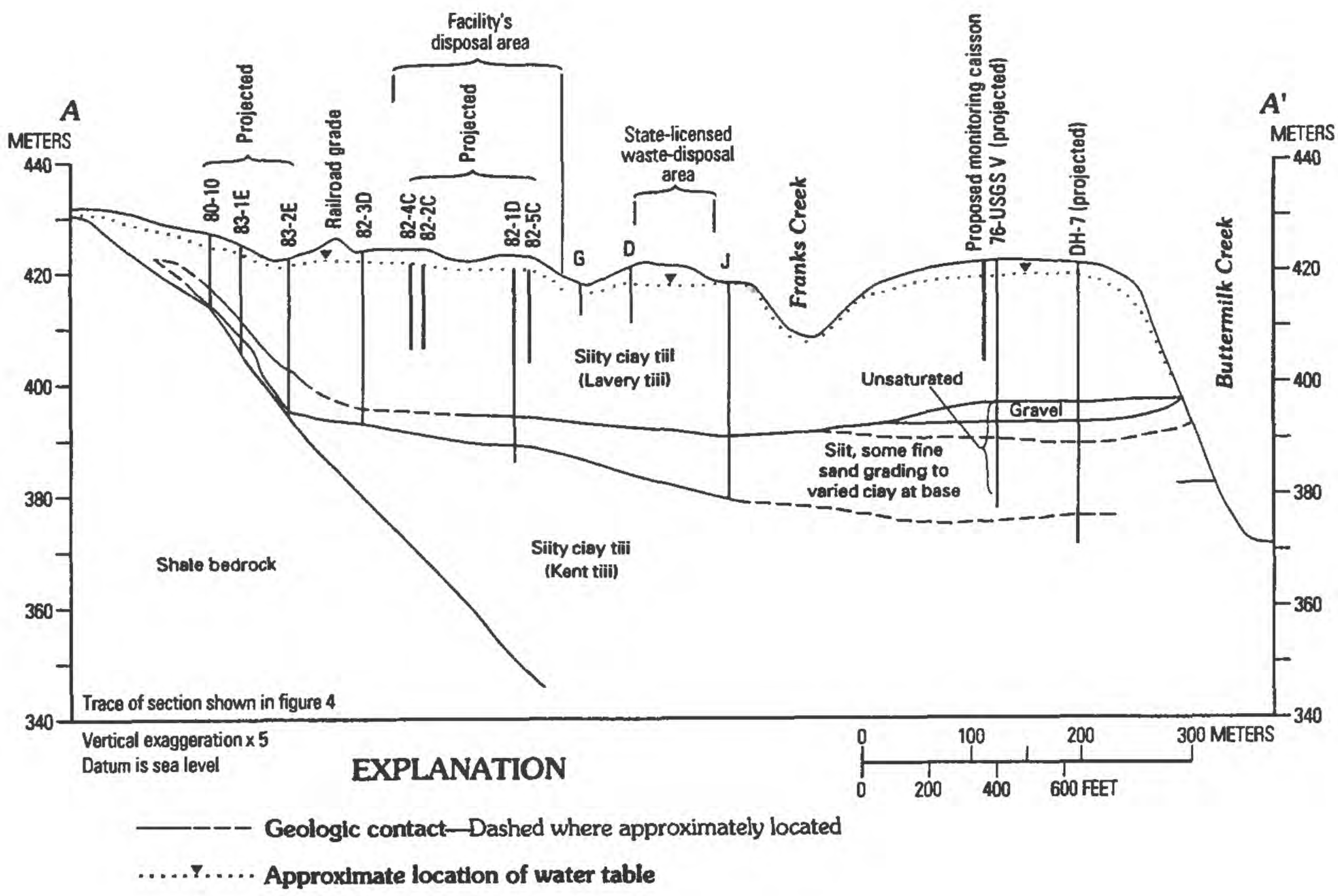


Figure 5. Geologic section showing major lithologic units at Western New York Nuclear Service Center. (Modified from Bergeron and others, 1987, fig. 6. Trace of section is shown in fig. 4.)

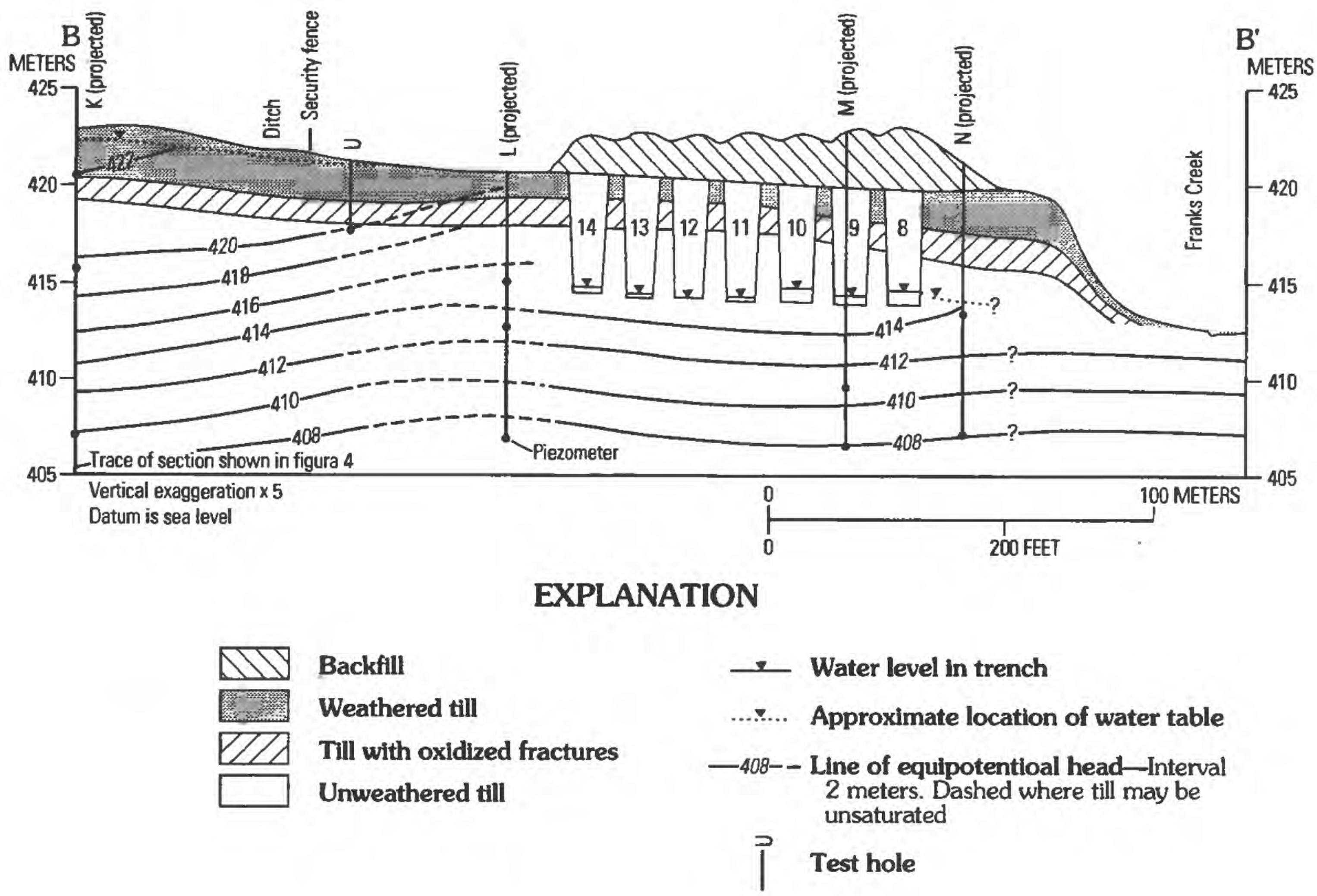


Figure 6. Hydraulic-head distribution along section B-B' near Western New York Nuclear Service Center waste-disposal areas. (From Prudic, 1986, fig. 13. Trace of section is shown in fig. 4 .)

piezometers, is 2×10^{-10} to 6×10^{-10} m/s (Prudic, 1986). Petrological investigations found no textural indication that the permeability should be anisotropic, and Prudic (1986) concluded that the unweathered till is nearly isotropic because the vertical hydraulic-conductivity values estimated from consolidation tests were nearly equal to the horizontal-hydraulic conductivity values. The weathered till also is assumed to be isotropic, and its hydraulic conductivity was estimated from numerical simulations conducted by Prudic (1986) to be 1 order of magnitude larger than that of the unweathered till.

Specific storage of the unweathered till, estimated from consolidation tests on four core samples, averaged 8×10^{-4} m^{-1}. The average porosity of 28 samples was 32 percent. A curve relating soil-moisture content to soil-moisture tension under unsaturated conditions, calculated by Prudic (1981) from mercury porosimeter tests, is given in figure 7. Prudic (1986) also calculated the ratio of hydraulic conductivity of the unsaturated till to that of saturated till over a range of soil-moisture tensions (fig. 7) from curves of soil-moisture content in relation to soil-moisture tension through an equation by Millington and Quirk (1961).

Previous Studies

A great deal of geohydrologic information on the Lavery Till is available from studies by the New York State Geological Survey (NYSGS) and the USGS, and by Dames and Moore, the site engineering consultants. Studies by the NYSGS, summarized by Albanese and others (1984), describe the geomorphology, stratigraphy, and sedimentology of the WNYNSC; the NYSGS also investigated the potential for radionuclide retention and migration at the burial trenches (Dana and others, 1980). The USGS has conducted several hydrologic studies at the WNYNSC. Prudic (1986) studied the ground-water hydrology of the Lavery Till in the vicinity of the State-licensed disposal area (fig. 4) and constructed a numerical model of ground-water flow. Bergeron and Bugliosi (1988) modeled flow through the Lavery

Till at the USNRC-licensed disposal facility, and Yager (1987) modeled flow through sand and gravel underlying the fuel-reprocessing plant (fig. 4). USGS studies of the surface-water hydrology of the WNYNSC are summarized in Kappel and Harding (1987). Dames and Moore has conducted several geotechnical and hydrologic studies in the vicinity of the reprocessing plant since 1973 (David Aloysius, Dames and Moore, oral commun., 1992).

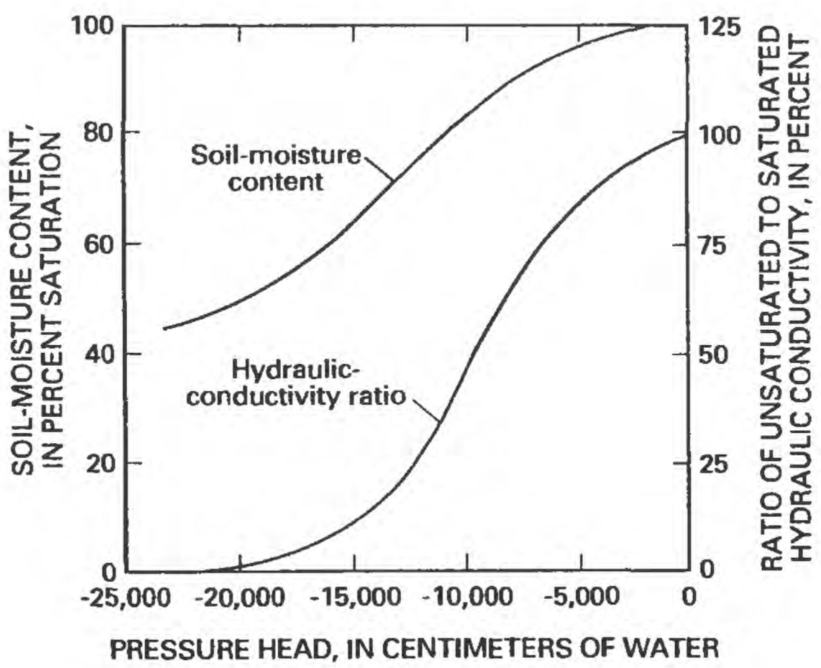


Figure 7. Relation of hydraulic conductivity and volumetric soil-moisture content to soil-moisture tension. (From Prudic, 1981, and 1986, fig. 11.)

STUDY PLAN

The proposed study will consist of three phases: (1) site characterization, (2) emplacement of the monitoring caisson to simulate waste burial with subsequent monitoring for 3 years, and (3) site remediation. This section describes the methods planned for each phase. (Equipment and tests are discussed in detail in the section "Field experiment.") The first step will be to estimate the depth of advective transport (flow through fractures) in the Lavery Till so that hydraulic tests of the grout used to seal the monitoring caisson can be conducted below that depth. If evidence of advective transport is found near the bottom of the Lavery Till, another site might be selected for the study, or the caisson could be placed in the Kent Till.

Site Characterization

The initial phase will estimate physical and hydraulic properties of the till and differentiate zones dominated by advection from those dominated by diffusion within the till. Previous studies of clayey till in Ontario have identified a surficial weathered zone 2 to 3 m deep in which fractures are abundant and readily visible from staining by mineral deposition; at greater depths the till is unweathered, and no fractures are discernible (Ruland and others, 1991). A transition zone of variable thickness separates the two zones and contains some high-angle (nearly vertical) fractures. Spacing between fractures increases, and the fractures become less discernible with depth in the transition zone (fig. 8). Ground water in the weathered zone and in some parts of the transition zone is chemically similar to recent recharge as a result of advective transport of solutes from land surface, and chemical concentration gradients at greater depths in the unweathered till indicate that water derived from recent recharge is slowly mixing by diffusion with older water of glacial origin (Desaulniers and others, 1981; D'Astous and others, 1989).

Physical and Hydraulic Properties of Till

A numerical hydromechanical model of the till deposit will be developed, and values of physical and hydraulic properties (listed in table 3) measured in laboratory tests will be applied to investigate the response of the till to excavation of the augered borehole and emplacement of the monitoring caisson. The model will be calibrated to the stress-strain response of the till measured in consolidation tests in which samples are successively subjected to loading and unloading to simulate changes in the state of stress in the till. The laboratory tests will use core samples obtained during drilling of vertical boreholes at the site.

Table 3. Physical and hydraulic properties of till to be estimated from laboratory tests

Particle-size distribution	Overconsolidation ratio; compression and recompression indices
Atterberg limits	Shear strength
Hydraulic conductivity	Compressive strength
Specific storage	
Porosity	

Depth of Advective Transport

The depth of advective transport in the till is assumed to correspond to the depth of fracturing. The depth of advective transport will be estimated through several methods, including direct observation of fractures in excavations, measurement of concentration gradients of selected constituents in pore water along vertical profiles, and measurement of seasonal fluctuations in pore pressure. The maximum depth of advective transport indicated by these methods at several sites in Ontario ranged from 5 to 10 m (Ruland and others, 1991). Some fractures are likely to extend below these depths, however, because fractures without weathering features are indiscernible in excavations, and vertical boreholes installed to measure chemical and hydraulic data are unlikely to intersect widely spaced, high-angle fractures. For these reasons, horizontal boreholes will be drilled in an attempt to intersect high-angle fractures at greater depths.

Direct Observation of Fractures

Fracture mapping will be conducted at the proposed research site to determine (1) the relation between fracture spacing and depth, and (2) the maximum depth of visible fractures in the till. Fractures in the walls of research trenches excavated 8 m into the till in a series of benches will be mapped. Fractures extending from the weathered zone into the transition zone have been observed directly in excavations in a similar clayey till in Ontario to depths of 5 to 6 m (Ruland and others, 1991). The visible fractures are coated with the products of chemical oxidation–for example, iron and manganese oxide–or are bordered by "oxidation haloes." Colored dye will be ponded on some parts of the till surface before excavation to penetrate the fractures and enhance their visibility. This technique has allowed other investigators to trace fractures to a depth of 3 m in a till on the western shore of Lake Champlain (Tammo Steenhuis, Cornell University, oral commun., 1992).

Geochemical Profiles

Geochemical profiles that indicate the changes in concentration of selected constituents with depth will be compiled from analyses of pore water extracted from core samples of the till obtained during drilling of vertical boreholes. The pore water will be analyzed for major inorganic constituents as well as stable and radioactive isotopes. Constituents to be measured, and their analytical detection limits, are listed in table 4. The depth of advective transport will be

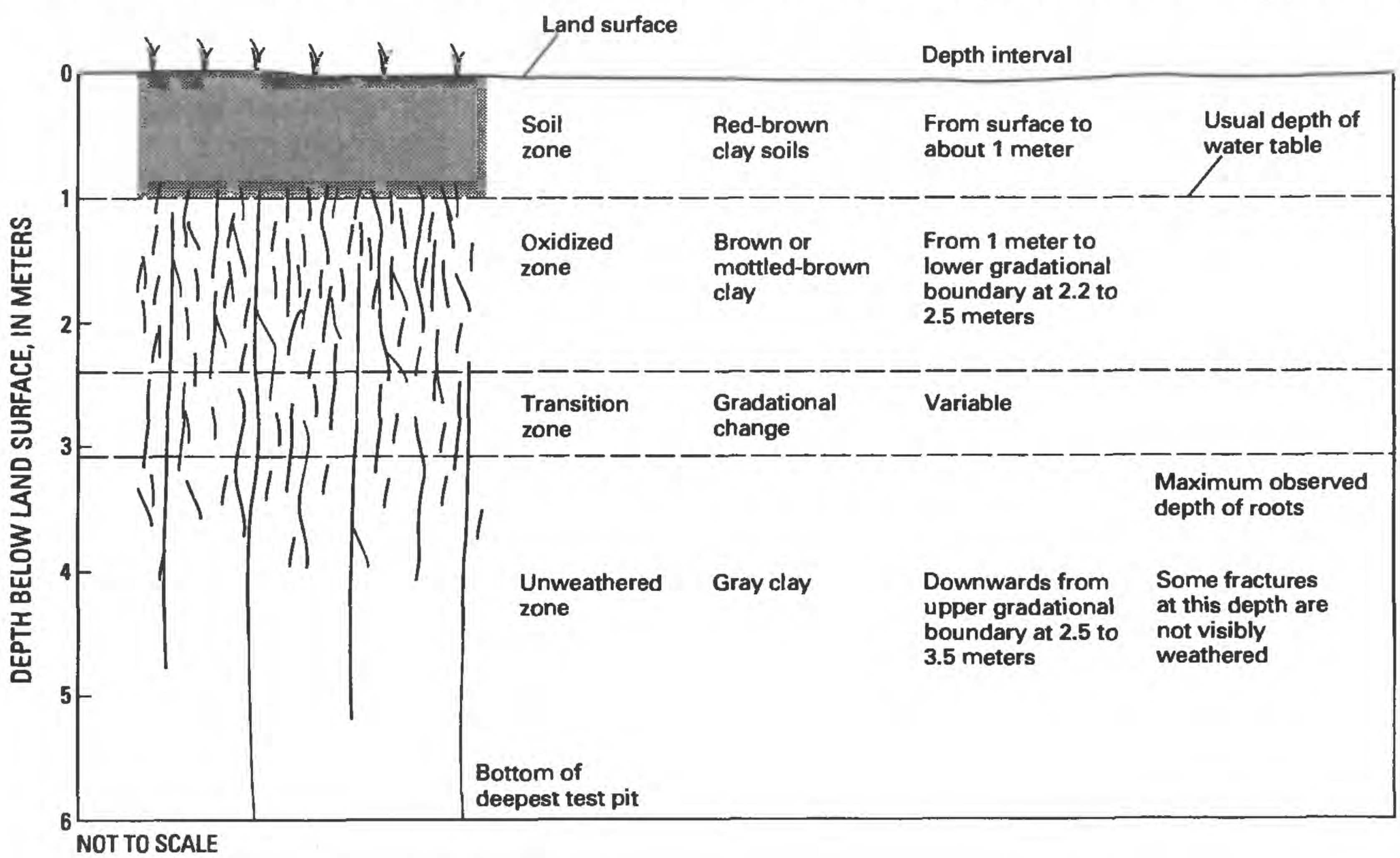


Figure 8. Relation between fracture spacing and depth in clayey till in southwestern Ontario. (Modified from Ruland and others, 1991, fig. 2, copyright © 1991, Journal of Ground Water.)

Table 4. Constituents for which pore water from till samples is to be analyzed, with analytical detection limits

PORE WATER EXTRACTED BY COMPRESSION	
Inorganic constituents (milligrams per liter unless noted)	Detection limit
Calcium	0.1
Magnesium	.1
Silica	.1
Sodium	.1
Potassium	.1
Bromide	.1
Chloride	.01
Fluoride	.1
Nitrate-nitrogen	.01
Orthophosphate-phosphorus	.01
Sulfate	1.0
pH (standards units)	.1
Specific conductance (μmho/cm)	.1
Alkalinity (as $CaCO_3$)	5.0
Trace metals (micrograms per liter)	
Iron	50
Manganese	50
Strontium	50
Isotopes (percent modern carbon)	
Carbon-13, carbon-14	.2
PORE WATERS EXTRACTED BY AZEOTROPIC DISTILLATION WITH TOLUENE	
Tritium (tritium units)	.8
Deuterium (per mil)	2.0
Oxygen-18 (per mil)	.2

indicated by abrupt changes in concentration gradients that indicate the limit to which recent recharge has penetrated the till.

Keller and van der Kamp (1988) found, in the weathered zone of clayey tills in Saskatchewan, an abundance of sulfate that they attributed to oxidation of sulfide minerals in the till. They estimated the depth of advective transport, from the depth distribution of sulfate in several boreholes, to be 5 to 6 m. Desaulniers and others (1981) measured stable isotopes of oxygen-18 (^{18}O) and deuterium (^{2}H) in water from a clayey till in Ontario and found that the isotopic content became lighter (depleted of ^{18}O) with depth, characteristic of water originating in cool, presumably glacial climates. Tritium (^{3}H), a radioactive isotope of hydrogen produced by atmospheric testing of thermonuclear weapons in the 1950's and 1960's also has been used to estimate the relative age of ground water in clayey till. Desaulniers and others (1981) and D'Astous and others (1989) both estimated the depth of advective transport in till, from the tritium distribution with depth, to be 3 to 4 m.

Seasonal Fluctuations in Pore Pressure

Seasonal fluctuations in pore pressure will be continuously recorded at selected depths in the till with pressure transducers to estimate the depth of fracturing and the hydraulic diffusivity. Transducers placed within the zone of advective transport in the till will respond to seasonal changes in recharge more rapidly and will indicate larger fluctuations than transducers in the unweathered till. Ruland and others (1991) measured head fluctuations exceeding 0.5 m at depths of 5 to 10 m in clay tills in Ontario. Keller and others (1989) analyzed the attenuation and delay in the downward propagation of head fluctuations to estimate the hydraulic diffusivity of a clayey till in Saskatchewan.

Horizontal Boreholes

Horizontal boreholes will be drilled at selected depths through the walls of two research trenches in an attempt to intercept high-angle fractures in the till. Core samples obtained during drilling will be analyzed for tritium to detect the presence of recent recharge. Tritium entering the till through fractures could have diffused 1 to 2 m into the unweathered till matrix since the 1960's and would form a tritium "envelope" around the fractures, as illustrated in figure 9 (Ruland and others, 1991). As a result, core samples spaced 2 m apart or less would indicate the presence of a fracture. Core samples will be obtained from a series of short (1 m) horizontal boreholes drilled at several locations into the trench wall and from longer (10 m) horizontal boreholes drilled to obtain several samples (fig. 10).

Diffusion-Dominated Transport

Chemical concentration gradients along a flow path in a ground-water flow system can be represented with the one-dimensional form of the advection-dispersion equation:

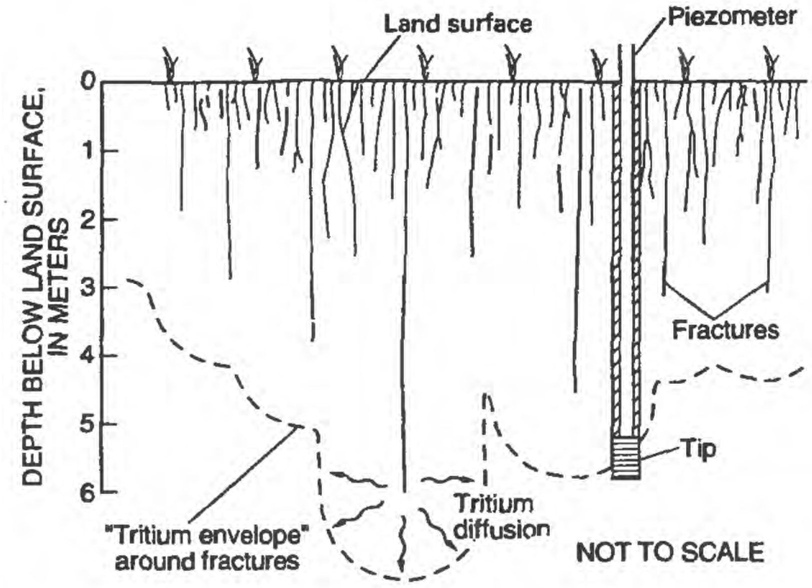


Figure 9. Distribution of tritium in clayey till in southwestern Ontario. (Modified from Ruland and others, 1991, fig. 8, copyright © 1991, Journal of Ground Water.)

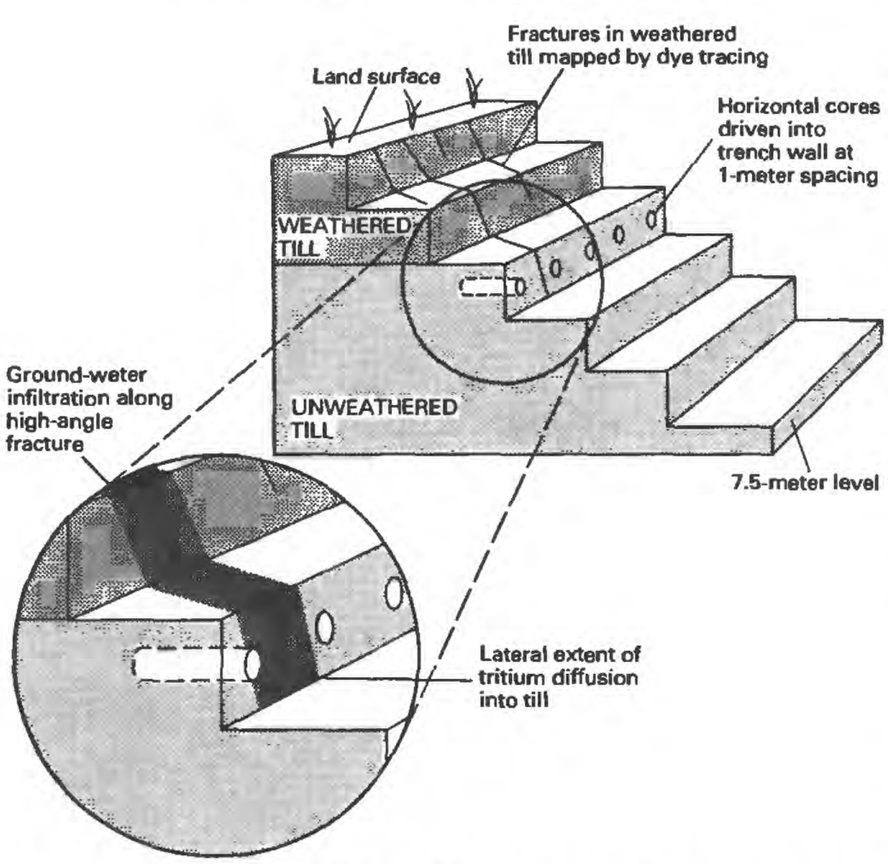


Figure 10. Extent of tritium diffusion along fractures in till, and spacing of till samples from horizontal boreholes cored in walls of research trench.

$$D \frac{\partial^2 C}{\partial x^2} - v \frac{\partial C}{\partial x} = \frac{\partial C}{\partial t} \qquad (1)$$

where D is coefficient of hydrodynamic dispersion, L^2T^{-1}

C is solute concentration, ML^{-3};

x is distance along the flow path, L;

t is time, T; and

v is average linear ground-water velocity, LT^{-1}.

At low ground-water velocities, v, the coefficient of hydrodynamic dispersion, D, can be approximated by the coefficient of molecular diffusion, D^*, and equation 1 reduces to the diffusion equation:

$$D^* \frac{\partial^2 C}{\partial x^2} = \frac{\partial C}{\partial t} \qquad (2)$$

If solute transport occurs predominantly through diffusion, then equation 2 can be used to predict the concentration gradient along the path of migration.

Desaulniers and others (1981) simulated concentration gradients of ^{18}O and ^{2}H in a clayey till in Ontario with the advection-dispersion and diffusion equations, on the assumption that pore water in the till initially contained an isotopic content typical of glacial meltwater but developed an isotopic content equivalent to that of contemporary meteoric water through dilution by recharge. Desaulniers and others (1981) then used the same values of velocity and molecular diffusion to predict the observed concentration gradient of chloride in the till. Their results indicate that ^{18}O and ^{2}H solutes in meteoric water had been transported by diffusion to a depth of 30 m over a period of 10,000 to 15,000 years. Prudic (1986) used a similar approach to show that tritium had migrated downward less than 3 m into unweathered till through diffusion from the bottom of an unlined trench containing low-level radioactive waste at the WNYNSC in 7 to 11 years.

In the proposed study, concentrations of ^{18}O and ^{2}H will be measured in pore water extracted from several depths in the till. Samples with isotopic contents lighter than that of present-day precipitation will be assumed to result from the mixing of meteoric water with glacial meltwater. The observed concentration gradients will be compared with those computed with the advection-dispersion and diffusion equations to determine which equation best represents the transport of ^{18}O and ^{2}H solutes in the till. The ground-water velocity used in the transport simulations will be computed through Darcy's law from the observed hydraulic gradient and from hydraulic conductivity and porosity values obtained from laboratory tests of core samples. The coefficient of molecular diffusion will be estimated from the range of values reported in the literature. The rates of advective and diffusive transport indicated by the calculation will be compared to determine whether diffusion is the dominant transport process in the unweathered till.

Emplacement of Monitoring Caisson

When the site-characterization phase has been completed, a monitoring caisson consisting of a hollow steel cylinder 20 m high and 1.8 m in diameter will be emplaced in a borehole augered into the till to simulate a waste-burial container. The annular space surrounding the caisson will be sealed with layers of three different grout materials. Each grout layer will contain a layer of sand into which water and tracer will be injected for hydraulic tests. Both cement and bentonite grouts will be used for comparison of their effectiveness in sealing the caisson. Instruments will be placed in the grout and the surrounding till to record changes in the state of stress that result from the emplacement and sealing of the caisson.

Caisson Design

The monitoring caisson (fig. 11) is based on a design described by Fisher (1992). The top of the caisson will be exposed at land surface for access but covered by a shelter, and the bottom will be sealed with a poured concrete floor. The interior will contain ladders on opposite walls that support moveable steel platforms to provide access to all depths within the caisson. Ventilation will be provided through air ducts, and electricity will be provided through electrical conduits installed between the ladders and the caisson wall. Equipment will be lowered into the caisson by a winch and tripod mounted at the top.

The caisson wall will contain instrument and injection ports. Wiring from instruments embedded in the sand and grout will pass through the instrument ports, which will be sealed from inside the caisson (fig. 12A); plastic PVC pipe extending from the caisson wall into the sand and grout layers will provide injection ports for conducting hydraulic tests and measuring pore pressure (fig. 12B).

Selection of Grout

Only grouts that have been used, or are planned for use, in sealing actual waste-disposal containers will be used to seal the annular space between the monitoring caisson and the borehole wall. The grout properties will be specified to ensure workability and to approximate the properties of the till at West Valley. Laboratory tests will be conducted on selected grout materials to identify (1) mixtures that yield the desired properties, and (2) proper field procedures for mixing and installing the grout.

Cement Grout

Cement grouts include mixtures of portland cement, sand, and water that form an assemblage of hydrated calcium silicates. The properties of cement grouts are determined primarily by the water content, the particle size of the cement and aggregate, and by the various admixtures that affect the curing, porosity, and mineral composition of the grout. The mineral composition of cement grouts changes with time, and this in turn can cause changes in other properties (Atkinson and others, 1985).

Factors of concern include the fluid properties of the grout during installation and hydration, and properties of the hardened material that determine its response to changes in the level of stress once it has cured. The cement grout to be tested can be pumped, will be self-leveling, and will be workable for about 2 hours after mixing. It will set in about 8 hours with little segregation of fine particles and no release of bleed water from the mixture. The curing temperature will be about 50°C (120°F). Once hardened, the cement grout will have a compressive strength greater than that of the till and a modulus of elasticity nearly equal that of the till. Because the permeability of the cement grout will be less than that of the till (10^{-10} m/s), a low water-to-cement ratio (w/c) will be required (Clifton and Knab, 1989); high-range, water-reducing admixtures (superplasticizers) probably will be needed in the mixture to provide the desired fluid properties at this low w/c ratio.

The volume of cement grout typically increases, then decreases, as the grout cures, and this could cause the grout to crack or pull away from the till, creating a gap. Expansive or shrinkage-compensating additives will be included in the grout mixture to create a swelling pressure that will seal the interface between the grout and the till and prevent the formation of cracks. Test holes at the Waste Isolation Pilot Plant (WIPP) site in New Mexico were sealed with a concrete grout that contains plaster (gypsum hemihydrite) as an expanding agent (Stormont, 1986).

Bentonite Grout

Bentonite grouts contain smectite clay minerals, typically montmorillonite, that are highly plastic and that swell when saturated. Bentonite grouts have much less strength than cement grouts but have an equally low permeability and resist cracking from the swelling pressure created by hydration of clay minerals. Bentonite grout is also self-healing because

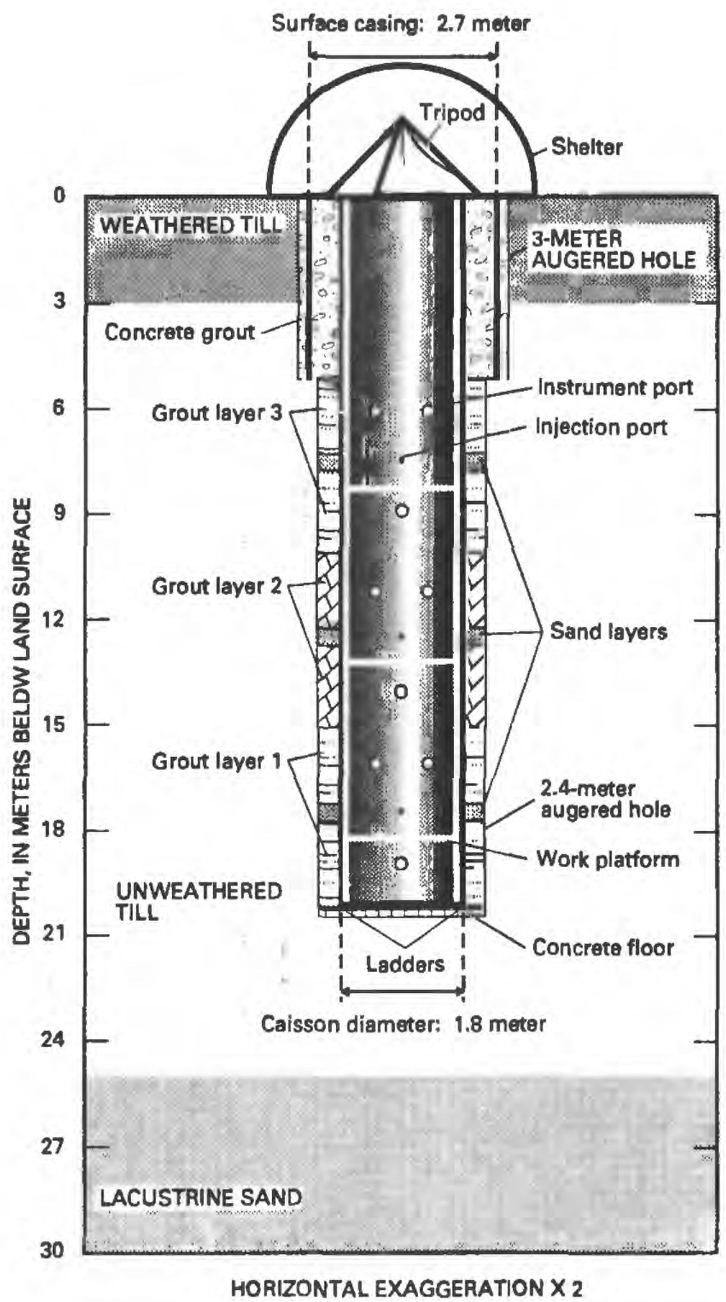


Figure 11. Proposed design of monitoring caisson.

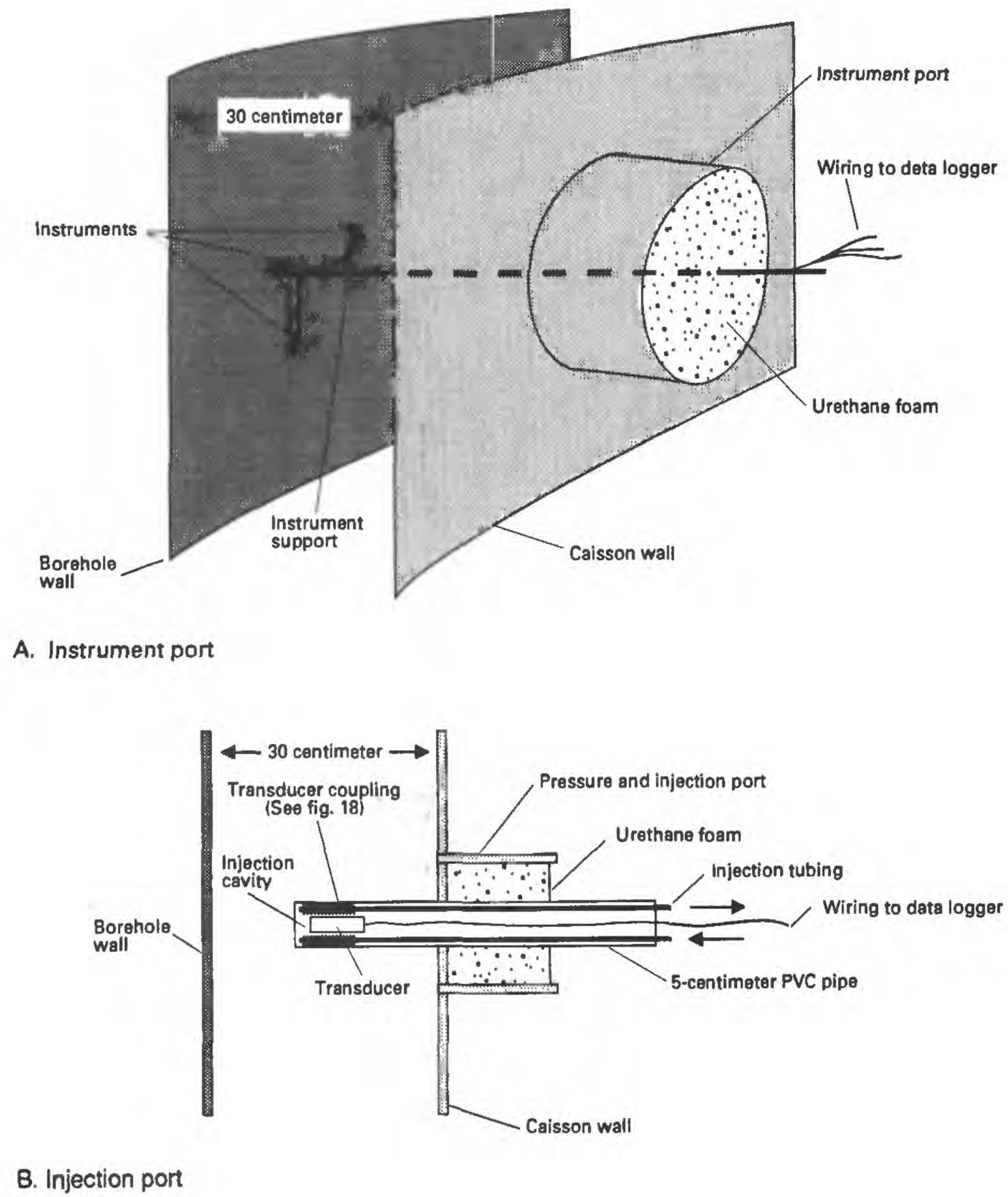


Figure 12. Proposed design of ports in wall of monitoring caisson: A. Instrument ports. B. Pressure and injection ports.

water flowing through cracks that form saturates the bentonite and causes it to swell, closing the cracks.

The properties of bentonite grout are largely determined by its water content and porosity. As air-dried bentonite becomes saturated, water enters the space separating adjacent clay-mineral layers, increasing the volume of clay aggregates within the grout. If the grout is confined and cannot increase in volume, the swelling of the clay aggregates decreases the porosity and thereby decreases its permeability. Once the porosity is decreased, additional swelling develops pressure that prevents formation of cracks. Specifying the initial water content and desired degree of consolidation can control the amount of swelling and the magnitude of swelling pressure generated by saturation.

Compacted bentonite grout was used to seal boreholes at the Underground Research Laboratory (URL) in Pinawa, Manitoba, with a 1:1 mixture of bentonite and silica sand at a moisture content of 17 to 19 percent (Kjartanson and others, 1991). In the proposed USGS study, however; the use of compaction tools to consolidate the bentonite mixture will be made difficult by the small size of the annular space surrounding the monitoring caisson (0.3 m). One alternative would be to confine the grout mixture beneath a layer of cement grout to prevent swelling as the bentonite mixture slowly becomes saturated by inflow of water from the till; another would be to add compacted bentonite pellets to the grout mixture to increase the swelling pressure and lower the permeability.

Monitoring Changes in the Level of Stress

Drilling the large-diameter borehole and emplacing the monitoring caisson will alter the natural state of stress in the till. Stress changes are borne by the matrix of particles that form the till and by the fluid that occupies the pore spaces between the particles. Changes in the total stress, σ , result in changes in effective stress (σ') applied to the matrix, and changes in pore pressure (p) applied to the fluid according to the following relation:

$$\sigma = \sigma' + p \qquad (3)$$

Changes in the state of stress will be recorded by instruments (1) placed in the till before excavation of the augered borehole, and (2) embedded in the grout-filled annulus surrounding the monitoring caisson.

Removal of till during excavation of the borehole will alter compressive and tensile loads on the surrounding till, and the resulting deformation of the till will result in displacement toward the borehole and negative pore pressures. Conversely, the weight of the grout in the annular space surrounding the monitoring caisson, and the volumetric changes associated with hydration, will place compressive loads on the till that could increase the pore pressures.

Deformation of the till will be measured with displacement indicators, including (1) a monument survey and settlement plates to detect vertical displacement, and (2) slope indicators to detect horizontal displacement. The monument survey will be conducted before and after excavation of the augered hole, and the slope indicators will be installed before excavation. Pore pressure in the till will be measured with pressure transducers installed in nearby piezometers constructed for the site characterization.

Volumetric changes in the cement grout during hydration will be measured with strain gages. The magnitude of the resultant stress will be measured with stress meters to record total stress and with pressure transducers to record pore pressure. Thermocouples will be used to measure the temperature of the cement grout during hydration and to determine when the hydration reactions are complete. This instrumentation was used to monitor hydration of concrete grout in borehole seals at the WIPP in New Mexico (Stormont, 1987).

Saturation of the bentonite grout with water from the till will be determined from changes in water content and water potential (negative pore pressure). Water content will be measured with time-domain reflectometry probes, and water potential will be measured with thermocouple psychrometers at water potentials of less than -70 kPa (-10 lb/in^2) and pressure transducers at higher potentials (near saturation). The swelling pressure resulting from hydration of the bentonite will be measured with stress meters. This instrumentation has been used to monitor hydration of bentonite grout in borehole seals at the URL in Manitoba (Kjartanson and others, 1991).

Movement of Water Along the Till/Grout Interface

Previous studies have identified the interface between cement grout and clay soils as the most probable pathway of radionuclide migration from waste buried in augered holes within saturated sediments (Vorauer and Chan, 1988). Hydraulic tests of borehole seals have also indicated that the limiting factor in seal performance is the hydraulic conductivity of the interface between the seal and the rock mass (Daemen and others, 1986; Peterson and others, 1987). Sealing this interface is essential to minimize advective transport.

Possible mechanisms for the formation of pathways for advective transport along this interface include: (1) deformation of the till in response to emplacement and sealing of the monitoring caisson, (2) formation of flow channels within the hydrated grout, and (3) alteration of till or grout properties in response to changes in water content and chemical reactions. The first of these mechanisms, deformation of the till, could result from changes in the state of stress in response to (1) the excavation process, and (2) hydration of the grout. An inelastic response of the till to these changes could cause a gap at the till/grout interface (fig. 13). The second mechanism, formation of channels along the interface during hydration of the grout, could result from either differential settlement in cement grout (piping) or nonuniform saturation of bentonite grout. The third mechanism, alteration of till or grout properties and subsequent development of cracks, could result from desiccation of the till near the borehole wall after excavation. Cracks also could form in the till or grout in response to volumetric changes induced by dissolution or precipitation reactions involving pore waters exchanged by the grout and till.

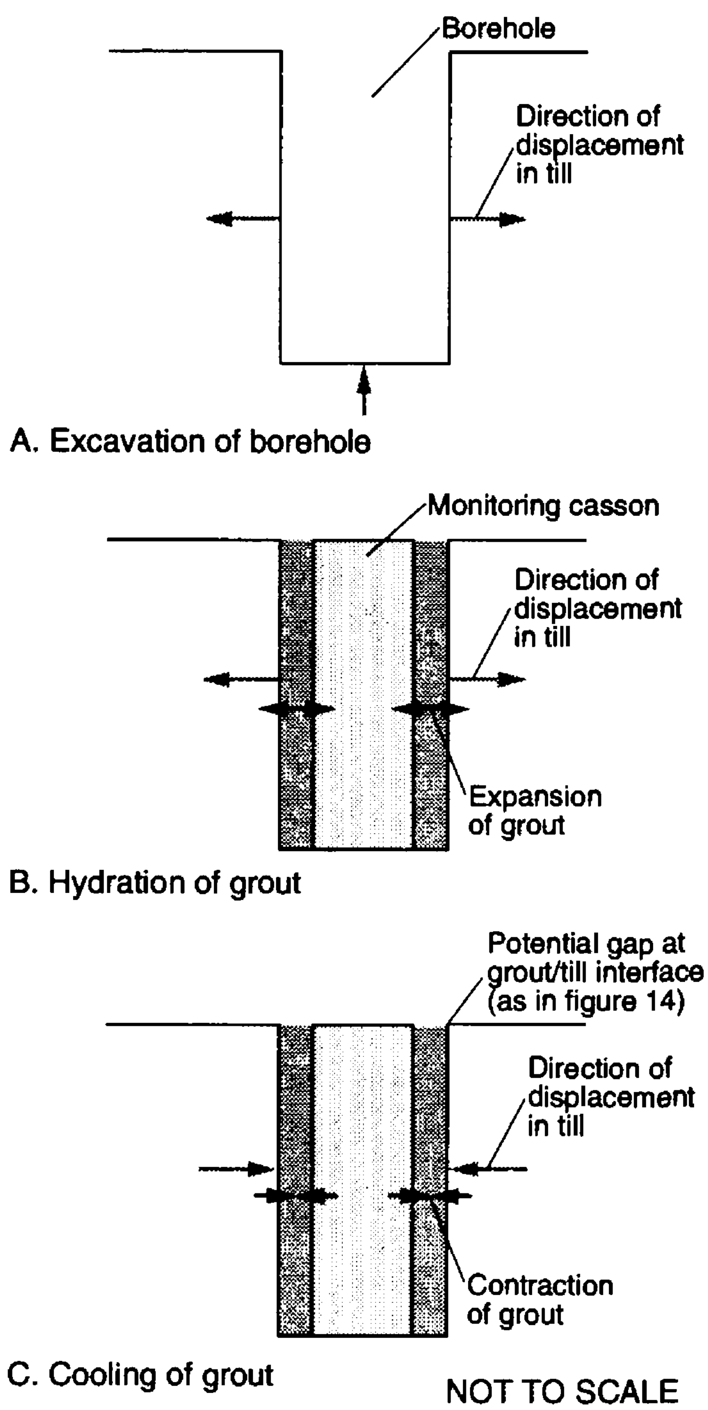


Figure 13. Causes and mechanisms for gap formation along the till/grout interface.

The maximum hydraulic conductivity of the till/grout interface will be estimated through constant-head injection tests in which water will be injected into the sand layer within each grout layer (fig. 14). The water will be injected simultaneously through four to eight injection ports to create radial flow within each sand layer. The tests will be repeated over a range of injection heads, and each test will continue for several days or weeks, depending on the injection rate. Pore pressures in (1) the injection interval, (2) the sand layers above and below the injection interval, and (3) the till, will be measured during the tests.

If pressures increase in adjacent sand layers, or if more water is injected than could enter the till or grout naturally, flow along the till/grout interface will be assumed. A tracer solution containing an electrically conductive solute and dye will then be injected into the sand layer, and sensors that are triggered by the presence of a conductive fluid will be monitored during the test to locate the flow path. A coring tube will then be driven through the area of suspected flow to obtain a sample of the till/grout interface for inspection and chemical analysis.

Chemical Alteration of Till and Grout

Chemical reactions between the till and the cement and bentonite grouts could alter the mineralogy. The till consists primarily of quartz and illite and contains calcium bicarbonate-type pore water with a dissolved solids concentration of less than 1,000 mg/L and a pH of 7 to 8 (Prudic, 1986). The cement grout is an assemblage of hydrated calcium silicates and calcium aluminates that is highly

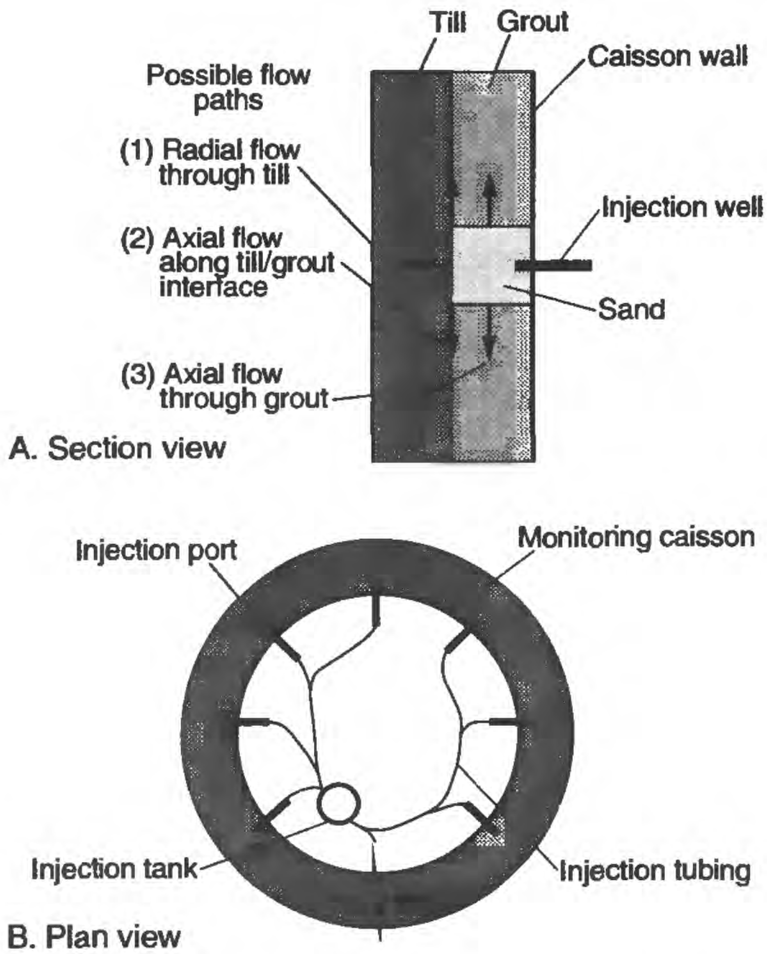


Figure 14. Placement of injection tubing for hydraulic tests of till/grout interface.

alkaline and whose primary aqueous species is calcium hydroxide (Atkinson and others, 1985). The bentonite grout consists mainly of smectite, and its role in chemical reactions is largely controlled by the concentrations of sodium or calcium ions that are sorbed to the surfaces of the clay minerals.

Cement grout. Previous studies have shown that, although clay in contact with cement grout undergoes a pH increase, changes in pH are slowed by sorption of calcium on the surfaces of clay minerals as the calcium hydroxide front moves through the clay (Jefferies and others, 1988). The increase in calcium activity can cause precipitation of calcite, which can decrease the plasticity of the clay and leave it susceptible to cracking from changes in stress. Conversely, sulfate and magnesium moving from the till to the grout can alter mineral phases in the cement grout. The sulfate reactions can cause expansion and cracking (Clifton and Knab, 1989), and the magnesium reaction results in loss of strength (Atkinson and others, 1985). The pore water of the till is relatively dilute, however, and thus might not have a significant effect on the cement grout. Cement grout is not susceptible to sulfate attack in water with a sulfate concentration of less than 150 mg/L (American Concrete Institute, 1988).

Bentonite grout. Ion-exchange reactions involving sodium and calcium could affect the clay structure of the till and the bentonite grout. The exchange of sodium from the grout for calcium in the till could increase the interlayer spacing between clay particles in the till and this, in turn, could disaggregate the clay particles and decrease the shear strength of the till. Exchange of calcium from the till for sodium in the bentonite grout would have the opposite effect in the grout—it would consolidate clay particles and increase porosity. Sawyer and Daemen (1987) report that the hydraulic conductivity of calcium montmorillonite is 2 orders of magnitude greater than that of sodium montmorillonite.

The potential for chemical alteration of till and grout in the interface region will be investigated through chemical and mineralogical analyses of samples obtained through coring. The core samples will be obtained by drilling from the caisson wall through the grout and into the till. Pore waters will be extracted from the core sample to determine the aqueous chemistry within the interface region, and thin slices of the sample will be analyzed to determine the mineralogy of solid phases in the till and grout.

Site Remediation

The monitoring caisson will be left in place for several years, during which its long-term effects on ground-water flow through the till will be investigated. Additional research suggested by results of the investigations might be undertaken at a future date. When all studies have been completed, the instrumentation will be removed from the piezometers and the monitoring caisson, and the power and telephone connections will be removed from the site. The research trench will be backfilled by compaction of excavated till, layer by layer. The piezometers will be backfilled with cement grout, and the upper 1 m of casing below the surface will be removed. The monitoring caisson will be backfilled with sand and gravel to the base of the transition zone between the weathered and unweathered till, and a layer of cement grout will be placed above the sand and gravel to the base of the weathered zone. The rest of the caisson will then be backfilled to land surface with sand and gravel, and the site will be graded and sown with grass.

FIELD EXPERIMENT

The methods used to perform the study components described previously are presented in two categories—those related to characterization of the till, and those related to the design and emplacement of the monitoring caisson and collection of data therefrom.

Characterization of Till

Equipment to support the research activities will be installed, then monitoring wells will be completed for collection of core samples and measurement of pore pressure. Pore pressures in monitoring wells will be recorded by a data logger that supports remote communication. Physical and hydraulic properties of core and pore-water samples and their chemical composition will be measured through laboratory analyses. Finally, two research trenches (fig. 15) will be excavated for investigations of fracture depth in the till.

Site Preparation

Several services will be needed for the proposed field experiment, including an access road, a trailer equipped with computers and communications equipment, and utility lines to provide electrical power and communication links (fig. 15). A gravel road will be built between a borrow area (excavated to obtain cover material for onsite disposal operations) and the research site to provide access for the drilling rig and crane that will install the monitoring caisson (fig. 15). The road will be about 460 m long and 4 m wide and will be built by the onsite general contractor to conform to WNYNSC site requirements. A gravel pad will be laid in the area where the caisson will be installed (fig. 15).

The study area is in the middle of an open field, 500 m from WNYNSC buildings. A construction trailer 2.5 m wide and 6 m long will house data collection, logging, and communication equipment; it also will provide onsite storage for equipment and supplies and serve as a processing area for samples retrieved during drilling and coring operations. Electricity and telephone lines will supply power to equipment and provide remote communication with the data logger. A high-power transmission line crosses the plateau close to the research site; a step-down transformer will be installed on a pole set near the trailer to provide 200-amp service. Telephone service will be provided by a buried cable installed from the research site to an existing cable about 790 m to the south (fig. 15).

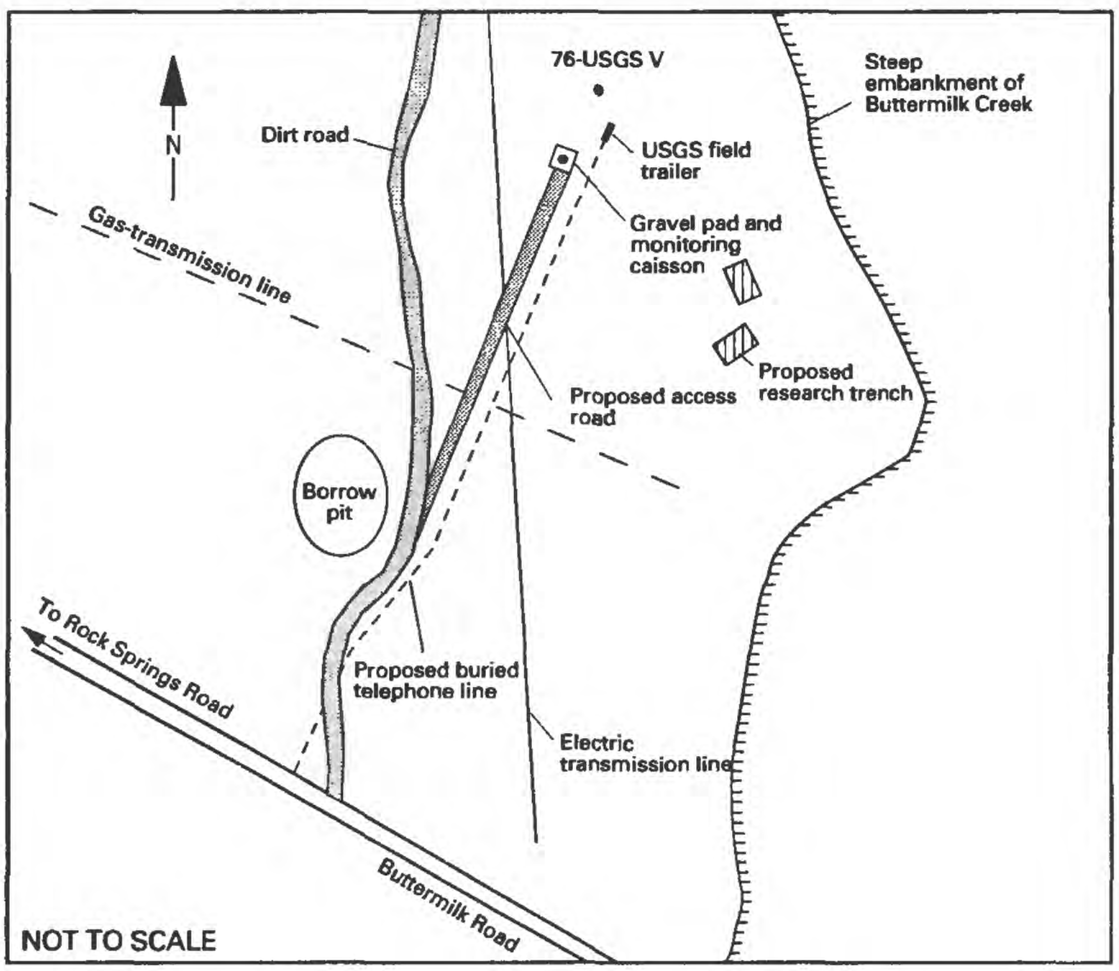


Figure 15. Location of facilities at the proposed research site. (Location is shown in fig. 4.)

Monitoring Wells

Vertical boreholes (fig. 16) will be drilled to provide core samples for analysis of (1) physical and hydraulic properties of the till, and (2) chemical properties of the pore water. Piezometers will be installed at five depths at each drilling location, and pore pressure in the till will be measured continuously with pressure transducers.

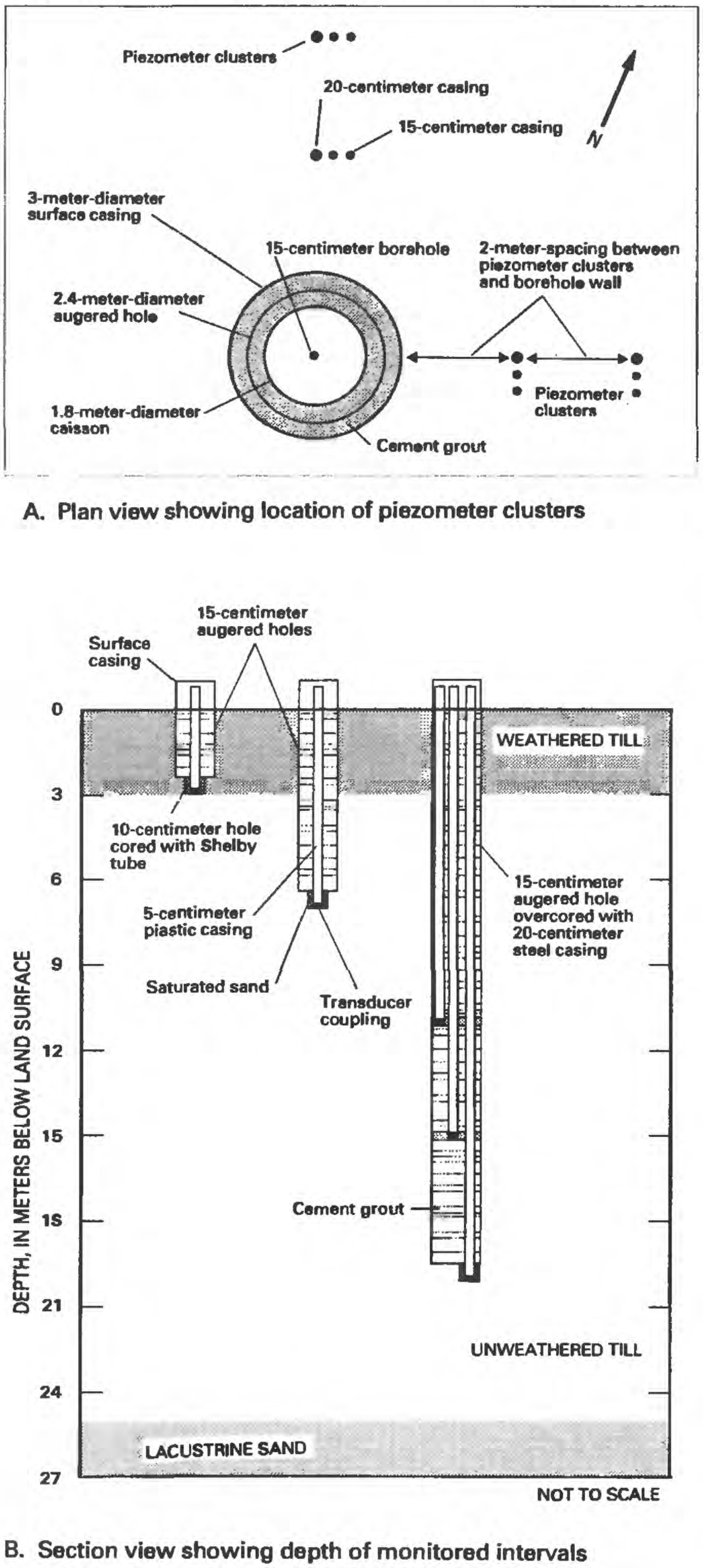


Figure 16. Proposed location and depth of piezometers at the research site. A. Plan view. B. Vertical Section.

Drilling and Coring

An auger rig will drill 15-cm (6-in) boreholes to a depth of 20 m to obtain continuous core of the till at five locations. One borehole will be at the center of the proposed location of the monitoring caisson, and the others will be 2 m and 4 m from the edge of the 2.4-m borehole for the monitoring caisson (fig. 16A). The center borehole will be screened in the unweathered till from about 8 to 20 m below land surface and will be used for a constant-head injection test. Clusters of five piezometers will be installed at each of the four surrounding locations, and monitoring zones will be at the base of the weathered till (3 m) and at four depths (7, 11, 15 and 20 m) in the unweathered till (fig. 16B).

Continuous core samples will be collected ahead of the drill bit with either 60-cm (2-ft) Shelby tubes or 80-cm (2.5-ft) sampling tubes to provide undisturbed samples. Shelby tubes 7.5 cm (3 in) in diameter will be pressed into the till ahead of the drill bit to obtain samples for consolidation tests, and sampling tubes 5.7 cm (2.25 in) in diameter and lined with a 3-mm (1/8-in) polybutyrate plastic liner will be driven into the till ahead of the drill bit as the augers are advanced to obtain samples for logging and geochemical analyses of pore water.

Two holes will be cored by alternately driving sampling tubes and Shelby tubes to obtain samples for inorganic and metal analyses and consolidation tests. Two others will be cored with sampling tubes for isotope analyses. The remaining hole will be cored with sampling tubes, then logged and archived for future reference.

Piezometer Clusters

Each piezometer cluster will consist of five piezometers; three will be installed in each of the four 20-m augered boreholes, and the remaining two will be installed in separate boreholes drilled to depths of 3 m and 7 m (fig. 16B). D'Astous and others (1989) have shown that drilling in clayey material causes smearing of the borehole wall that decreases the hydraulic connection between ground water and piezometers in the borehole; to remove the smear layer, they suggest overcoring the borehole with a larger diameter drill bit. To do this, a 20-cm (8-in) steel casing will be driven to the bottom of the borehole with an air-rotary drilling rig, and the drill cuttings will be removed from the hole with a 20-cm (8-in.) drill bit.

Preparation of the monitored interval of the single piezometers in the two shallow boreholes and the bottom piezometer in the 20-m borehole will entail driving a 5-cm (2-in) Shelby tube beyond the bottom of the augered hole (fig. 17A) and overcoring this pilot hole with a 10-cm (4-in) Shelby tube. A piezometer screen will then be installed with 5-cm, flush-joint PVC casing, and the annular space above the monitored zone will be backfilled with 30 cm of sand through a tremie tube. The sand layer will be saturated with water poured through the PVC casing to saturate the sand pack. The remainder of the annulus of each shallow borehole will be filled to land surface with cement grout installed through a second tremie tube. In each 20-m borehole, two additional piezometer screens will be placed in saturated sand layers at depths of 11 and 15 m by the same procedure (fig. 17B-D).

Pressure Measurements in the Till

Pore pressures measured by transducers will be recorded with a data-logging system that supports remote communication by phone line. Sealed-gage, vibrating-wire transducers with a range of 70 kPa (10 lb/in^2) manufactured by Geokon[1] will be used to measure pore pressure in the 20 piezometers. A Setra model 270 strain-gage transducer will be used to measure atmospheric pressure, and a CR10 data logger manufactured by Campbell Scientific Instruments will be used to record pressures measured by the transducers. The logger is programmable, contains nonvolatile memory, and supports remote communication by phone line or radio link. A telephone line will be used to communicate with the logger and will allow remote data retrieval at regular intervals to minimize loss of data through equipment failure.

1. Use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

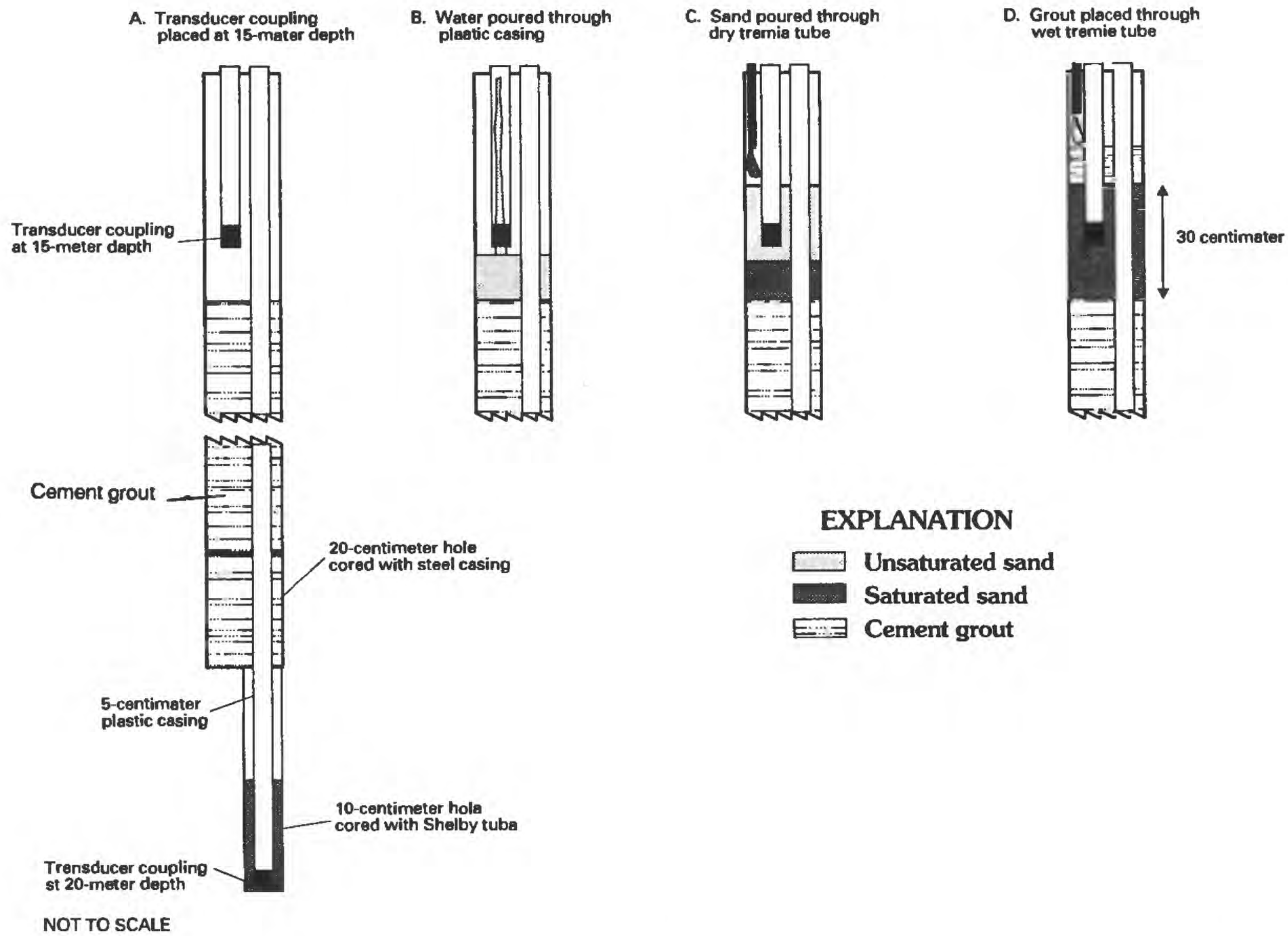


Figure 17. Procedure for completing piezometers: (A) Transducer coupling is placed at 15-m depth. (B) Transducer is saturated with water poured through plastic casing. (C) Sand is emplaced through dry tremie tube. (D) Grout is emplaced through wet tremie tube.

The long-term stability of 20 sealed-gage, vibrating-wire transducers manufactured by Geokon was evaluated in 1992 in a 100-day test in which pressures were recorded every 15 minutes (Zarriello, 1995). The transducers were placed in a water bath or connected to a pressurized tank during the test, and the transducer output was corrected for fluctuations in atmospheric pressure. The output of 10 transducers remained stable over the test period with random fluctuations less than 0.14 kPa (0.02 lb/in^2), which is within the reported accuracy of 0.34 kPa (0.05 lb/in^2). The output of 7 of the remaining 10 transducers drifted steadily during the test period, either increasing or decreasing but remaining within the reported accuracy, and the remaining 3 recorded random fluctuations of as much as 0.55 kPa (0.08 lb/in^2). A quarterly recalibration was deemed necessary to ensure reliability of pore-pressure measurements in the field and to restrict the drift in output to within the stated accuracy of the transducers.

Water levels in piezometers open to the atmosphere equilibrate slowly to changes in hydraulic head within materials of low permeability. Isolating the piezometer from atmospheric pressure reduces the volume of wellbore storage and greatly decreases the response time. To measure rapid pressure changes in the grout and till, the pressure transducers will be inserted within custom-made couplings that mate securely with the endcap of the piezometer casing to seal them from atmospheric pressure. The transducer coupling is designed to be installed or removed from land surface to allow recovery of the transducers from the piezometers for recalibration. The coupling is attached to threaded sections of 1.9-cm (3/4-in), schedule 80 PVC pipe that extend to land surface (fig. 18). The coupling has an O-ring that seals against the end cap of the outside 5-cm PVC casing. The end cap will be covered by a filter fabric to prevent sand from entering the open end of the casing. The 1.9-cm pipe can be withdrawn to remove the transducer from the piezometer.

A constant-head injection test will be conducted in the center borehole at the proposed location of the monitoring caisson to determine whether lenses with high hydraulic conductivity are present that would allow horizontal flow through the unweathered till. A constant head will be maintained during the test with a Mariotte bottle, and the flow

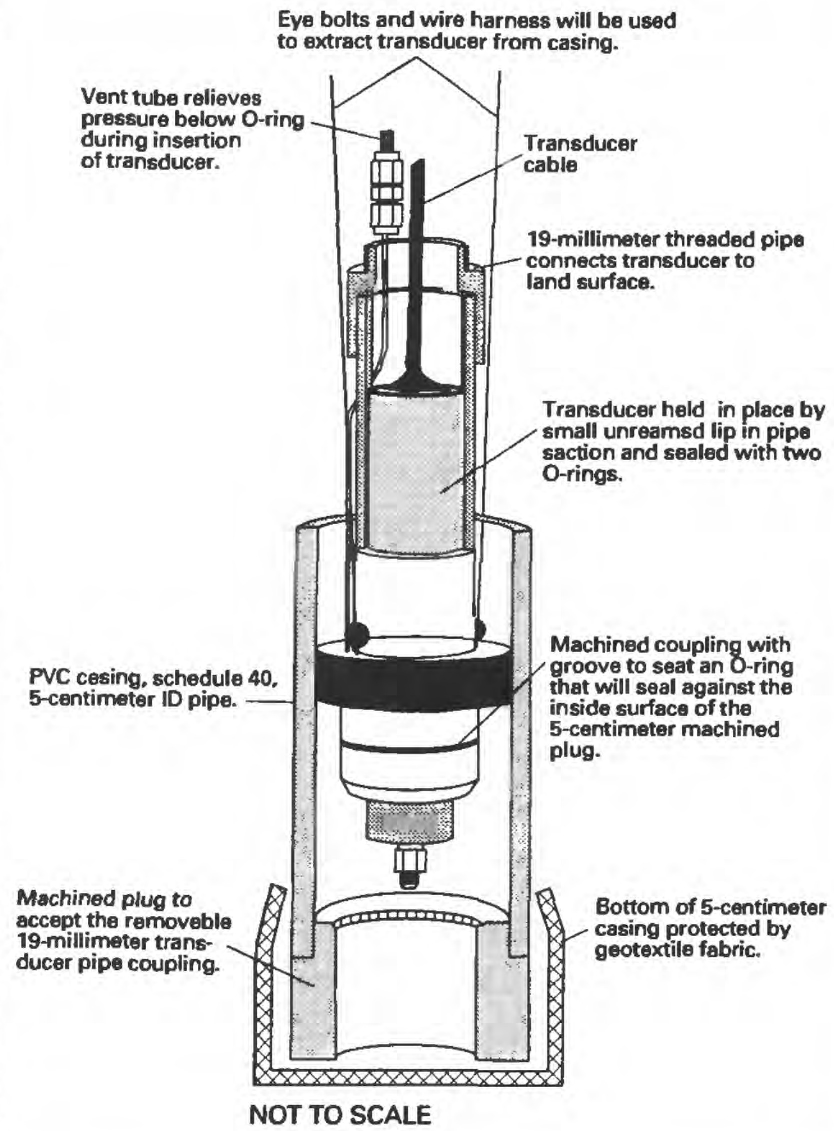


Figure 18. Design of transducer coupling to isolate monitored interval from atmospheric pressure.

rate will be computed from the decline in water level in the Mariotte bottle as measured with a wave staff, an electrical device that can detect the location of the water surface along a thin vertical wire (Lapcevic and Novakowski, 1992). Pressure transducers will be used to monitor the hydraulic gradient during the test. If lenses of permeable sediments in the unweathered till are continuous, the hydraulic conductivity will be significantly higher than that estimated from laboratory analysis of previous core samples (10^{-10} m/s) and could necessitate a different location for the monitoring caisson.

Laboratory Analyses of Core Samples and Pore Water

Undisturbed core samples will be collected in sampling tubes driven ahead of the drill bit. Samples to be analyzed for physical and hydraulic properties, major inorganic constituents, and trace metals will be capped and sealed with tape; those to be analyzed for tritium will be transferred to glass sample jars within a glove box pressurized with argon gas to prevent atmospheric contamination.

Physical and Hydraulic Properties of Till

Porosity and specific storage will be measured in continuous-loading consolidation tests with a back-pressured consolidometer to ensure complete saturation of the samples. The consolidation tests will be combined with constant-flow tests to estimate the hydraulic conductivity of the samples over a range of effective stress (Olsen and others, 1991). Additional consolidation tests will be conducted to measure the preconsolidation stress in the till, which will be compared with the present overburden stress to estimate the overconsolidation ratio at selected depths in the till. The compression and recompression indices will be computed from the relation between stress and strain obtained during the consolidation tests to predict the response of the till to changes in effective consolidation stress that result from emplacement of the monitoring caisson. The shear strength of the till will be calculated from consolidated-undrained, triaxial-compression tests, and the shear strength at differing states of stress will be calculated from a Mohr-Coulomb failure envelope (Holt and Kovacs, 1981). Pore pressure will be measured in the triaxial tests to define the relation between porosity and shear deformation in the till.

Chemical Analyses of Pore Water

Pore water will be extracted from core samples and analyzed for major inorganic constituents and trace metals, and selected isotopes at the University of Waterloo's Water Quality Laboratory within 90 days of sample collection. A compression device will consolidate the core to extract the pore water (Patterson and others, 1978); the procedure yields about one-half the water in the sample, about 3 mL per centimeter of core. About 40 mL of pore water will be extracted by compression for major inorganic constituents and trace-metals analysis, and an additional 1 L of pore water may be required for ^{13}C and ^{14}C analysis with an accelerator mass spectrometer; the volume required for the latter will be computed from the results of the alkalinity analysis. An azeotropic distillation procedure with toluene described by Revesz and Woods (1990) will be used to extract about 300 mL of pore water for analysis for enriched ^{3}H, ^{2}H, and ^{18}O.

Research Trenches

Two research trenches will be excavated for mapping of fractures in the weathered and unweathered till. The trenches will be excavated by bulldozer and backhoe to a depth of about 8 m (fig. 19) in a series of 1.5-m-high benches by an onsite general contractor. The trenches will be excavated parallel and perpendicular to the steep embankment of Buttermilk Creek that borders the plateau near the research site to provide orthogonal mapping faces

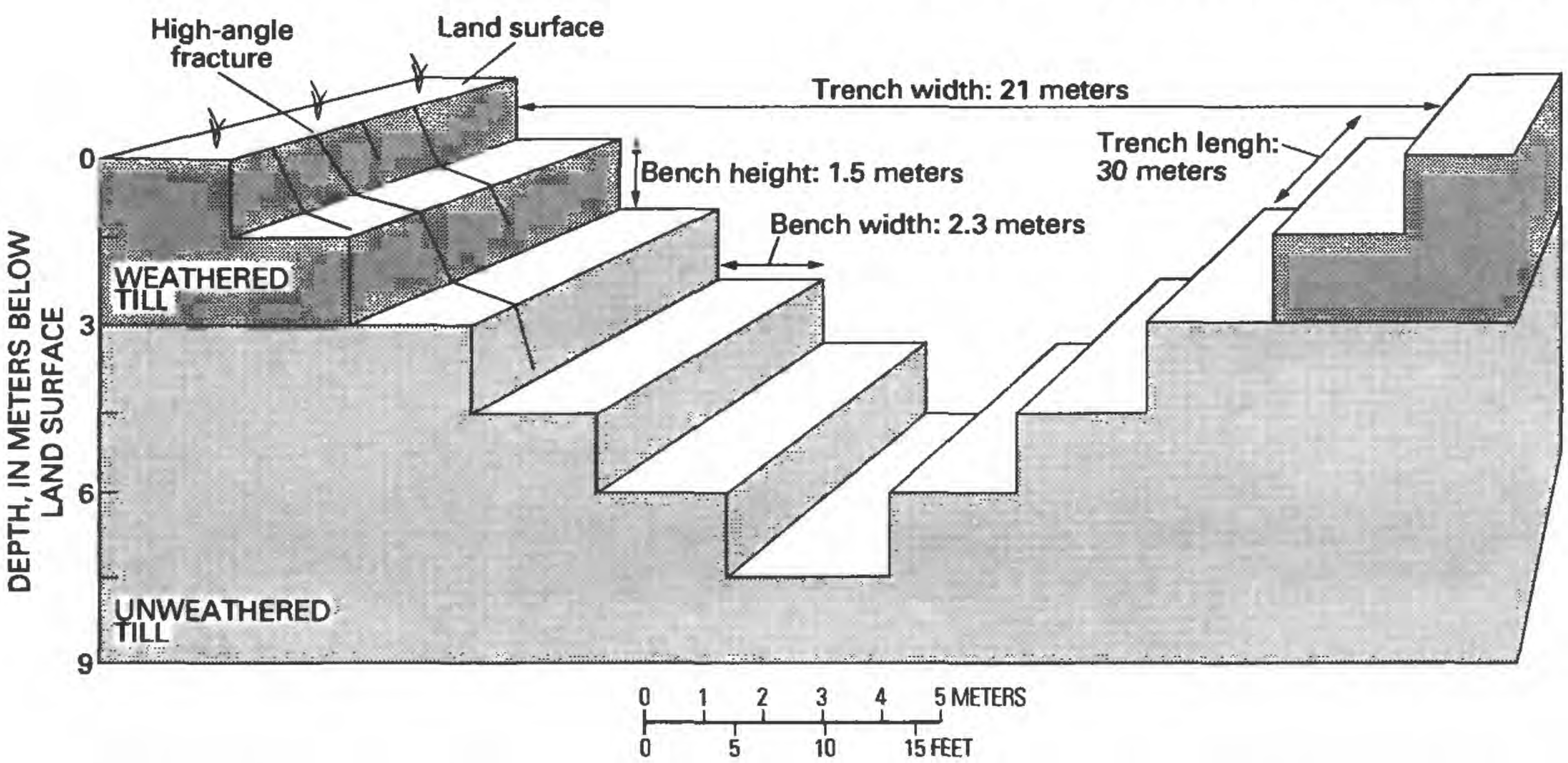


Figure 19. Design of research trench.

that will intersect all possible fracture orientations. Any lenses of stratified sediments encountered will be investigated to determine their lithology, lateral extent, and degree of saturation.

Fracture Mapping

Oxidized fractures in both the weathered and unweathered till will be mapped to determine fracture density and orientation. The smear zone on the trench wall formed by excavation will be removed with trowels and shovels before mapping. Trench walls will be covered with plastic sheets to retard desiccation of the till when mapping is not in progress. Blue dye No. 1 will be ponded on top of some benches and allowed to penetrate before excavation proceeds. This dye has been found to penetrate natural fractures without becoming absorbed into the clay matrix and thus will distinguish natural fractures from those caused later by excavation and subsequent exposure.

Horizontal Cores

A series of closely spaced, horizontal core samples obtained with Shelby tubes driven into the trench wall will be analyzed for enriched tritium to detect the presence of vertical fractures at selected depths within the unweathered till. The cores will be collected from three benches in the excavation at depths of 4 m, 6 m, and 8 m (fig. 19). A hydraulic jack will be used to alternately drive sampling tubes and casing to as far as 10 m into the trench wall to collect additional horizontal cores. If the coring procedure proves successful, it will later be used to drive boreholes into the till from inside the monitoring caisson.

Effects of Borehole Excavation and Sealing of Monitoring Caisson Annulus

Changes in the state of stress within the till will be simulated with a hydromechanical model, and the results will be used in the design of the monitoring caisson and in the selection of grout to seal the annulus of the augered borehole. The selection of grout mixtures will be based on the results of laboratory studies to determine the fluid and hardened properties of the cement grouts and the relation between water content and swelling pressure of the bentonite grout. Chemical studies will be conducted to identify reactions that are likely to occur at the till/grout interface. Field tests of the selected grout mixtures will entail sealing boreholes augered at the bottom of a research trench and estimating the hydraulic conductivity of the borehole plugs through hydraulic tests.

The monitoring caisson will be fabricated offsite according to specifications provided by an engineering firm and will be lowered into the augered hole in the till; it then will be stabilized with concrete grout and sealed with three layers of differing grout mixtures. Instruments will be placed in the till to measure displacement toward the augered hole, in the grout layers to measure volumetric changes caused by hydration, and in sand layers within the grout to measure pore pressure and detect solute migration during injection tests. The injection tests will be conducted when the hydration of the grout layers approaches steady state.

Simulation of Hydromechanical Effects

A numerical hydromechanical model will be developed to simulate the stress caused in the till by the borehole excavation and sealing of the annulus after the caisson has been installed. The model will predict the distribution of stress and pore pressure in the till and the direction and magnitude of the till displacement toward the augered borehole. This information will be used to (1) estimate the depth and diameter of a borehole that can be augered in the till without causing failure of the borehole wall, (2) calculate the required strength of the caisson, and (3) determine grout properties that best match those of the till so that gap formation along the interface between the grout and till can be minimized.

A finite-element model, STUBBS, developed by the U.S. Army Corps of Engineers to simulate inelastic deformation and hysteresis in saturated and unsaturated sediments (John Peters, U.S. Army Corps of Engineers, oral commun., 1992) will be used to develop a two-dimensional, axially symmetric simulation of the proposed caisson and surrounding till. Transient-state simulations will be conducted that represent separate stress periods for (1) unloading of the till after borehole excavation, (2) loading of the till after placement and hydration of the grout, and (3) unloading of the till after cooling and contraction of the grout. (See fig. 13.)

The model based on till and grout properties measured in previous studies will be used to compare the states of stress resulting from differing borehole sizes and types of grout. The model results will be used to delineate areas in the till where changes in stress could cause failure or cracking of the borehole wall or uptake of water from the grout. These results will indicate the size of the excavation and the grout properties that minimize these effects. Once the caisson has been emplaced and sealed, the accuracy of the model predictions will be evaluated. The distribution of stress and pore pressure predicted by the model will be compared with those measured by stress meters and piezometers, and the predicted displacement of the till will be compared with that measured by slope indicators and monument surveys.

Laboratory Studies of Grout Materials

Laboratory studies will be conducted to identify the physical and chemical properties of grout materials selected for sealing the caisson, and the results will provide a basis for selection of grout composition and of methods for analysis of core samples of the till/grout interface. The laboratory tests will be conducted at the U.S. Army Corps of Engineers Waterways Experiment Station in Vicksburg, Miss.

Cement grouts

The fluid and hardened properties of the cement grouts will be evaluated through standard tests, listed in table 5; results will be used to specify (1) the proportions of cement, aggregate, water, and admixtures to be used in the grouts for the annulus, and (2) the instructions for mixing and placing. Chemical properties of the cement grouts will be investigated through an analysis of composite samples in which core samples of till are encased in cement grout. The composite samples will be split open with a "Brazilian" test (CRD-C 77-91 in U.S. Army Corps of Engineers, 1992) to expose the interior; the mineralogical composition of the till/grout interface will be examined to identify chemical reactions that are likely to occur along the interface in the field installation. Analytical techniques will include polarized-light microscopy, X-ray diffraction, scanning electron microscopy, and energy-dispersive X-ray. Some composite samples will undergo a "push-out" test that will indicate the interface bond strength produced by the cement grout.

Table 5. Laboratory tests to be conducted on cement and bentonite grout materials

Test	CRD-C test number[1]
CEMENT GROUT	
Fluid properties:	
flow	11-89
time of setting	614-91
expansion and bleeding	613-91
Hardened properties:	
permeability	48-73
compressive strength	14-87
elasticity	19-89
volume stability	600-89
BENTONITE GROUT	
permeability	
swelling pressure	
water content	
density	

1. U.S. Army Corps of Engineers (1992)

Bentonite grouts

Flow tests will be conducted on the bentonite grouts by methods described by Ouyang and Daemen (1992) to determine the rate of water uptake and the resulting water content. The properties listed in table 5 will be measured, and the resulting information will determine the proportions of bentonite, sand, and compacted bentonite pellets to be used in the mixture used to seal the monitoring-caisson annulus. The effect of ion-exchange reactions between the till and bentonite will be investigated in composite samples in which the two materials are placed side by side, saturated, and then split open to yield samples of till and bentonite near the interface. These samples will be analyzed to identify exchangeable cations adsorbed to surfaces of the clay minerals; the results will be compared with the exchangeable cations in samples of unaltered till and bentonite to indicate the rate of migration of sodium ions into the till and calcium ions into the bentonite. Bentonite samples obtained near the interface in the composite sample will be analyzed by X-ray diffraction to determine whether the spacing of clay layers decreases in response to the exchange of calcium for sodium on clay surfaces in the bentonite.

Hydraulic Tests of Borehole Plugs

The cement and bentonite grout mixtures selected to seal the monitoring caisson also will be used to construct plugs in several 15-cm (6-in) boreholes augered into the unweathered till at the bottom of a research trench (fig. 20A), and hydraulic tests will be run to estimate their hydraulic conductivity and sealing performance. These tests will provide field experience in the mixing and placement of the grout and operation of instrumentation before the emplacement and sealing of the monitoring caisson.

A surface casing will be installed around the boreholes, and excavated till will be used to backfill around the surface casing (fig. 20A). The boreholes will be filled with alternating layers of grout and sand to construct a water-injection interval and a water-collection interval separated by a grout plug (fig. 20B). A steel casing will extend from each borehole to 0.5 m above the bottom of the research trench to provide access to the injection interval, and a layer of saturated sand will be placed on the bottom of the trench to prevent desiccation of the unweathered till (fig. 20A).

The hydraulic tests will be conducted by methods for a steady-state, constant-head injection adapted from Kimbrell and others (1987). Water containing a dye tracer will be injected at a constant pressure of 35 to 70 kPa (5 to 10 lb/in^2) through a piston displacement pump driven by nitrogen gas. A linear-voltage displacement transducer (LVDT) connected to the piston will measure the injection rate, and a pressure transducer will record the injection pressure. Lower injection pressures could be provided with a Mariotte bottle containing a wave staff to measure the decline in water level during the test. The rate of flow into the collection interval will be measured by a small pressure transducer or wave staff placed in a narrow tube connected to the interval (fig. 20B).

The cement-plug test results will be analyzed for each of the following flow conditions:
(1) impermeable borehole plug and radial flow into the till (eq. 4), (2) impermeable till and axial flow through the borehole plug (eq. 5), or (3) impermeable till and borehole plug and axial flow through a gap at the till/grout interface (eq. 6).

The rate of radial flow into the till, Q_{till}, is given by Ziegler (1976):

$$Q_{till} = \frac{2\pi L_i K_{till} \Delta h}{\ln [r_e/r_w]} \tag{4}$$

where L_i is length of injection interval, (L);
K_{till} is hydraulic conductivity of till, (LT^{-1});
Δh is injection head, (L);
r_w is radius of borehole, (L); and
r_e is radius of influence of test, (L).

Q_{till} for the test configuration in figure 20B at an injection pressure of 35 kPa (3.4 m of water), a K_{till} of 10^{-10} m/s, and an r_e of 10 m, would be 12 mL/d.

The rate of axial flow through the borehole plug, Q_{plug}, is given by Kimbrell and others (1987):

$$Q_{plug} = \frac{\pi r_w^2 K_{plug} \Delta h}{L_p} \tag{5}$$

where K_{plug} is hydraulic conductivity of the plug, (LT^{-1}); and
L_p is length of the plug, (L).

Q_{plug} for the same test conditions as above, and a K_{plug} of 10^{-10} m/s, would be 1 mL/d.

The rate of axial flow through a gap at the till/grout interface, Q_{gap}, is given by Tokunaga (1988) as

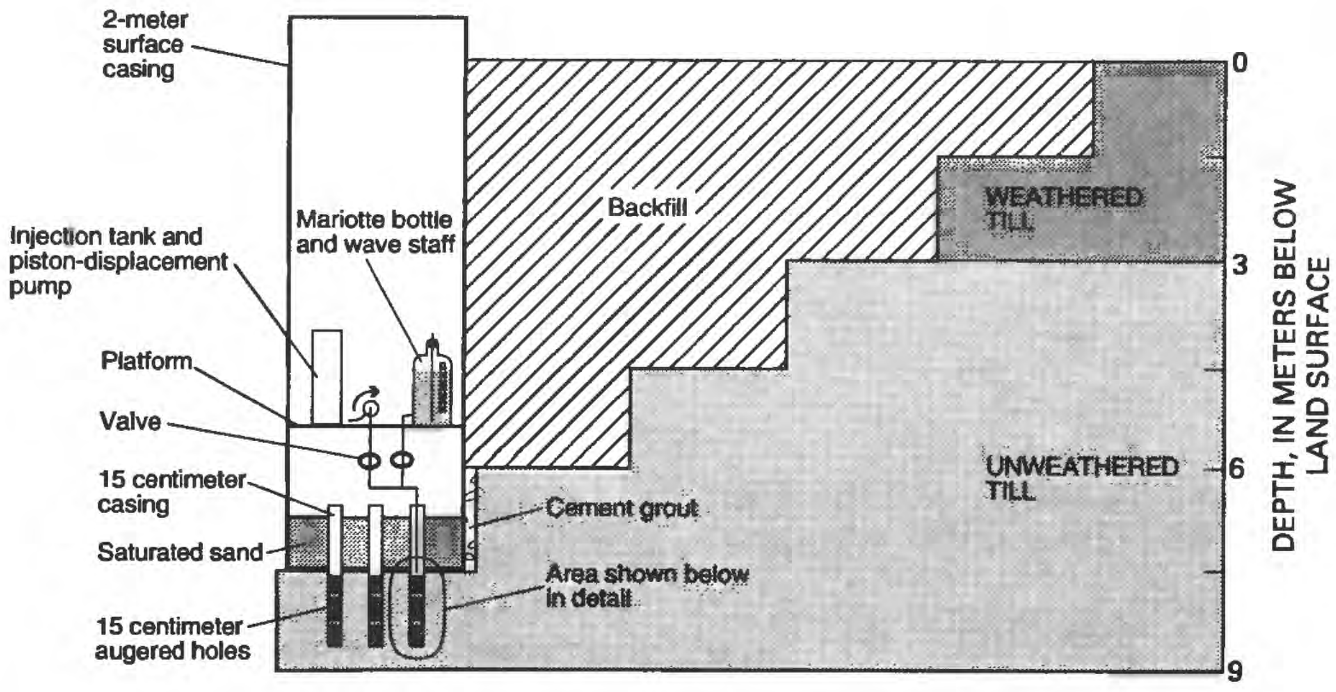
$$Q_{gap} = 2\pi r_w \left[\frac{\delta^3}{12} + \frac{k\delta}{2}\right] \frac{\rho g}{\mu} \frac{\Delta h}{L_p}, \tag{6}$$

where δ is gap width, (L);
k is intrinsic permeability of plug, (L^2);
ρ is density of water, (ML^3); and
μ is dynamic viscosity of water (MLT^{-1}).

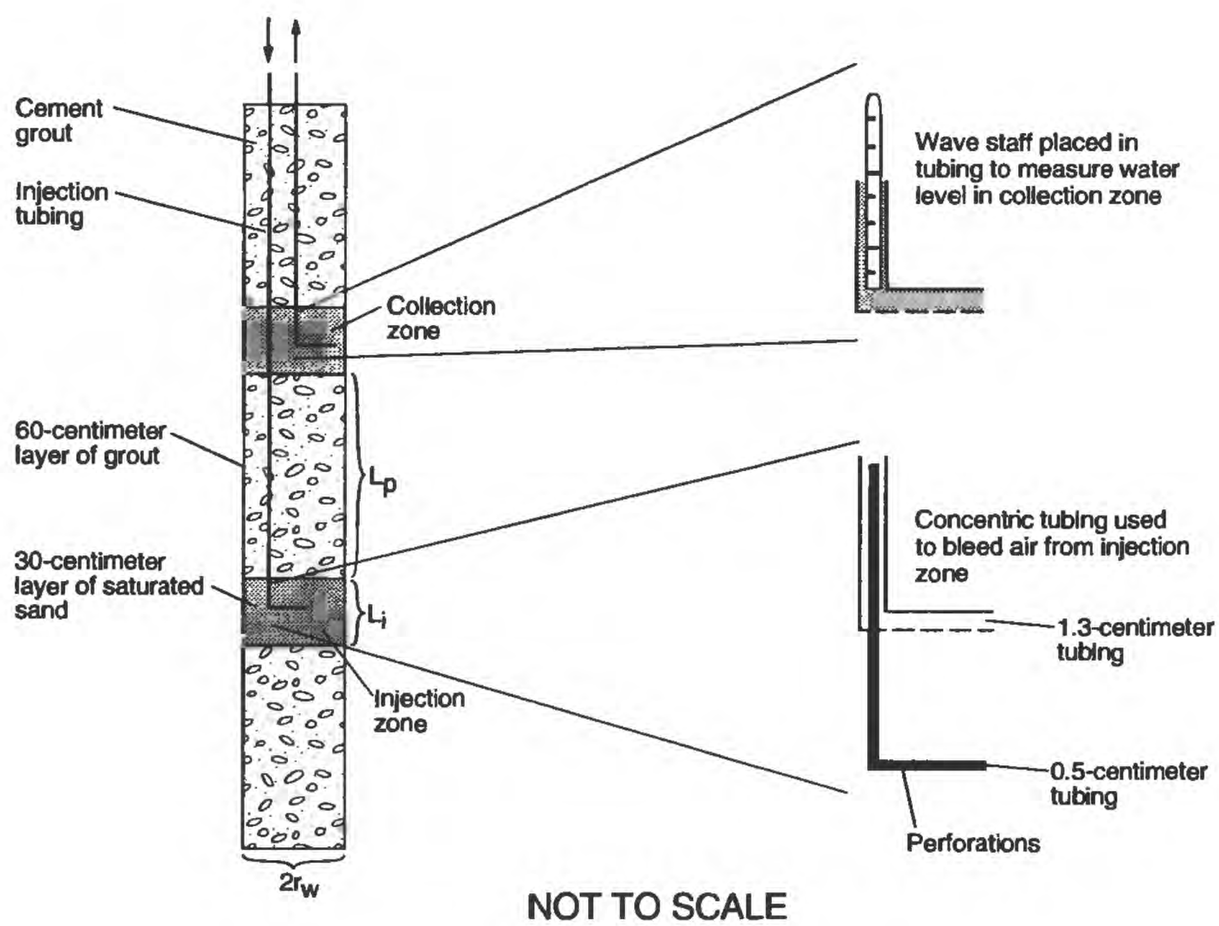
Thus, Q_{gap} through a gap width of 5 µm at the density and viscosity of water at 15°C, is 23 mL/d.

Each hydraulic test will require several days to complete because the expected flow rates are only a few milliliters per day. Flow rates in the range of tens of milliliters per day or greater would indicate leakage around the borehole plug. The actual flow path of the injected water during the test will be determined during the borehole excavation and examination of the till and grout for presence of the dye.

Hydraulic tests of bentonite plugs will be difficult to analyze because the intrinsic permeability of bentonite is related to its water content, which changes during the test (Ouyang and Daemen, 1992). For this reason, the water content of the bentonite plug will be estimated during the injection test with time-domain reflectometry probes (discussed further on). Upon completion of the hydraulic tests, the bentonite plug will be excavated from the borehole, and sections of the plug will be analyzed to determine the actual water content. The intrinsic permeability of the bentonite estimated from the test results will be compared with values computed with a refined



A. Location of augered holes



B. Design of borehole plugs

Figure 20. Installation of borehole plugs at the bottom of the research trench: A. Location of augered holes. B. Design of borehole plugs.

version of the Kozeny-Carman equation, which accounts for changes in the microstructure of clay particles in response to changes in water content (Ouyang and Daemen, 1992, p. 195). This refined equation has been shown by Ouyang and Daemen (1992) to accurately predict measured permeability of clays over a wide range of porosity.

Monitoring Caisson

The monitoring caisson will be designed by an engineering firm to ensure safety and provide a suitable working environment. Material specifications and engineering drawings will be provided by the firm for contract specifications.

Fabrication

The monitoring caisson will be fabricated from a hollow steel cylinder. Brackets will be welded to the interior of the caisson to support the aluminum ladders, the ventilation duct, and the electrical conduit. Supports will be provided at several locations within the caisson to brace the blast-hole drill and hydraulic jack that will be used to core horizontal boreholes through the grout layers and drive thin-walled steel casing at the bottom of the caisson. A flange will be welded to the base of the caisson to minimize differential settlement in the augered hole. The caisson exterior will be finished with a bituminous coating to increase bonding strength with the grout and impede corrosion.

The wiring from instruments embedded in the grout layers that seal the borehole annulus will be passed through instrument ports to the interior of the caisson. The instrument ports will be 0.3 m-diameter holes in the caisson wall that are ringed with steel pipe to facilitate sealing from inside the caisson. (See fig. 12.) Once the instruments and the wiring have been installed, the instrument ports will be sealed with urethane foam, a procedure that has been successfully used to seal ports in a similar caisson installed at Beatty, Nev. (Fisher, 1992).

Pressure-measurement ports will be constructed in the grout layers and in the sand layers within the grout. The pressure ports will be smaller in diameter than the instrument ports and will contain a piece of plastic casing for pressure measurements and injection of water. Each sand layer will contain eight or twelve pressure ports distributed radially to allow uniform injection of water. The pressure ports will be sealed with the same urethane foam as the instrument ports.

Installation

The monitoring caisson will be placed in an augered borehole drilled with a two-step procedure. A shallow hole about 3 m (10 ft) in diameter will be augered to a depth of 5 m, and a surface casing 2.7 m (9 ft) in diameter will be placed within it. The annular space between the surface casing and the borehole wall will be backfilled with concrete grout containing an air-entraining admixture to resist cracking caused by freezing and thawing. A 2.4-m (8 ft)-diameter hole will then be augered inside the surface casing to a depth of 20 m. The augered borehole will be inspected with a downhole camera for oxidized fractures and lenses of stratified sediments within the unweathered till before the monitoring caisson is installed.

The monitoring caisson will be lifted from the delivery vehicle and lowered into the augered borehole by a 50-ton crane, and the annular space surrounding the caisson at the bottom of the borehole will be backfilled with concrete grout to stabilize the caisson. Alternating layers of grout and sand will then be placed in the annulus with tremie tubes to seal the excavation. The grout layers will be mixed and installed according to procedures developed through the laboratory studies described previously. Samples of the grout mixture will be obtained for quality-control field tests of flowability, for example, and later laboratory analysis.

Each grout layer will be poured in two stages to enable placement of the sand layer within the grout. This will require six separate pours, and the grouting procedure will require 4 to 5 days to complete. Instrumentation (described in the following section) will be placed in the borehole annulus before the sand or grout layers are poured. The sand layer will be saturated, and a thin layer of powdered cement will be spread on top and allowed to set before additional grout is placed in the annulus. This cement layer will prevent piping of water from the saturated sand into the overlying cement grout layer and creating channels within the grout that increase its permeability (Kimbrell and others, 1987). The upper 5 m of the annulus will be backfilled with concrete grout to seal the surface casing.

Thin-walled steel casing 0.3 m (1 ft) in diameter will be driven 0.5 m into the unweathered till at the bottom of the monitoring caisson to serve as an infiltrometer for the diffusion test (described later). Once this casing is in place, a concrete floor will be poured at the bottom of the caisson. A shelter will be bolted to the top of the caisson.

Instrumentation

Instruments will be placed in the till and in the borehole annulus within layers of sand and grout to record the effects of the emplacement and sealing of the monitoring caisson. Measurements made by instruments placed in the borehole annulus will be recorded by data loggers mounted inside the monitoring caisson. The types of instruments to be emplaced in the grout have been used to monitor the sealing performance of grout in previous studies. The final selection of instruments to be used will be based on the results of laboratory studies in which the instruments are embedded in borehole plugs of the grout materials used to seal the caisson. Additional tests will be conducted in which the instruments will be embedded in the borehole plugs installed at the bottom of a research trench, as described previously.

Till

Displacement indicators will be installed in the till at the site of the augered borehole before it is excavated, and displacement will be measured when the drilling is completed and again when the monitoring caisson has been installed and sealed. A radial array of monuments will be placed at land surface to indicate vertical displacement. The monuments will be surveyed to a precision of 0.3 mm (0.001 ft) and referenced to a benchmark elevation. The distance between the monuments will be surveyed to the same accuracy to indicate horizontal displacement. Settlement plates may also be installed in the till to indicate vertical displacement below land surface. Horizontal displacement in the till can be calculated from the results and from displacements measured by slope indicators placed in holes drilled to a depth of 3 m. (Slope indicators consist of slotted casing into which a measurement probe is inserted to measure changes in the slope of the casing.) The location and spacing of the displacement indicators will be based on results of the hydromechanical model simulations of the emplacement and sealing of the caisson.

Sand Layers

Pressure transducers like those installed in nearby boreholes will measure pore pressure in the sand layers. Transducer couplings (described previously) will be used to seal the transducers at the ends of plastic pipes that extend through pressure ports in the caisson wall. Tubing passed through the transducer coupling will connect the cavity at the end of the pipe to the interior of the caisson. The tubing will be used to bleed air from the cavity and to inject water during hydraulic tests.

Leak sensors will be attached to the borehole wall just above and below the sand layers. The sensors will contain an element of platinum wire or gold foil that passes large amounts of electrical current in the presence of an electrically conductive fluid. An array of sensors will be placed around the circumference of the till/grout interface to detect flow of the conductive tracer during injection tests.

Cement Grout

Four types of instruments will be placed in the cement grout to record the effects of hydration reactions: thermocouples, stress meters, strain meters, and pressure transducers. Three of these (thermocouple, stress meter, and strain meter, see table 6) have been embedded in concrete grout in tests of borehole seals at the WIPP site in New Mexico (Stormont, 1986). The stress meters will be oriented to measure radial stress, and the strain meters will be oriented to measure both radial and circumferential strain. The pressure transducers will be installed through plastic pipe sealed in pressure ports with the

Table 6. Resolution, range, and estimated accuracy of instruments embedded in concrete grout at the Waste Isolation Pilot Plant, New Mexico

Instrument	Unit of measure	Resolution	Range	Estimated accuracy (percent)
Type E thermocouple	degrees Celsius	0.003	20 to 250	3
Carlson stress meter	kiloPascal	30	0 to 5,500	30
Carlson strain meter	microstrain	6	-2,600 to 1,300[1]	15

[1]Negative strain indicates compression, positive strain indicates tension.

same design as used in the sand layers. All instruments will be supported in the annulus by a support tree constructed with metal rod (see fig. 12). An epoxy plug will fasten the wiring from the instruments to a central support rod to facilitate sealing of the wiring where it passes through the instrument port in the caisson wall.

Bentonite Grout

Instruments emplaced in the bentonite grout will include stress meters, thermocouple psychrometers, pressure transducers, and time-domain reflectometry probes. Stress meters and thermocouple psychrometers have been used in studies of bentonite borehole seals at the URL in Manitoba (Kjartanson and others, 1991). The stress meters will be the same as those used in the cement grout and will be oriented to measure radial stress. Water potential in the bentonite grout will be estimated with thermocouple psychrometers and pressure transducers. The thermocouple psychrometer measures relative humidity of the air in partially saturated media, and the water potential can be calculated from the humidity. The psychrometer has an operating range of -50 to -7,000 kPa (-7 to -1,000 lb/in^2) and a resolution of 10 kPa (1.4 lb/in^2) (Wescore, 1990). Pressure transducers operating under tension will be used to measure water potentials greater than -70 kPa (-10 lb/in^2). The psychrometers and pressure transducers will be mounted in the couplings discussed earlier and will be inserted in plastic pipe through pressure ports of the same design as used in the sand layers.

Water content will be estimated with time-domain reflectometry (TDR) probes. TDR probes can measure water content of 10 to 30 percent (Baker and Goodrich, 1987); this range includes the minimum expected water content of the bentonite grout (17 to 19 percent). The TDR probes are transmission lines used to propagate an electromagnetic wave, the velocity of which is related to the dielectric constant of the partially saturated medium, which is in turn related to its water content. Two parallel probes will be used, each 20 cm long and placed about 3 cm apart. TDR probes will be placed horizontally within the bentonite grout to detect the position of a wetting front moving radially inward toward the caisson from the saturated till at the till/grout interface by the method of Topp and others (1982); TDR probes also will be placed vertically within the bentonite grout at predetermined distances from the monitoring caisson to indicate the radial distribution of water content.

Field Tests of Water Movement

Hydraulic and chemical properties of the interface between the till and grout will be investigated through injection tests with water and conservative tracers and analyses of core samples of the interface region. Tracer-injection tests will be conducted in the sand layer within each grout layer, and a diffusion test will be conducted in unweathered till at the bottom of the monitoring caisson. Upon completion of the injection and diffusion tests, core samples will be driven into the till from inside the caisson and analyzed for mineralogy and aqueous chemistry.

Tracer-Injection Tests

Injection tests in the sand layers will be conducted to determine hydraulic conductivity of the till/grout interface by the same method that was applied in the hydraulic tests of borehole plugs at the bottom of the research trench. Water will be injected at a constant head into the sand layers through the cavity at the end of the plastic pipes that extend through the pressure ports (fig. 21). The constant head will be maintained by a Mariotte bottle placed above the injection layer, and the flow rate will be calculated from the weight of the contents of the bottle or the decline in water level in the bottle with a wave staff. Elevating the bottle in the caisson will give injection heads of 1.5 to 3 m (35 to 70 kPa); higher heads could be attained with a nitrogen-driven piston pump. Pressure transducers in the sand layer will record the injection head during the test.

The test results will be analyzed to estimate the hydraulic conductivity of the interface through equations 4 to 6 (p. 29) and by numerical simulations. The values of hydraulic conductivity of the unweathered till and grout used in the analyses will be those estimated previously from laboratory tests. Greer and Daemen (1991) used a model developed by Neuman and Narasimhan (1977) to analyze hydraulic tests of borehole plugs of cement grout; a model developed by Sudicky and McLaren (1992) to simulate flow through discretely-fractured porous media could also be used to analyze the tests.

Estimated rates of flow through the till (Q_{till}), grout (Q_{grout}) and interface (Q_{gap}), calculated from the values given in the discussion of the tests of borehole plugs and applied to equations 4 through 6, are 28, 31, and 110 mL/d, respectively. As in the tests of borehole plugs, large flow rates will indicate flow along the till/grout interface. More water will be injected during the injection tests in the sand layers than in the tests of borehole plugs because the cross-sectional area of the flow field is larger. As a result, the sand-layer test duration is expected to be shorter.

Once the initial injection tests are completed, a tracer solution containing an electrically conductive, conservative solute and blue No. 1 dye will be injected into the sand layers in which flow is suspected to occur along the till/grout interface. Leak detectors in the interface will be monitored during the injection test to determine the flow path of the solute. If a flow path can be identified, a coring tube will be driven from inside the caisson, through the grout and into the till in the area of suspected flow.

Diffusion Test

The diffusion test will be conducted in the unweathered till at the bottom of the monitoring caisson (fig. 22). Thin-walled casing will be driven into the till, and the till within the casing will be removed to a depth of 30 cm below the bottom of the caisson to expose undisturbed sediments below the smear zone created by augering. The empty casing will then be filled with a solution containing a conservative solute. The top will be sealed and a vent pipe inserted to just above the exposed till at the bottom of the casing to convert the casing to a Mariotte bottle. This will produce a small hydraulic gradient between the solute reservoir in the Mariotte bottle and the pore water in the till that will minimize advection so that transport of the solute into the till will be through diffusion. When the test is completed, a coring tube will be driven through the center of the casing for a sample of the till. Sections of the till sample will be analyzed to determine the concentration gradient below the solute reservoir.

The observed concentration gradient in the till will be compared with the gradient predicted by the analytical solution for one-dimensional diffusion (eq. 2, p. 16) to estimate the coefficient of molecular diffusion for a solute in till, D^*. At an assumed D^* value of 10^{-10} m^2/s, the conservative solute will travel tens of centimeters over several years (Freeze and Cherry, 1979, p. 393). The estimated D^* value will be used to compute the empirical coefficient, ω, that relates the diffusion coefficient of the solute in till to the diffusion coefficient in water, D:

$$\omega = D^*/D \tag{7}$$

According to Bear (1979), ω is related to the tortuosity of the porous medium. An estimate of the value of ω will enable computation of the diffusion coefficient in till for other solutes for which the diffusion coefficient in water is known.

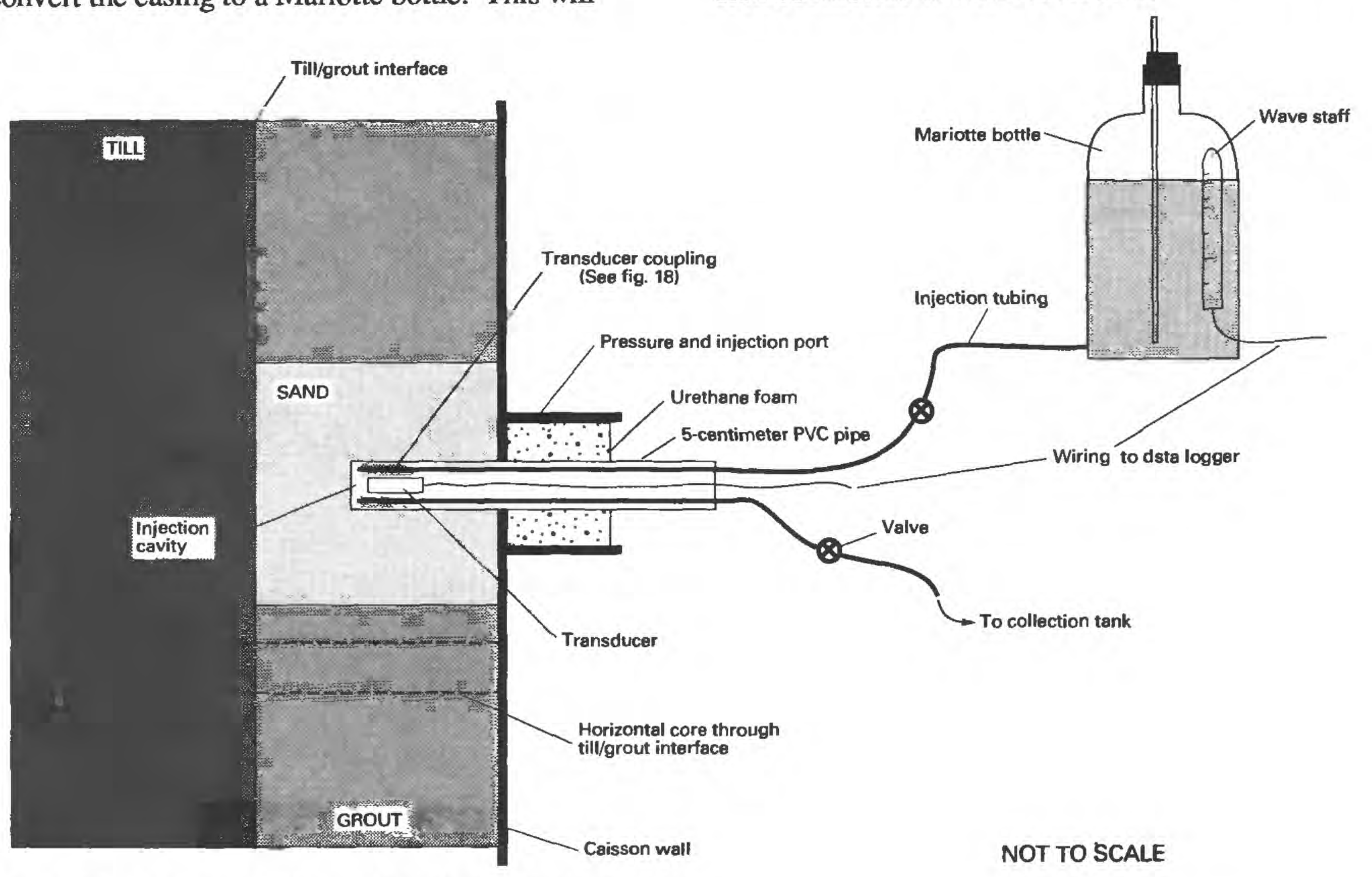


Figure 21. Apparatus for hydraulic tests of till/grout interface.

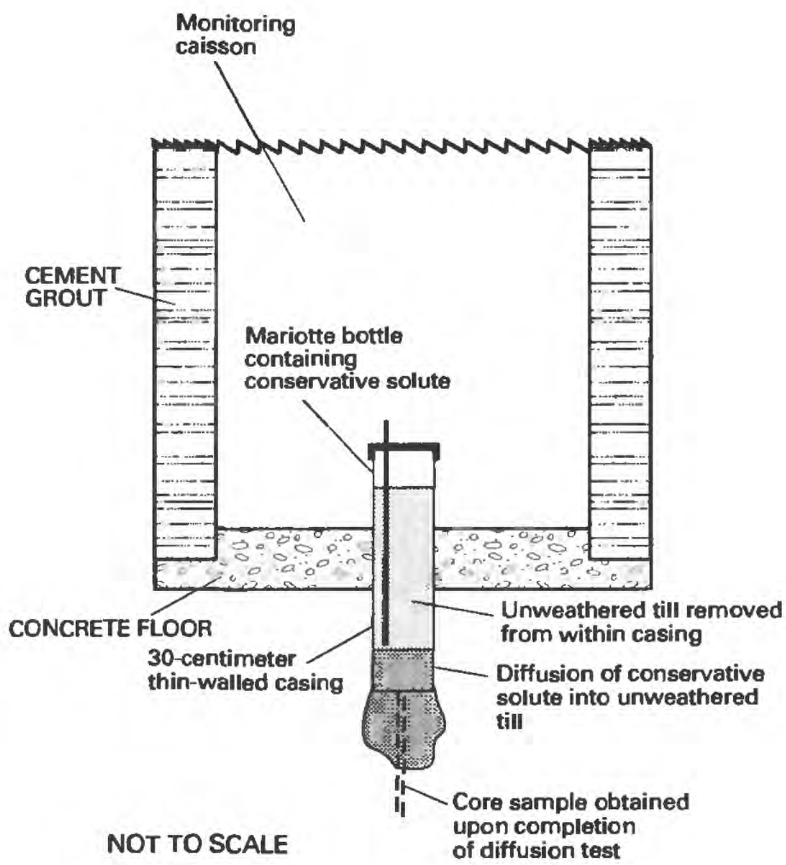


Figure 22. Apparatus for diffusion test at bottom of monitoring caisson.

Horizontal Cores

Horizontal boreholes will be drilled through the grout materials and into the undisturbed till to obtain core samples of the interface regions. The samples will be analyzed to determine (1) the extent of tracer migration during the injection tests, and (2) whether alteration of till and grout properties in the vicinity of the interface could enhance the movement of water. Samples of undisturbed till at distances up to 10 m from the caisson will be analyzed to detect the presence of vertical fractures.

The horizontal boreholes will be drilled through the caisson wall and grout and into the till with a blast-hole drill. Cores will be driven farther into the till with the hydraulic jack and by the drilling procedure used to obtain horizontal cores from the research trench. The aqueous chemistry and mineralogy of the samples will be determined by the analytical methods used to characterize samples of till and grout in laboratory studies. Samples of the till/grout interface will be examined to identify the nature of the physical bond between the till and grout and for evidence of mineral alteration that could cause increased permeability and porosity of the materials in the interface region.

SUMMARY

Nuclear powerplants are expected to account for about 75 percent of the volume and 98 percent of the activity of low-level radioactive waste in New York State during the next 60 years as they are decommissioned and dismantled. Radionuclides of concern in the low-level radioactive waste include ^{60}Co, ^{137}Cs, and ^{55}Fe during the first 100 years and ^{14}C, ^{59}Ni, and ^{63}Ni over the next 400 years. The Low-level Radioactive Waste Policy Amendments Act of 1986 requires each State to dispose of low-level radioactive waste either within its borders or in a host state under an interstate compact.

Three types of subsurface disposal have been suggested for disposal of low-level radioactive waste: improved shallow-land burial, augered holes, and mined cavities. The disposal option of choice for states in humid areas is burial of waste below the zone of weathering in saturated, fine-grained sediments with a permeability sufficiently low that advection is virtually absent and diffusion is the dominant mechanism by which radionuclides can migrate. The use of this disposal option in the United States requires that the diffusion-dominated flow system persist for at least 500 years to allow time for the principal radionuclides in the waste to decay to harmless levels. This method is currently used in Canada by Ontario Hydro to store low- and inter-mediate-level radioactive waste.

Little information is available to predict whether the effects of this disposal method could cause fractures within the host material or the grout used to seal the excavation and thereby provide paths for advective transport from the waste to the land surface. The proposed study will investigate the effects of excavating and sealing an underground waste container on the movement of water through the saturated, fine-grained host material. The augered-hole type was selected for this study because a full-scale structure can be constructed that will allow field tests whose results can be compared directly with those from actual facilities in Canada. The study will entail placing a hollow steel cylinder (monitoring caisson) within an augered hole in the till to simulate a full-size waste container, and sealing the annular space surrounding the caisson with layers of selected grout materials.

The proposed study will be conducted in a thick, clayey till at the Western New York Nuclear Service Center (WNYNSC) near West Valley, N.Y., in

Cattaraugus County, about 48 km south of Buffalo. The WNYNSC was previously the location of a nuclear-fuels reprocessing plant, and the hydrogeology of the area has been well documented. The till at the proposed site is the uppermost deposit in a 150 m-thick complex of glacial deposits of till and lacustrine, deltaic, and fluvial sediments. The upper 2 to 3 m of the till is weathered and contains oxidized fractures that provide secondary permeability near land surface and scattered lenses of stratified sediments that appear to be discontinuous. The hydraulic conductivity of the till is estimated to be 2 to 6 x 10^{-10} m/s where it is unweathered and 1 order of magnitude greater near land surface, where it is weathered. Most of the water entering the weathered till flows laterally through fractures and animal burrows toward depressions and gullies; the remainder enters the unweathered till and flows downward toward the underlying lacustrine sediments. The rate of ground-water flow in the unweathered till was estimated, from numerical simulations conducted by Prudic (1986), to be 3 to 23 mm/yr.

The proposed study will consist of three phases: (1) site characterization, (2) emplacement and operation of the monitoring caisson to simulate waste burial, and (3) site remediation. The site-characterization phase will measure physical and hydraulic properties of the till and distinguish zones dominated by advection from those dominated by diffusion within the till. The depth of advective transport, assumed to correspond to the depth of fracturing, will be measured through several methods, including direct observation of fractures in excavations, measurement of chemical concentration gradients along vertical profiles, and measurement of seasonal fluctuations in pore pressure. Horizontal boreholes will be drilled at selected depths through the sidewalls of research trenches to intercept high-angle fractures in the till. Core samples obtained during drilling will be analyzed for tritium to detect recent recharge, indicating the presence of high-angle fractures. The diffusion-dominated part of the flow system will be identified through comparison of ^{18}O and ^{2}H gradients measured in the till with those computed through the advection-dispersion equation to estimate the age of pore waters. If diffusion is the dominant transport process, the pore water in the till is thousands of years old, as was found in Ontario by DeSaulnier and others (1981).

After completion of the site-characterization activities, a monitoring caisson consisting of a hollow steel cylinder will be placed in an augered borehole drilled into the till to simulate a waste container. The monitoring caisson will be 1.8 m in diameter and 20 m high and will contain moveable steel platforms to provide access to all depths within the caisson. The annular space surrounding the caisson will be sealed with layers of three different grout materials. Laboratory tests will be conducted on potential grout materials to (1) identify mixtures that yield the properties that best match the properties of the till, and (2) determine proper field procedures for mixing and installing the grout. Both cement and bentonite grouts will be tested so that the effects of grout composition on the sealing properties can be determined. Field tests of the selected grout mixtures will entail (1) sealing boreholes augered at the bottom of a research trench, and (2) estimating the hydraulic conductivity of the borehole plugs through hydraulic tests.

Instruments placed in the annulus and the surrounding till will record changes in the state of stress that result from the emplacement and sealing of the monitoring caisson. Displacement in the till will be measured with slope indicators and a monument survey. Hydration of the cement grout will be recorded by strain gages, stress meters, thermocouples, and pressure transducers. Saturation of bentonite grout will be monitored with stress meters, time-domain reflectometry probes, thermocouple psychrometers, and pressure transducers. Other instruments will be placed in sand layers within the grout to measure pore pressure and detect solute migration during injection tests.

The most probable pathway of radionuclide migration from waste buried in augered holes in saturated sediments is the interface between the till and grout, and sealing this interface is essential to prevent advective transport in the vicinity of a subsurface disposal container. The hydraulic conductivity of the till/grout interface will be estimated through constant-head injection tests in which water is injected into the sand layer within each grout layer. The test results will be analyzed in terms of three possible flow conditions: (1) impermeable grout and radial flow into the till, (2) impermeable till and axial flow through the grout, and (3) impermeable till and grout and axial flow through a gap at the till/grout interface. The test results will also be analyzed by numerical simulation to determine the hydraulic conductivity of the interface. The rates of flow through the interface during the tests will be in the range of tens of milliliters per day unless flow is also occurring along the till/grout interface, in which case the rate will exceed 100 mL/d. Large flow rates will therefore indicate flow along till/grout interface.

If the injection-test results indicate flow along the till/grout interface, a tracer solution containing an electrically conductive solute and dye will be injected into the sand layer and leak sensors that are triggered by the presence of a conductive fluid will be monitored to locate the flow path. A coring tube will be driven through the area of suspected flow to obtain a sample of the till/grout interface for inspection and chemical analysis. A diffusion test will be conducted in unweathered till at the bottom of the monitoring caisson to estimate the coefficient of molecular diffusion of a conservative solute.

The potential for chemical alteration of till and grout in the interface region will be investigated through an analysis of core samples obtained by drilling from the caisson wall through the grout and into the till. Pore water will be extracted from the core to determine the aqueous chemistry, and thin slices of the core will be analyzed to determine the mineralogy of solid phases in the till and grout within the interface region. Previous studies have shown that differences in pH between clay and cement grout and differences in exchangeable cations between clay and bentonite grout result in chemical reactions that could affect the structure of the till and the cement and bentonite grouts.

REFERENCES CITED

Albanese, J.R., Anderson, S.L., Fakundiny, R.H., Potter, S.M., Rogers, W.B., and Whitbeck, L.F., 1984, Geologic and hydrologic research at the Western New York Nuclear Service Center, West Valley, New York: Albany, N.Y., New York State Geological Survey, NUREG/CR-3782, 118 p.

American Concrete Institute, 1988, ACI manual of concrete practice, part 3: Detroit, Mich., American Concrete Institute, 1,500 p.

Atkinson, A., Goult, D.J., and Hearne, J.A., 1985, An assessment of the long-term durability of concrete in radioactive waste repositories, *in* Wermy, L.O., ed., Scientific basis of nuclear waste management XIV: Pittsburgh, Pa., Materials Research Society, symposium proceedings v. 50, p. 239-246.

Baker, T.H.W., and Goodrich, L.E., 1987, Measurement of soil water content using the combined time-domain reflectometry—thermal conductivity probe: Canadian Geotechnical Journal, v. 24, p. 160-163.

Bear, Jacob, 1979, Hydraulics of Groundwater: New York, N.Y., McGraw-Hill, Inc., 569 p.

Bechai, M., and Heystee, R.J., 1989, Radioactive waste disposal in shallow tunnels in glacial till or clayey soil, geotechnical and hydrogeological considerations: Vienna, Austria, International Atomic Energy Association, IAEA-SM-289/13, p. 151-168.

Bergeron, M.P., 1985, Records of wells, test borings, and some measured geologic sections near the Western New York Nuclear Service Center, Cattaraugus County, New York: U.S. Geological Survey Open-File Report 83-682, 95 p.

Bergeron, M.P., and Bugliosi, E.F., 1988, Groundwater flow near two radioactive-waste disposal areas at the Western New York Nuclear Service Center, Cattaraugus County, New York-- Results of flow simulation: U.S. Geological Survey Water-Resources Investigations Report 86-4351, 30 p.

Bergeron, M.P., Kappel, W.M., and Yager, R.M., 1987, Geohydrologic conditions at the nuclear fuels reprocessing plant and waste-management facilities at the Western New York Nuclear Service Center, Cattaraugus County, New York: U.S. Geological Survey Water-Resources Investigations Report 85-4145, 49 p.

Campbell Scientific, Inc., 1988, Instruction manual for the use of the AVW1 and AVW4 with Geokon model 4500 vibrating wire piezometers and pressure transducers: Campbell Scientific, Inc., Logan, Utah, 32 p.

Cherry, J.A., Gillham, R.W., Grisak, G.E., and Lush, D.L., 1979, Hydrogeological factors in shallow subsurface radioactive waste management, *in* Carter, M.W., Kahn, B., and Moghissi, A.A., eds., Management of low-level radioactive waste: New York, N.Y., Pergamon Press, v. 2, p. 1021-1040.

Clifton, J.R., and Knab, L.I., 1989, Service life of concrete, Gaithersburg, Maryland: National Institute of Standards and Technology, NUREG/CR 5466, 75 p.

Daemen, J.J.K., Greer, W.B., Fuenkajorn, K., Yazdandoost, A., Akgun, H., Schaffer, A., Kimbrell, A.F., Avery, T.S., Williams, J.R., Kousari, B., and Roko, R.O., 1986, Experimental assessment of borehole plug performance, Tucson, Ariz., University of Arizona, NUREG/CR-4642, 478 p.

Dana, R.H., Jr., Ragan, V.S., Molello, S.A., Bailey, H.H., Fickies, R.H., Fakundiny, R.H., and Hoffman, V.C., 1980, General investigation of radionuclide retention in migration pathways at the West Valley, New York, low-level burial site: Albany, N.Y., New York State Geological Survey, NUREG/CR-1565, 75 p.

D'Astous, A.Y., Ruland, W.W., Bruce, J.R.G., Cherry, J.A., and Gillham, R.W., 1989, Fracture effects in the shallow groundwater zone in weathered Sarnia-area clay: Canadian Geotechnical Journal, v. 26, p. 43-56.

Denson, R.H., Bennett, R.D., Wamsley, R.M., Bean, D.L., and Ainsworth, D.L., 1987, Recommendations to the NRC for review criteria for alternative methods of low-level radioactive waste disposal—Task 2a, Below-Ground Vaults: Vicksburg, Miss., U.S. Army Engineers Waterways Experiments Station, NUREG/CR-5041, v. 1, 100 p.

Desaulniers, D.E., Cherry, J.A., and Fritz, P., 1981, Origin, age and movement of pore water in argillaceous Quaternary deposits at four sites in southwestern Ontario: Journal of Hydrology, v. 50, p. 231-257

Edwards and Moncreiff, P.C., 1987, Field investigation and proposed solution to resolve the problem of water infiltration into trench 14 of the low-level radioactive disposal area near West Valley, New York: Springville, N.Y., Edwards and Moncreiff, P.C., 50 p.

Fisher, J.M., 1992, Sediment properties and water movement through shallow unsaturated alluvium at an arid site for disposal of low-level radioactive waste near Beatty, Nye County, Nevada: U.S. Geological Survey Water-Resources Investigations Report 92-4032, 48 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, Inc., 604 p.

Geokon, Inc., 1989, Instruction manual for the vibrating wire piezometer model 4500.: Geokon, Inc., Lebanon, N.H., March 1989 revision, 31 p.

Greer, W.B., and Daemen, J.J.K., 1991, Analyses and field tests of the hydraulic performance of cement grout borehole seals: Tucson, Ariz., University of Arizona, NUREG/CR 5684, p. 487.

Holt, R.D., and Kovacs, W.D., 1981, An introduction to geotechnical engineering: Englewood Cliffs, N.Y., Prentice-Hall, Inc., 733 p.

Instrument Society of America, 1979, Process instrumentation terminology,S51,1-1979: American Standard Institute, Instrument Society of America, Research Triangle, N.C., 42 p.

Jefferies, N.L., Tweed, C.J., and Wisbey, S.J., 1988, The effects of changes in pH within a clay surrounding a cementitious repository, *in* Apted, M.J., and Westerman, R.W., eds., Scientific basis of nuclear waste management XIV: Pittsburg, Pa., Materials Research Society, symposium proceedings v. 112, p. 43-52.

Kappel, W.M., and Harding, W.E., 1987, Surface-water hydrology of the Western New York Nuclear Service Center, Cattaraugus County, New York: U.S. Geological Survey Water-Resources Investigations Report 85-4309, 36 p.

Keller, C.K., and van der Kamp, G., 1988, Hydrogeology of two Saskatchewan tills—II. Occurrence of sulfate and implications for soil salinity: Journal of Hydrology, v. 101, p. 123-144.

Keller, C.K., van der Kamp, G., and Cherry, J.A., 1988, Hydrogeology of two Saskatchewan tills—I. Fractures, bulk permeability, and spatial variability of downward flow: Journal of Hydrology, v. 101, p. 97-121.

_____1989, A multiscale study of the permeability of a thick clayey till: Water Resources Research, v. 25, no. 11, p. 2299-2318.

Kimbrell, A.F., Avery, T.S., and Daemen, J.J.K., 1987, Field testing of bentonite and cement borehole plugs in granite: Tucson, Ariz., University of Arizona, NUREG/CR 4919, p. 320.

Kjartanson, B.H., Gray, M.N., and Pulles, B.C.M., 1991, Developments for in situ tests on compacted bentonite-base buffer material, *in* Abrajano, T.A., and Johnson, L.H., eds., Scientific basis of nuclear waste management XIV: Pittsburg, Pa., Materials Research Society, symposium proceedings, v. 212, p. 467-474.

LaFleur, R.G., 1979, Glacial geology and stratigraphy of Western New York Nuclear Service Center and vicinity, Cattaraugus and Erie Counties, New York: U.S. Geological Survey Open-File Report 79-989, 17 p.

Lapcevic, P.A., and Novakowski, K.S., 1992, A new method for conducting constant-head tests in clay environments—development of the apparatus and field example: Burlington, Ontario, Canada, National Water Research Institute, 20 p.

Mayo, Paul, McMullin, Kathleen, and Blood, Peter, 1989, Source term report—low level radioactive waste projections for New York State: Albany, N.Y., New York State Low Level Radioactive Waste Siting Commission, 15 p.

Millington, R.J., and Quirk, J.P., 1961, Permeability of porous solids: Transactions of Faraday Society, v. 57, p. 1200-1207.

Neuman, S.P., and Narasimhan, T.N., 1977, Mixed explicit-implicit iterative finite element scheme for diffusion-type problems—I. Theory: International Journal for Numerical Methods in Engineering, v. 11, p. 309-323.

New York State Department of Environmental Conservation, 1987, Regulations of low-level radioactive waste disposal facilities, 6 NYCRR Part 382: Albany, N.Y., New York State Department of Environmental Conservation, 57 p.

New York State Energy Research and Development Authority, 1992, New York State radioactive waste report for 1991: Albany, N.Y., New York State Energy Research and Development Authority, 36 p.

Olsen, H.W., Gill, J.D., Willden, A.T., and Nelson, K.R., 1991, Innovations in hydraulic-conductivity measurements: Transportation Research Record, no. 1309, p. 9-17.

Ontario Hydro, 1985, Bruce nuclear power development—radioactive waste operating, site 2, inground container safety report: Toronto, Canada, Ontario Hydro, 35 p.

Ouyang, S., and Daemen, J.J.K., 1992, Sealing performance of bentonite and bentonite/crushed rock borehole plugs: Tucson, Ariz., University of Arizona, NUREG/CR-5685, 314 p.

Patterson, R.J., Frape, S.K., Dykes, L.S., and McLeod, R.A., 1978, A coring and squeezing technique for the detailed study of subsurface water chemistry: Canadian Journal Earth Science, v. 15, pp. 162-169.

Peterson, E.W., Lagus, P.L., and Lie, K., 1987, Fluid flow measurements of test series A and B for the small scale seal performance tests, Albuquerque, N.M., Sandia National Laboratories, SAND87-7041, 130 p.

Prudic, D.E., 1981, Computer simulation of ground-water flow at a commercial, radioactive-waste landfill near West Valley, Cattaraugus County, New York, *in* Little, C.A., and Stratton, L.E., eds., Modeling and low-level waste management—an interagency workshop: Oak Ridge, Tenn., Oak Ridge National Laboratory, ORO-821, p. 215-248.

_____1986, Ground-water hydrology and subsurface migration of radionuclides at a commercial radioactive waste burial site, West Valley, Cattaraugus County, New York: U.S. Geological Survey Professional Paper 1325, 83 p.

_____1990, Burial of low-level radioactive wastes in the humid northeastern United States, *in* Bedinger, M.S. and Stevens, P.R., eds, Safe disposal of radionuclides in low-level radioactive waste repository sites: U.S. Geological Survey Circular 1036, 125 p.

Revesz, K.M., and Woods, P.H., 1990, A method to extract soil water for stable isotope analysis: Journal of Hydrology, v. 115, p. 397-406.

Ruland, W.W., Cherry, J.A., and Feenstra, Stan, 1991, The depth of fractures and active ground-water flow in a clayey till plain in southwestern Ontario: Ground Water, v. 29, no. 3, p. 405-417.

Sawyer, W.D., and Daemen, J.J.K., 1987, Experimental assessment of the sealing performance of bentonite borehole plugs: Tucson, Ariz., University of Arizona, NUREG/CR-4995, 290 p.

Schwarz, W.F., 1990, Low-level radioactive-waste disposal technologies—Current concepts, *in* Bedinger, M.S., and Stevens, P.R., eds., Safe disposal of radionuclides in low-level radioactive waste repository sites: U.S. Geological Survey Circular 1036, 125 p.

Stormont, J.C., 1986, Development and implementation—Test series A of the small-scale seal performance tests: Albuquerque, N.M., Sandia National Laboratories, SAND85-2602, 53 p.

_____1987, Small-scale seal performance test series A, Thermal/structural data through the 180th day: Albuquerque, N.M., Sandia National Laboratories, SAND87-0178, 61 p.

Streigl, R.G, 1990, Radioactive gases at low-level radioactive waste repository sites, *in* Bedinger, M.S., and Stevens, P.R., eds., Safe disposal of radionuclides in low-level radioactive waste repository sites: U.S. Geological Survey Circular 1036, 125 p.

Sudicky, E.A., and McLaren, R.G., 1992, The Laplace transform Galerkin technique for large-scale simulation of mass transport in discretely-fractured porous formations: Water Resources Research, v. 28, no. 2, p. 499-514.

Tokunaga, T.K., 1988, Laboratory permeability errors from annular flow: Soil Science Society of America Journal, v. 52, p. 24-27.

Topp, G.C., Davis, J.L., and Annan, A.P., 1982, Electromagnetic determination of soil water content using TDR—I. Applications to wetting fronts and steep gradients: Soil Science Society of America Journal, v. 46, p. 672-678.

U.S. Army Corps of Engineers, 1992, Handbook for concrete and cement: Vicksburg, Miss., U.S. Army Corps of Engineers Waterways Experiment Station, 1,500 p.

U.S. Nuclear Regulatory Commission, 1986, Final rule on land disposal of low-level radioactive waste, U.S. Code of Federal Regulations, Title 10, Part 61, revised as 12/27/82, 23 p.

Voraurer, A.G., and Chan, H.T., 1988, Sealing of large-diameter boreholes for low-level and intermediate-level reactor waste disposal: Ontario Hydro Research Division Report No. 88-105-K, 41 p.

Wescore, 1990, Water potential systems: Logan, Utah, Wescore, 16 p.

Yager, R.M., 1987, Simulation of ground-water flow near the nuclear-fuel reprocessing facility at the Western New York Nuclear Service Center, Cattaraugus County, New York: U.S. Geological Survey Water-Resources Investigations Report 85-4308, 58 p.

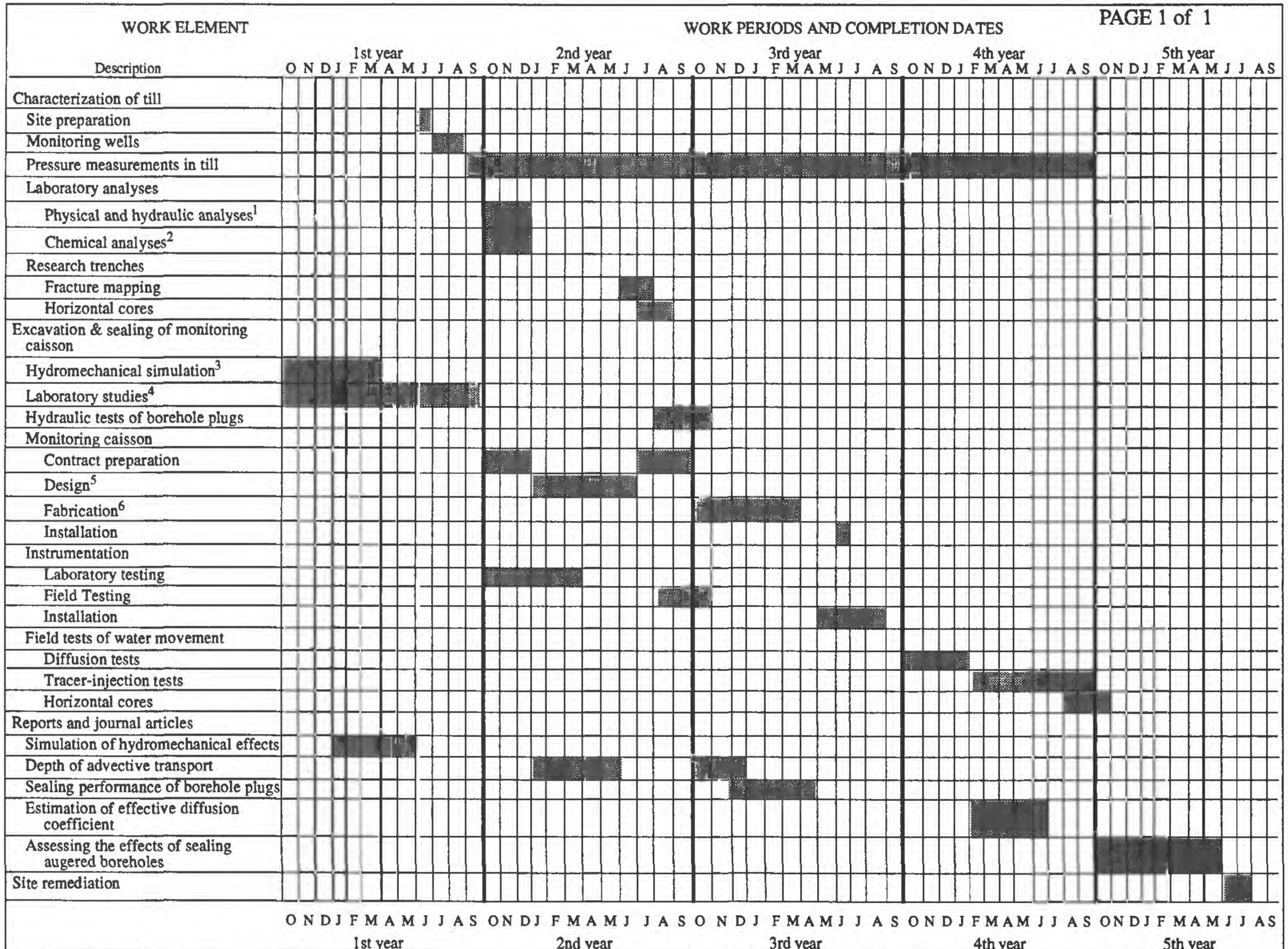
Zarriello, P. J., 1995, Accuracy, precision, and stability of a vibrating-wire-transducer measurement system for measuring hydraulic head: Ground-water monitoring and Remediation, v. 15, no. 2, p. 157-158..

Ziegler, T.W., 1976, Determination of rock mass permeability: U.S. Army Corps of Engineers Waterways Experiment Station, Technical Report S-76-2, 88 p.

STUDY WORK PLAN AND PROPOSED REPORTS

The study would proceed for 5 years, at which time a decision would be made whether to continue for pursuit of additional objectives. Components of the workplan are shown in figure 23. Proposed reports would be published in USGS series or as journal articles and would address the following topics:

- Estimation of depth of advective transport in a clayey till near West Valley, N.Y.
- Simulation of hydromechanical effects of excavating and sealing a waste-disposal facility in a clayey till
- Estimation of the effective diffusion coefficient of a clayey till through field tests
- Field tests of the sealing performance of cement and bentonite borehole plugs in a clayey till
- Assessing the effects of sealing augered boreholes used to dispose of low-level radioactive waste on water movement through a clayey till near West Valley, N.Y.



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[3] John Peters, U.S. Army Corps of Engineers, Rock and Soil Mechanics Division
[4] John Boa and Sam Wong, U.S. Army Corps of Engineers, Concrete Technology Division
[5] Civil engineering firm not yet identified
[6] Manufacturing firm not yet identified

Figure 23. Components of workplan and timeline for proposed study.