Innovative Technology

Summary Report

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Frozen Soil Barrier

Subsurface Contaminants Focus Area

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INNOVATIVE TECHNOLOGY
Summary Report

Frozen Soil Barrier

OST Reference #51

Subsurface Contaminants
Focus Area

Demonstrated at
Oak Ridge National Laboratory
Oak Ridge, Tennessee

INNOVATIVE TECHNOLOGY
Summary Report

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine if a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

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SECTION 1

SUMMARY

Technology Summary

Problem
Hazardous and radioactive materials have historically been disposed of at the surface during operations at Department of Energy facilities. These contaminants have entered the subsurface, contaminating soils and groundwater resources. Remediation of these groundwater plumes using the baseline technology of pump and treat is expensive and takes a long time to complete. Containment of these groundwater plumes can be alternative or an addition to the remediation activities. Standard containment technologies include slurry walls, sheet piling, and grouting. These are permanent structures that once installed are difficult to remove.

How It Works
Frozen Soil Barrier technology provides a containment alternative, with the key difference being that the barrier can be easily removed after a period of time, such as after the remediation or removal of the source is completed. Frozen Soil Barrier technology can be used to isolate and control the migration of underground radioactive or other hazardous contaminants subject to transport by groundwater flow.

Frozen Soil Barrier technology consists of a series of subsurface heat transfer devices, known as thermoprobes, which are installed around a contaminant source and function to freeze the soil pore water. The barrier can easily be maintained in place until remediation or removal of the contaminants is complete, at which time the barrier is allowed to thaw.

Major elements of the Frozen Soil Barrier system include (Figure 1):

- below-ground **thermoprobes** installed vertically at equal intervals around the perimeter of a known source of contaminants (These devices utilize liquid-to-gas phase change of a passive refrigerant [carbon dioxide] to remove heat from the surrounding soil.);

Figure 1. Frozen Soil Barrier system at Oak Ridge National Laboratory

- above-ground **refrigeration units and interconnecting piping** (Units are standard commercial machines that function to condense carbon dioxide vapor on the interior walls of the thermoprobes.

The heat energy removed from the condensing carbon dioxide is transferred to the refrigeration units and expelled.);

- **insulation and a waterproof membrane** installed at grade (The insulation prevents heat gain at the ground surface, while the membrane prohibits infiltration of rain water into the isolated zone.);
- a collection of **temperature monitoring instruments and a data collection and storage system** (Soil temperatures are monitored and recorded at several locations and depths in order to monitor system performance.).

Potential Markets

Frozen Soil Barrier technology can be used at most sites where containment of contaminants, such as a source zone, is desired. However, the technology is most effectively applied in fine-grained, saturated soils where the source of contamination is fairly well defined. One especially attractive potential application of the technology is the isolation and containment of groundwater plumes contaminated with relatively short-lived radionuclides, such as tritium, with a half-life of 12.32 years.

Advantages

Frozen Soil Barriers offer several advantages over other subsurface barrier technologies (grouting, liners, slurry walls).

- Frozen Soil Barriers are “self-healing”,
- Contaminants can be completely encircled or immobilized within the frozen matrix itself, and
- Frozen Soil Barriers are easily removed when no longer needed.

Unlike other barriers, maintenance of frozen soil requires application of electrical power for the life of the barrier. Therefore, use of these barriers is best restricted to short to medium durations (20 years or less).

Demonstration Summary

This report covers the demonstration of Frozen Soil Barrier technology at Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee from September 1996 through September 1998. The demonstration site is a former earthen impoundment used from 1958 through 1961 for retention/settling of liquid radioactive wastes generated from operation of the Homogeneous Reactor Experiment (HRE) (Figure 2). In 1986, it was estimated that approximately 75 Curies (Ci) of ^{90}Sr and 16 Ci of ^{137}Cs were contained in the buried sediments of the impoundment. Groundwater movement through these sediments was suspected as a likely source of contamination detected in surface waters located just to the east and south of the site.

Figure 2. Demonstration area prior to installation of Frozen Soil Barrier. Impoundment is covered by asphalt cap in lower portion of photo

At the impoundment site, highly weathered shale forms a clay-rich cover over undisturbed limestone and shale bedrock, typically encountered at depths of approximately 15 feet. The bedrock is complexly fractured, and these fractures likely dominate groundwater flow and contaminant transport directions.

In general, the hydraulic gradient at the site tends to be from the northwest to the southeast. The water table is shallow, typically measured at depths from 2 to 9 feet below the surface. While seasonal variations in the water table are small, storm-driven variations have been observed to be quite substantial in many locations around the demonstration site. The shallow groundwater discharges to surface water at several locations around the impoundment.

In the spring/summer of 1997, a soil freezing system designed by Arctic Foundations Inc. (AFI) was installed at the HRE impoundment site. A series of fifty, 30-foot long thermoprobes were installed in drilled holes around the original shoreline of the impoundment and manifolded to two above-ground commercial refrigeration units. In early fall of 1997, the system was powered up to commence freezing of the soil around each thermoprobe. A 12-foot thick frozen soil wall was ultimately established in January 1998. Verification monitoring was conducted by the Environmental Protection Agency's (EPA) Superfund Innovative Technology Evaluations (SITE) Program.

A previous demonstration of Frozen Soil Barrier technology was successfully conducted at a clean site at the SEG facility in Oak Ridge Tennessee in 1994. The vendor for that demonstration was RKK, Ltd. and Freewall. Laboratory tests showing the effectiveness of the technology for chromate, cesium, and trichloroethylene plumes were completed. An Innovative Technology Summary Report, available on the DOE web page, was prepared on the results of that demonstration in 1995, (DOE, 1995). Ground freezing technology has been used for many years in the mining and construction industries.

Key results

- Under ambient gradient conditions, **the Frozen Soil Barrier was shown to be effective in hydraulically isolating the impoundment** from the surrounding site as determined by groundwater monitoring and dye tracer evaluation.
- **The total cost of the demonstration was approximately $1,809,000.** This includes design, installation, startup, and operation of the system by the contractor, as well as ORNL engineering and site support/oversight, site infrastructure upgrades, pre- and post-barrier verification studies.
- Once established, **electrical power required for maintaining the Frozen Soil Barrier was approximately 288-kilowatt hours per day**, equivalent to a cost of less than $15 per day at ORNL rates.

Current plans call for continued operation and maintenance of the Frozen Soil Barrier system at ORNL until a final Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) remediation decision is made. Other U.S. Department of Energy (DOE) sites, including Savannah River Site and Hanford Site are considering the use of Frozen Soil Barriers for containment of radiologically contaminated groundwater plumes. A site in Smithville, Ontario, Canada is also assessing the use of this technology for containment of subsurface polychlorinated biphenyls (PCBs) and dense non-aqueous phase liquids (DNAPLs). The technology is currently commercially available.

A National Environmental Policy Act (NEPA) Categorical Exclusion (CX) was granted for the construction of the frozen barrier system. The Tennessee Department of Environment and Conservation (TDEC) issued an underground injection permit for pre-barrier dye studies. No other regulatory permits, new or modified, were required for operation of the frozen barrier at the HRE impoundment site.

This demonstration was the result of a team approach involving the following organizations:

- U.S. Department of Energy
- U.S. Environmental Protection Agency
- Tennessee Department of Environment and Conservation
- Arctic Foundations Inc.

- Bechtel Jacobs Company LLC
- Cambrian Ground Water Company
- Lockheed Martin Energy Research
- Lockheed Martin Energy Systems
- Tetra Tech EM Inc.

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All published Innovative Technology Summary Reports are available on the OST Web site at http://em-50.em.doe.gov under "Publications." The Technology Management System, also available through the OST Web site, provides information about OST programs, technologies, and problems. The OST Reference number for Frozen Soil Barrier is 51.

SECTION 2

TECHNOLOGY

Overall Process Definition

The key objectives of the Frozen Soil Barrier demonstration at ORNL included designing, installing, operating, and evaluating the performance of the barrier for isolating and containing radiological contaminants in-situ.

Soil freezing can be accomplished using several different conventional techniques. An innovative technology was selected following a DOE competitive bid for the demonstration at ORNL (Figure 3). This technology:

- utilizes a series of proprietary heat transfer devices, known as thermoprobes, installed vertically around an area of subsurface contamination to freeze the moisture in the soil and bedrock formations.
- forms a barrier (the frozen soil) against groundwater movement through the area of contamination preventing migration of contaminants into adjacent areas.
- may be adapted to provide horizontal bottom, U-, V-, or other shaped barriers in addition to the vertical wall configuration (this demonstration relied on unfrozen, competent bedrock as the “floor” for the isolated zone).

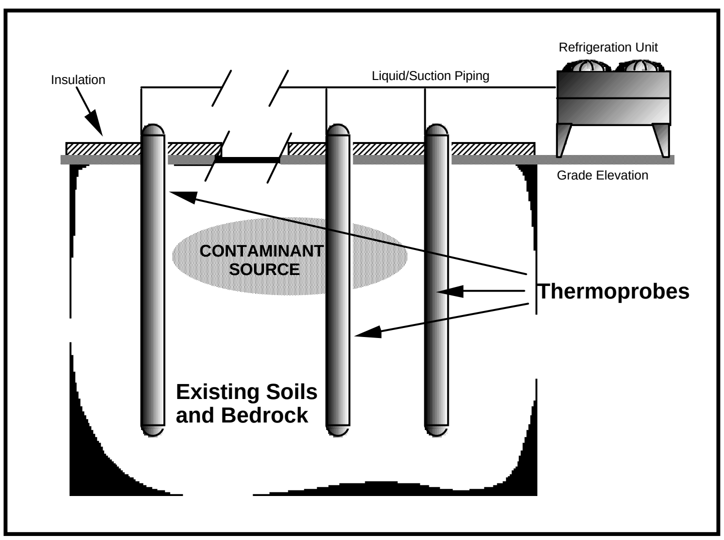

Figure 3. Frozen Soil Barrier concept used at ORNL

The technology has been used extensively in cold climates to prevent damage to buildings and other structures caused by cyclic ground freezing and thawing.

System Description

Thermoprobes – An array of 50 sealed, passive heat transfer devices known as thermoprobes (Figure 4) were installed around the original perimeter of the HRE impoundment. The thermoprobes, fabricated from six-inch Schedule 40 steel pipe, were installed on six-feet centers to a depth of approximately 30 feet below grade. Liquid and vapor-phase carbon dioxide function as the working fluid to move heat against gravity. As the surrounding soil at initial ambient temperatures of 60-70 degrees F warms the thermoprobe walls, the liquid phase carbon dioxide boils and the vapor rises towards the upper portion of the device. At the top of the thermoprobe a heat exchanger coil connected to an above-grade refrigeration unit cools and condenses the carbon dioxide vapor back to its liquid phase. The liquid carbon dioxide flows down the inside walls of the thermoprobes, drawing heat energy from the surrounding soil, again vaporizing the liquid, and the cycle repeats. The carbon dioxide charge in the thermoprobe is fixed and does not require renewal during normal operation. There are no moving or otherwise active components in the thermoprobe.

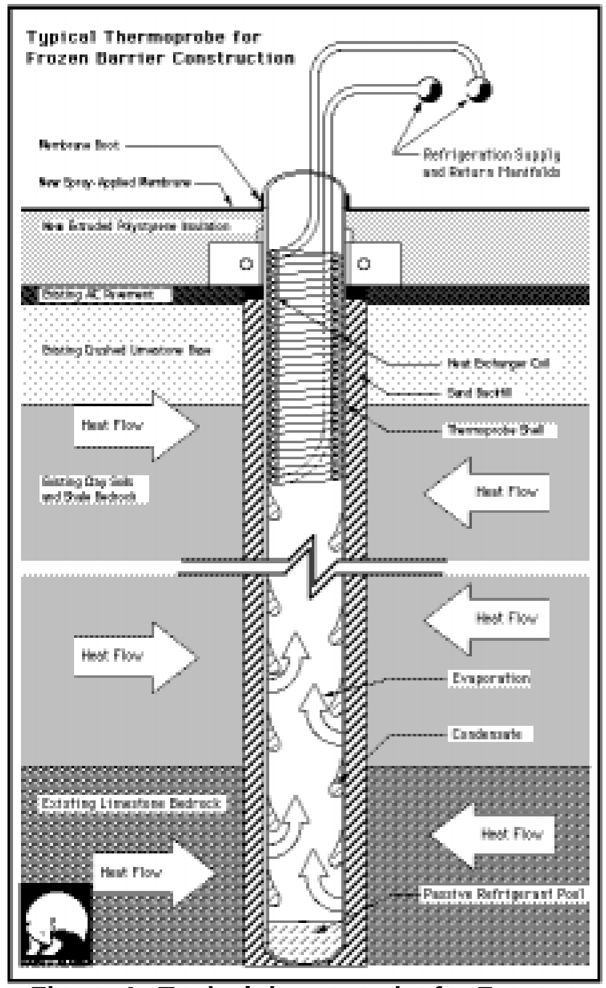

Figure 4. Typical thermoprobe for Frozen Barrier formation

Above-Ground Refrigeration System – Heat exchanger coils in the top of each thermoprobe are part of the above-ground, or "active," refrigeration system (Figure 5). A "zero ozone-depleting" refrigerant, R-404a, is circulated to each thermoprobe coil from standard light industrial refrigeration units via above grade copper piping loops. Two separate refrigeration units are utilized, with each unit driving 25 thermoprobes. The two piping loops are configured such that every other thermoprobe in the array is plumbed to the same refrigeration unit.

Thermal expansion valves at each thermoprobe modulate to allow flow of R-404a from the refrigeration units through the heat exchanger coils. Each expansion valve is controlled by a pressurized bulb attached to the suction side of its respective heat exchanger coil, opening whenever the suction side temperature is above –25 degrees F. Each thermoprobe can be isolated from the active system by quarter-turn ball valves.

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Figure 5. Above-ground refrigeration units

Each refrigeration unit consists of two motor/compressors in parallel each with two fan coils in parallel. During initial operation, both units were operated simultaneously to rapidly remove heat from the soil surrounding the thermoprobes. Once the Frozen Soil Barrier reached an average thickness of 12 feet, the units were cycled to run for alternating periods of 24 hours each, sufficient to maintain the barrier at design thickness.

Insulation and Membrane – In order to limit heat transfer to the upper portion of the Frozen Soil Barrier, a 20-foot wide strip of extruded polystyrene, centered along the midline of the barrier, was installed (Figure 6). The insulation was placed in three, two-inch layers for a total thickness of six inches.

Figure 6. Insulation installed prior to membrane covering

To preclude surface water from infiltrating the isolated zone, a two-part polyurea coating was spray applied over a non-woven geotextile fabric. This coated membrane is secured along the perimeter by galvanized steel straps, the membrane is protected from wind-induced lift by an array of concrete pavers and curb blocks with a total weight of approximately 70,000 pounds.

Temperature Monitoring and Data Collection System – Eight PVC monitoring wells were installed to monitor ground temperature at varying depths and distances from the walls. Strings of seven or eight thermistors were installed in each well and hardwired to a local data logger (Figure 7). Soil temperatures were determined from regular automatic resistance measurements of these instruments.

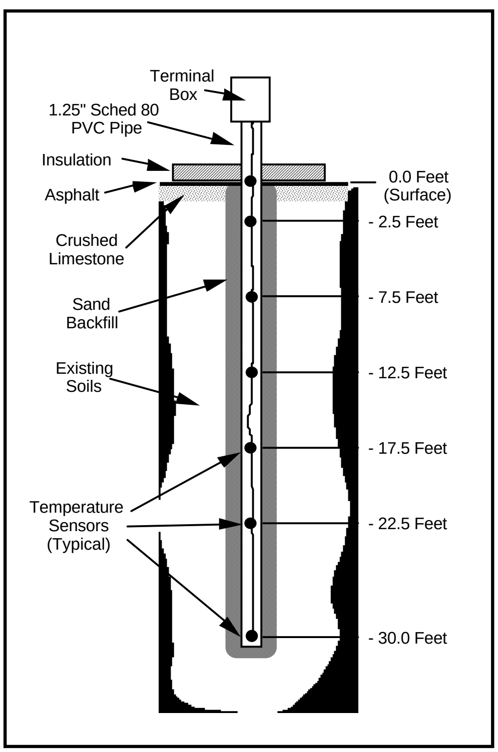


Figure 7. Typical temperature monitoring well

A platinum 100-ohm resistive temperature device (RTD) is installed on the external surface midway down the length of each thermoprobe (i.e., approximately 15 feet below grade) to provide an indication of the operating temperature of each thermoprobe. Additional performance data are collected from the four thermoprobes located approximately mid-way in each wall, using heat flux sensors (differential thermocouples fitted with spacers between the thermocouple junctions) and pressure transducers, which respond to the internal pressure of the carbon dioxide. This pressure can be used to determine the internal thermoprobe temperature more accurately than the RTDs.

A commercial data logger housed in an environmentally-controlled enclosure records data from the field instruments and the refrigeration units. The stored data are accessed remotely via modem for subsequent analysis or may also be downloaded locally with a portable PC.

System Operation

Following equipment installation, the system is operated in two sequential phases: freeze-down and maintenance freezing.   During the freeze-down phase:

- During the freeze-down phase the two refrigeration units are operated simultaneously (each thermoprobe removes heat from the soil). The soil gradually freezes radially outward from each thermoprobe forming a continuous wall of frozen soil (referred to as “freezing to closure”). Freezing continues until the frozen soil wall reaches its design thickness (12 feet).
- Following freeze-down, the maintenance freezing phase requires significantly less energy input than that needed to initially establish the barrier. The refrigeration units are alternately cycled for 24-hour periods to drive alternating thermoprobes. The barrier thickness remains essentially constant and can be maintained indefinitely. Human operators are not required on-site for normal system operation.

Maintenance of system components is typically required only in the event of a mechanical failure of the refrigeration units. Because the units are off-the-shelf items, they are of known reliability and are serviceable by qualified heating and air conditioning technicians. Maintenance and repair of thermoprobes, while infrequent, usually requires the attention of a designer/fabricator representative due to the proprietary nature of the devices.

No safety concerns or environmental risks beyond those regularly accepted for refrigeration systems exist for operation of the frozen soil system. Generation of drill cuttings tainted with the contaminants being isolated can be expected during system installation. However, no secondary waste is generated as a result of system operation.

SECTION 3

PERFORMANCE

Demonstration Plan

Site Description

The ultimate goal of the demonstration was to evaluate the effectiveness of a Frozen Soil Barrier to isolate buried radioactively-contaminated sediments in a former impoundment (Figure 2). The demonstration site was formerly a 75 by 80 by 10 feet deep, unlined, earthen impoundment with a capacity of approximately 310,000 gallons. The impoundment was constructed in 1955 by excavating and building up compacted earth on a hillside just behind the HRE facility at ORNL. The impoundment was used from 1958 until 1961 as a retention/settling pond for liquid radioactive wastes generated from reactor operations. In 1970 the impoundment was back-filled with local soils, covered with approximately eight inches of crushed stone and capped with asphalt. A series of unscreened standpipes were also installed at this time to provide a limited future monitoring capability (Figure 8 and 9). Four screened monitoring wells were installed later.

A 1986 study estimated that the impoundment contained approximately 75 Curies (Ci) of ^{90}Sr and 16 Ci of ^{137}Cs in the buried sediments. As groundwater moved through the area, it was suspected that radioactive contaminants were transported out of the impoundment to surrounding locations, including surface waters lying just to the south and east of the site.

Bedrock underlying the HRE impoundment area consists of two geologic units of the Conasauga Group: the Rogersville Shale and the underlying Friendship Formation (formerly Rutledge Limestone). The bedrock is complexly fractured, and these fractures and fracture intersections likely dominate groundwater flow and contaminant transport directions. Highly weathered shale saprolite, which is typically encountered at depths between 10 and 15 feet, forms a clay-rich cover over the undisturbed bedrock surrounding the impoundment.

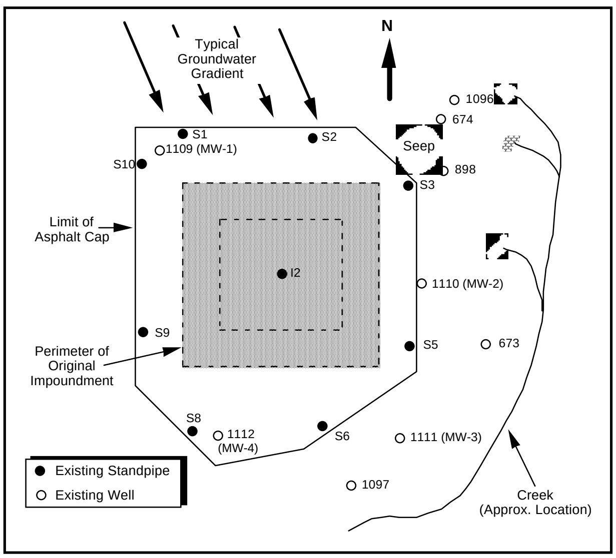


Figure 8. Pre-barrier site plan

In general, the hydraulic gradient at the site tends to be from the northwest to the southeast. The water table is shallow, typically measured at depths from 2 to 9 feet below the surface. While seasonal variations in the water table are small, storm-driven variations have been observed to be quite substantial. The shallow groundwater discharges to local surface water around the impoundment. Due to the fractured nature of the bedrock, the site hydrology can best be described as complex.

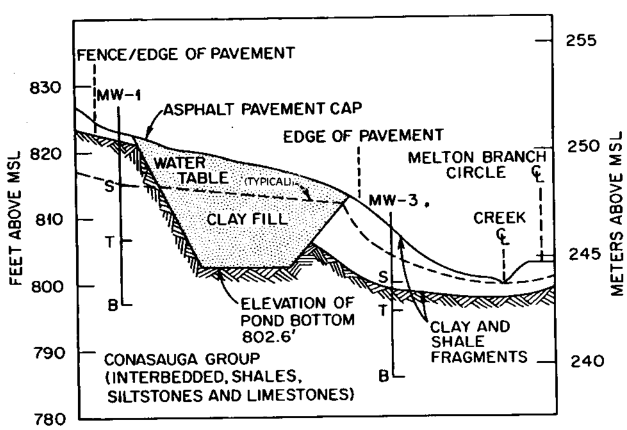


Figure 9. Geologic cross section, northwest to southeast

Demonstration Elements

Key elements of the Frozen Soil Barrier demonstration included:

- **Pre-barrier studies** to establish baseline site hydrologic and geophysical conditions;
- **Installation** of below-grade heat transfer devices and above-grade refrigeration equipment at the radiologically-contaminated HRE Site;
- **Operation** of the system to establish and maintain subsurface vertical walls of frozen soil around the impoundment; and
- **Post-barrier studies** to evaluate the capability of the Frozen Soil Barrier to isolate the impoundment and contents from adjacent areas.

Results

Pre-Barrier Studies

- The barrier verification process was originally designed to systematically compare pre- and post-barrier activities of radionuclides at selected locations, with any observed differences attributed to the presence of the barrier. However, due to the extensive variability of radioactivity in the subsurface materials, potential contributions from other contaminant sources in the area, and the lengthy monitoring period required to identify trends, direct measurement of radionuclide activity was eliminated as a method of barrier verification.
- Groundwater tracers were selected as the primary means to demonstrate hydraulic isolation of the impoundment following establishment of the barrier.
- A secondary verification method relied on hydrologic data analysis (level and temperature of groundwater) and subsurface soil temperature monitoring.
- To support verification activities, several site studies were performed prior to installing the Frozen Soil Barrier system: 1) collecting and reviewing site historical data, 2) performing tracer studies and groundwater level/temperature monitoring to better understand groundwater movement through the impoundment, and 3) conducting a geophysical survey of the site in an attempt to identify subsurface obstructions.

Pre-barrier study results included:

- Dye and gas tracer studies confirmed that the interior of the impoundment was hydraulically connected to adjacent areas prior to installation of the soil freezing system; therefore contaminant transport out of the impoundment was highly probable.
- Monitoring of groundwater revealed small seasonal variations in the elevation of the water table; extreme level responses to storm events within and outside of impoundment boundary were also measured (see Appendix A and reference 7 for additional detail).
- A geophysical survey indicated general areas of high-conductivity and other localized anomalies consistent with subsurface heterogeneitics.

These data were used to establish a baseline characterization of the HRE impoundment prior to establishing the Frozen Soil Barrier.

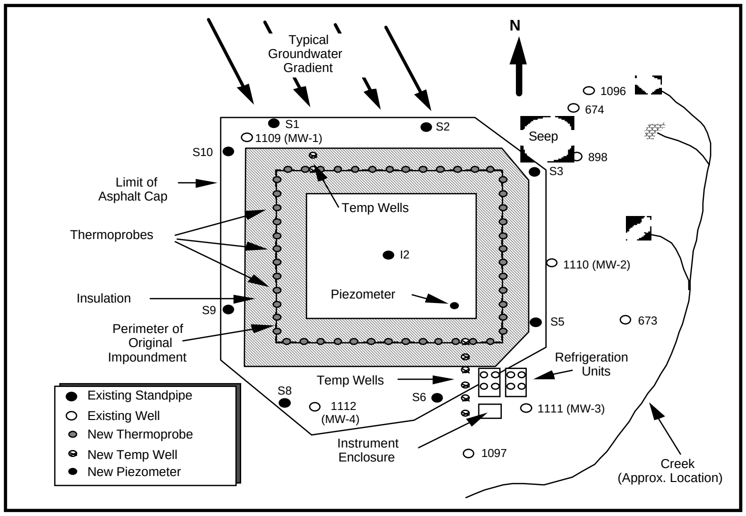
System Installation

Thermoprobes were fabricated and tested at AFI's manufacturing facility in Anchorage, Alaska, shipped to

ORNL, and installed at the site by a local drilling contractor (May 1997) (Figure 10).

Boreholes for thermoprobe installation were created by augering to refusal, then switching to air rotary drilling until the required 30 feet (nominal) depth was achieved. Once all thermoprobes and temperature monitoring wells were in place, the above-ground system components were assembled, installed, and tested (Figure 11).

Figure 10. Thermoprobe installation

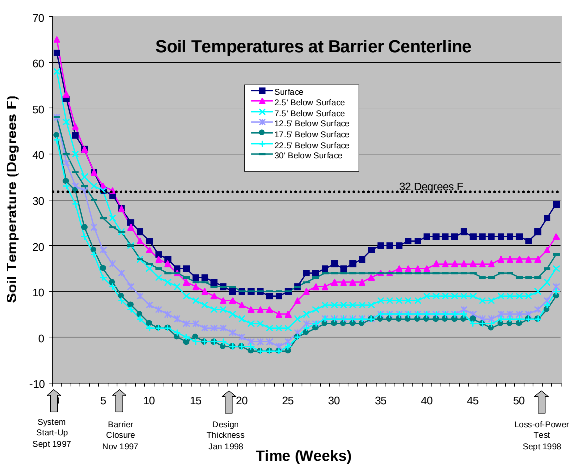


System installation was completed in approximately four months, with no safety-related or contamination incidents or occurrences.

Figure 11. Site plan following system installation

System Operation

Soil freezing was initiated in September 1997, when the two above-ground refrigeration units were powered-up for continuous operation. Data from the monitoring wells were collected daily to monitor subsurface soil temperature changes. In approximately seven weeks of operation, a continuous Frozen Soil Barrier was formed around the perimeter of the impoundment, from the surface to a nominal depth of 30 feet (Figure 12 and 13).



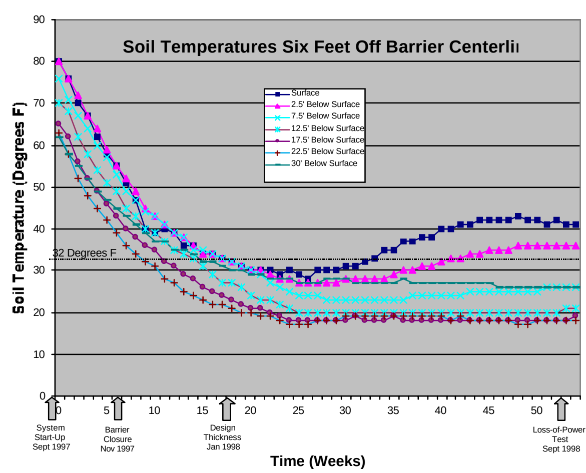


Figure 12. Soil temperatures along

Figure 13. Temperatures six feet
barrier centerline (T-2)

away from barrier centerline (T-1)

With both refrigeration units operating continuously, soil freezing progressed outward from the barrier centerline. Approximately 18 weeks after initial system start-up, the barrier walls reached their average design thickness of 12 feet. At this point, the full heat removal capability of the dual refrigeration units was no longer required. System operation was modified such that only one unit was operated at a time, driving 25 alternately spaced thermoprobes. This operating procedure has been shown to be effective at maintaining the average barrier thickness at or above design thickness, even through the warm summer months at ORNL.

Physical data for the Frozen Soil Barrier are summarized in Table 1 below.

Table 1. Physical data, Frozen Soil Barrier at HRE impoundment

Time to Establish Barrier:	18 Weeks
Total Length of Barrier:	300 Linear Feet
Barrier Depth:	30 Feet Minimum
Barrier Thickness:	12 Feet Average
Barrier Centerline Area:	9000 Square Feet
Frozen Soil Volume:	108,000 Cubic Feet
Total Volume Contained:	168,750 Cubic Feet

Post-Barrier Evaluation

Data collection activities during and following barrier establishment included continued groundwater level/temperature monitoring and dye tracer injection/recovery. These data were compared against the pre-barrier baseline in an effort to evaluate performance of the Frozen Soil Barrier. Extended, follow-on sampling by TDEC will be conducted to determine long-term impact of the barrier on the level of contamination in adjacent surface waters. A test was also conducted to evaluate the response of the frozen soil to a one-week loss of power.

Groundwater Monitoring - Groundwater level fluctuations within the impoundment essentially damped out following establishment of the barrier. Responses due to storm events, extreme before barrier formation, ceased to occur following ground freezing. This behavior is consistent with hydraulic isolation of the impoundment (see Appendix A and reference 7 for additional detail).

Groundwater level measurements upgradient of the frozen barrier remained essentially unchanged. Downgradient groundwater levels showed a moderate drop and stabilization at a lower elevation. This is illustrative of groundwater being re-routed around the barrier.

Dye Tracer Study - Eosine dye injected upgradient of the impoundment was not detected inside the barrier, but was rapidly transported to and recovered in surface water east of the injection well. This indicated the frozen soil mass was re-directing local groundwater flow around the impoundment.

Phloxine B dye injected in the center of the impoundment showed no movement over an initial two-week time period. A Phloxine B "hit" was then detected outside the barrier, but upgradient of the injection point. This was inconsistent with other data. After further investigation, it was determined that this anomaly was due to transport through an abandoned, subsurface inlet pipeline to the pond. A temporary, artificial reverse-gradient condition was created by "chasing" the Phloxine B dye with deionized water, pushing the dye through the pipe, which was at least partially void of soil/water during initial freezing. This was a site anomaly considered unrelated to performance of Frozen Soil Barrier technology, although it serves as a "lesson learned" for future deployments. It is highly probable that the water that filled the pipe during the reverse gradient condition eventually froze in place, thus eliminating the pipeline as a future pathway into or out of the impoundment.

Loss of Power Test - A one-week test was conducted in September 1998 to simulate a loss of electrical power to the system. With the refrigeration units pumped down (i.e., no longer removing heat from the thermoprobes), soil temperatures along the barrier centerline rose approximately 4 degrees F at each depth measured during the seven-day test. Even at the ground surface, temperatures did not rise to 32 degrees F along the barrier centerline. At six feet out from the barrier centerline, increases in soil temperature were insignificant, on the order of one degree F or less. These results indicate that the barrier can be expected to retain its integrity for a reasonable period of time during power outages or while shutdown for maintenance.

Technical Performance Summary

The demonstration at the HRE impoundment showed that Frozen Soil Barrier technology can be effectively used to isolate and reduce or eliminate groundwater transport of subsurface contaminants.

- The zone within the frozen soil boundary is behaving as if isolated hydraulically from the surrounding area.
- Tracer dyes injected outside the impoundment were not transported into the isolated zone, but were redirected along a path parallel to the frozen soil boundary.
- Tracer dyes injected within the impoundment were contained with one notable exception. An anomalous breach of Frozen Soil Barrier in the northwest corner was determined to be due to the presence of an abandoned subsurface pipeline, coupled with an artificially-induced reverse gradient condition.
- The barrier can be expected to fully maintain its integrity for several weeks following a loss of power or refrigeration.
- While no soil surface heave was initially detected, later observations indicated some soil heave may have occurred along the eastern edge of site.

SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Competing Technologies

- The Frozen Soil Barrier technology is competitive with other groundwater flow-control technologies such as liners, slurry walls, sheet piling, and grouting.
- Grouted barriers have been used to isolate buried radioactive waste in situ from groundwater; grouting is typically considered the baseline application where soil freezing is a potential alternative.
- Other alternative remediation strategies include excavation followed by ex situ treatment and disposal or traditional pump and treat processes.

Direct comparison with grouting technologies is complicated by the unique inherent aspects of ground freezing, primarily its potential for complete containment, its characteristic self-healing response, and its removability. Ground freezing requires operation and maintenance activities that grouting does not. A qualitative comparison of the advantages and disadvantages of Frozen Soil Barriers and grouted barriers is provided in Table 2 below.

Table 2. Frozen soil vs grouted barrier comparison

	Advantages	Disadvantages
Frozen Soil Barrier	Does not degrade over time.	Requires energy input to remain in place.
	Self healing; fractures due to ground movement begin to refreeze immediately.	Requires maintenance of above-ground mechanical systems.
	Can be installed uniformly in heterogeneous soils.	Not optimal for long-term containment.
	Performance can be predicted by analytical models.	Requires adequate moisture in soil.
	Performance/integrity can be monitored in “real time”.	
	Barrier easily removed.	
Grouted Barrier	After initial installation, no energy input is required.	Fractures due to ground movement must be detected and repaired.
	No mechanical support systems required for operation of barrier.	Performance/integrity not easily monitored in “real time”.
	No above-ground support structures required following installation.	Cannot be easily removed.
		Different grouting techniques (i.e., permeation and jet grouting) may be required for low-permeability and high-permeability materials at same location.
		Not typically applied in fine-grained soils because the process relies on filling soil pore space.

Technology Applicability

Frozen Soil Barriers can be utilized to either contain the subsurface contaminants or immobilize the contaminants within the frozen soil matrix itself. When considering the application of soil freezing technology as an alternative to grouted barriers for containment of subsurface contamination, a number of issues should be considered. Several of these are presented below:

- Frozen Soil Barrier technology can be effectively applied in fine-grained, saturated soils.
- Utilization of Frozen Soil Barriers requires sufficient soil moisture to enable freezing of the area to generate the frozen barrier. Active measures to increase soil moisture content can be used, although laboratory studies conducted in 1994 (Andusland et.al. 1994) indicated the difficulties with uniformly distributing water to all pores. Studies were conducted using Hanford site soils investigating the effects of different contaminants on the freezing process and the process of water addition to arid soils.
- Frozen Soil Barrier technology can be effectively applied in mild as well as severe climate conditions.
- Frozen Soil Barriers are self-healing, thus they are suitable for areas subject to ground movement.
- The proximity of engineered structures (roads, foundations, piping, tanks, etc) must be taken into account when considering the use of Frozen Soil Barriers to avoid potential frost heave effects.
- Subsurface frozen soil thaws slowly, and therefore the technology can be used at remote sites, or locations where immediate on-site response to power loss or other system failure is not possible.
- All types of contaminants can be contained with frozen soil technology but, sites with short-lived radionuclides (such as tritium) may be the best application.
- Low-freezing point contaminants such as trichloroethylene or rapidly moving plumes may require more aggressive freezing techniques (i.e., liquid nitrogen temperatures).
- The technology is best suited to short or medium-term durations (20 years or less). When the barrier is no longer needed, it is easily removed.

Patents/Commercialization/Sponsor

Frozen Soil Barrier technology is commercially available from several vendors, as it has been used in the construction industry for a number of years. This specific demonstration was conducted by AFI. The previous demonstration at Oak Ridge was conducted by RKK, Ltd.

SECTION 5

COST

Methodology

Information in this section was prepared from actual cost data collected from key demonstration participants. Cost data were provided by the DOE – Oak Ridge Operations, the United States Environmental Protection Agency, AFI, Lockheed Martin Energy Systems Inc., Lockheed Martin Energy Research Inc., and Tetratech EM Inc. Total cost includes not only capital costs, but all costs incurred as part of the demonstration project.

An independent cost analysis comparing the Frozen Soil Barrier technology to the baseline, grouted barrier technology, was performed by MSE Technology Applications, Inc. This analysis utilized estimated costs for each barrier at an identical site.

Cost Analysis

The total reported cost for activities associated with demonstrating the Frozen Soil Barrier technology at ORNL's HRE impoundment site was $1,809,000. Major elements of the project along with approximate costs for each element are depicted in Table 3 below.

Table 3. Cost of Frozen Soil Barrier demonstration at HRE impoundment

Project Element/Description:	Cost:
1. Site Infrastructure/Surveys/Site Maintenance Services	$43,000
2. System Design, Fabrication, Procurement, Installation, Start Up	$1,253,000
3. ORNL Site Support; Site Integration and Management; Engineering, ES&H, and Waste Management Support and Oversight	$274,000
4. Barrier Verification	$239,000
Total	**$1,809,000**

One may consider the capital cost of the project as the sum of items 1 and 2 in Table 3. Item 3 includes the costs associated with doing business at the site. These costs were for a first-time demonstration of the technology at a radioactive site. Therefore, costs for follow-on deployments (on a unit cost basis) may be expected to be less, particularly with respect to site support (item 3) and barrier verification activities (item 4). It is also noted that the unique geologic conditions at the HRE impoundment site required several design approaches, including membrane installation and freezing completely to grade, which may not be required on other containment projects.

Key results of a cost analysis comparing the Frozen Soil Barrier and a grouted barrier at a contaminated site are summarized in Table 4 below. With the exception of the annual operating costs, estimated Frozen Soil Barrier costs are shown as fractions of the estimated baseline (grouted barrier) costs, which are represented by a value of 1.00.

Table 4. Cost comparison, grouted barrier vs Frozen Soil Barrier

	Grouted Barrier (Baseline)	Frozen Soil Barrier
Initial Capital Cost	1.00	0.77
5-Year Net Present Value (NPV) Cost (includes salvage and decommissioning)	1.00	0.57
20-Year Net Present Value (NPV) Cost (no salvage, minimum decommissioning)	1.00	1.30
Annual Operating Costs	$0	$22,000

Based on the independent cost analysis, the Frozen Soil Barrier may be expected to be less costly for initial installation and operation. The "break-even point", or period of operation at which NPV costs for each barrier are similar, is estimated to be approximately eight-to-nine years.

Cost Conclusions

Unit costs of the Frozen Soil Barrier may be determined from the total project cost of $1,809,000 and selected parameters of the barrier presented in Section 3. Unit costs can be determined as either the volume of frozen soil (i.e., length of barrier) or as the volume of contaminated soil contained (i.e., source area mitigated). These unit costs for the demonstration are shown in Table 5 below:

Table 5. Unit costs, Frozen Soil Barrier

Barrier Parameter:	Unit Cost:
Frozen Soil Volume	$16.75/Cubic Foot
Volume Contained	$10.72/ Cubic Feet

While scaling of unit costs is common for estimating costs of follow-on deployments, caution must be used. The Frozen Soil Barrier installed at the HRE impoundment is a small demonstration. Extrapolating demonstration costs for estimating large-scale deployment costs may lead to substantially inflated estimates. As a specific example, AFI has projected that a Frozen Soil Barrier project 2 to 3 times the size of that at ORNL could be performed with no additional increase in the number (or cost) of on-site project management, health, and safety personnel.

When compared to grouting, it is estimated that Frozen Soil Barrier costs, while initially less, become equivalent to grouted barrier costs after an eight-to-nine year operating period. The break-even period must be balanced with the inherent benefits a Frozen Soil Barrier offers over grouting for specific applications.

Electrical power usage, a drawback to conventional methods of achieving and maintaining frozen soil, was a positive aspect with the thermoprobe technology. Approximately 72,000 kilowatt hours of electrical power was required to establish the barrier, which equates to a cost of less than $4000 at ORNL rates ($0.052 per kilowatt hour). Over a one-year operating period, power consumption for maintenance of the Frozen Soil Barrier has averaged about 288-kilowatt hours per day (less than $15/day).

SECTION 6

REGULATORY AND POLICY ISSUES

Regulatory Considerations

The Frozen Soil Barrier project was an innovative technology demonstration. Because it was not a remediation or removal action, CERCLA requirements were not applicable and evaluation of the nine CERCLA criteria was not conducted, although many of the criteria are addressed in other sections of this document. A NEPA CX was granted for installation of the system at ORNL. System emissions during operation were limited to water condensate and heat, typical of commercial refrigeration systems, requiring no special operating permits.

An underground injection permit was issued by TDEC for pre-barrier dye tracing study. However, no injection permit was required for post-barrier dye tracing.

Radiologically contaminated drill cuttings were managed in accordance with ORNL waste management procedures.

Safety, Risks, Benefits, and Community Reaction

Worker Safety

- The primary health and safety concerns during system installation are associated with drilling activities. Because the site contains subsurface radioactive contaminants, careful work planning and continuous monitoring of site conditions during drilling were paramount.
- Radioactively contaminated drill cuttings generated during installation were managed in accordance with ORNL waste management procedures.
- Installation of the system was completed with no safety-related incidents or occurrences.
- Operation of the system typically does not require the presence of personnel at the site. No health or safety concerns beyond those for commercial refrigeration systems exist during maintenance activities.

Community Safety

- Operation of the Frozen Soil Barrier system produces no release of contaminants, which remain isolated in-situ.
- Non-toxic materials are utilized as the working fluids in both the passive and active portions of the system (carbon dioxide and R404a, respectively).

Environmental Impacts

- Drilling for installation of thermoprobes is required. Drill cuttings generated can be expected to be tainted with contaminants and must be managed accordingly.
- In mild climates, refrigeration units can be expected to operate continuously with accompanying compressor noise.
- Refrigerants with “zero ozone-depletion” factors are utilized in refrigeration units.

- Working fluids used in the hybrid thermoprobe system are non-corrosive and will not attack piping, refrigeration unit components, or thermoprobes.
- Working fluids in the system are not miscible with water, and will therefore not degrade the Frozen Soil Barrier if a subsurface leak were to occur.
- Subsurface components are externally corrosion-protected.
- In the event of a loss of refrigeration failure mode, the Frozen Soil Barrier can be expected to maintain integrity for a considerable period of time (weeks to months) before breaching becomes a concern.

Socioeconomic Impacts and Community Perception

- Installation and operation of Frozen Soil Barriers will have minimal impact on the local labor force or economy.
- The general public has limited familiarity with freezing the soil as a barrier to subsurface contaminant migration.

SECTION 7

LESSONS LEARNED

Implementation Considerations

- Verification of the integrity of the Frozen Soil Barrier at the HRE impoundment was problematic due to the complex hydrology and pre-existing conditions (i.e., presence of an abandoned buried pipeline) at the site. Future deployments would benefit from characterizing site conditions to the extent possible prior to system design and installation.
- On-going groundwater collection and pumping operations in nearby facilities induced local groundwater responses that affected barrier verification studies. These operations were not identified early in the project, and resulted in significantly more data analysis and evaluation than originally planned.
- It is uncertain if the barrier was installed around the most serious contamination source at the project site. While this did not affect demonstration of the technology as an effective barrier, it does have implications to long-term operation of the barrier at the HRE impoundment.

Technology Limitations and Needs for Future Development

- Effectiveness of the frozen soil technology for containment of contaminants in dry soils has not been demonstrated. Further development of suitable methods of homogeneously adding and retaining moisture in arid soils is needed.

Technology Selection Considerations

- The Frozen Soil Barrier demonstration utilized existing, commercially available technology. Design of system hardware is mature and is of known reliability.
- The refrigeration plant was oversized for this demonstration in order to achieve rapid freeze-down. Capital equipment costs can therefore be traded against barrier formation time.
- While the proprietary hybrid thermoprobe system design was used in this system, other mechanisms for forming the Frozen Soil Barrier can be employed, although similar performance may not be realized.
- Competent local bedrock was utilized as the “bottom” of the barrier. While suited for the HRE impoundment, applications at other sites may consider alternate design shapes.
- The use of a surface insulation and membrane system was dictated by the existing site conditions. These elements may not be necessary or required at other sites.

Appendix A

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Appendix B

SELECTED GROUNDWATER DATA

Pre- and post-barrier groundwater level and temperature data were recorded and analyzed for a number of locations at the demonstration site. A summary of the data for three monitoring points, I2 (center of impoundment, inside barrier), S5 (down gradient, outside southeast corner of barrier), and S10 (upgradient, outside north west corner of barrier) is presented below (from Moline, G.R., 1998). The elevations of the geologic features (e.g., berm) shown in each of the hydrographs (Figures B-1, B-2, and B-3) are purely estimates.

Monitoring Point I2 (Figure B-1): Connection to high permeability exists because of the rapid drainage down to that level after rain events. The water level data during the long slow decline prior to the post-barrier dye tracer injection have been smoothed to remove the noise created by lack of maintenance of the transducers during that period. The data can really only show the declining trend, which is probably a combination of slow drainage through the base of the pond and wicking of water to the barrier walls as they develop.

The jump in water level occurring just before the tracer injections resulted from changeover of the monitoring equipment and installation of a downhole Troll datalogger, which caused a volume displacement within the standpipe. That is not the water level in the impoundment -- it would take some time for the water level in the standpipe to drop because that part of the standpipe is surrounded by low permeability material. Thus, it will follow the same slow decline as before.

The spikes after monitoring equipment change over all correspond to injections of water into the standpipe to flush the tracer. There have been NO responses to precipitation events during any of the time that the Troll has been in place.

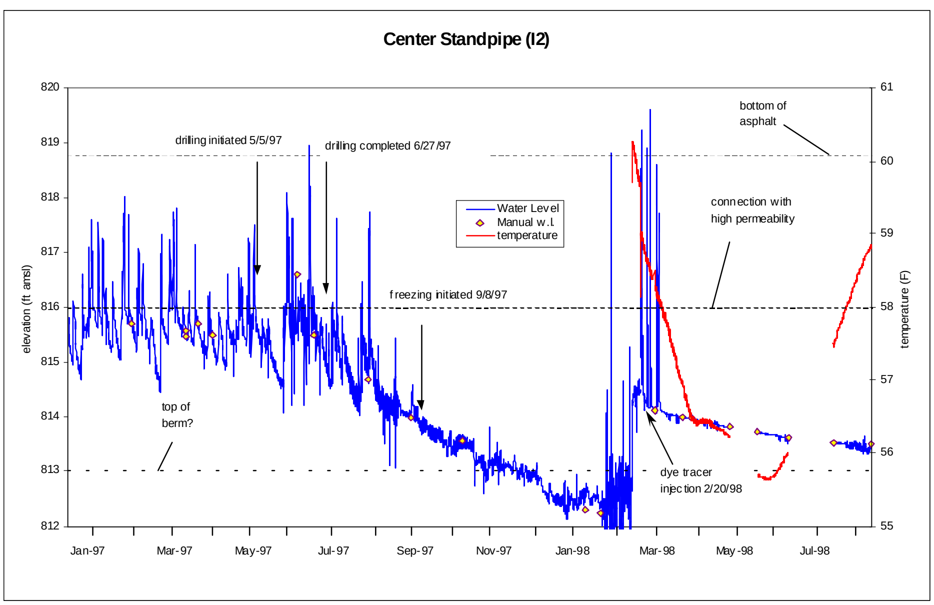

Figure B-1. Hydrograph for Monitoring Point I2.

Monitoring Point S10 (Figure B-2): This plot shows the "flashiness" of the storm response characteristic of the entire area surrounding the impoundment. What these data show is the fact that the storm response and seasonal temperature fluctuations upgradient of the pond have not changed during the period of record. This supports the interpretation of changes in wells downgradient of the barrier as resulting from the barrier and not from any overall change in the region not related to the barrier. S10 may be considered as the upgradient control well.

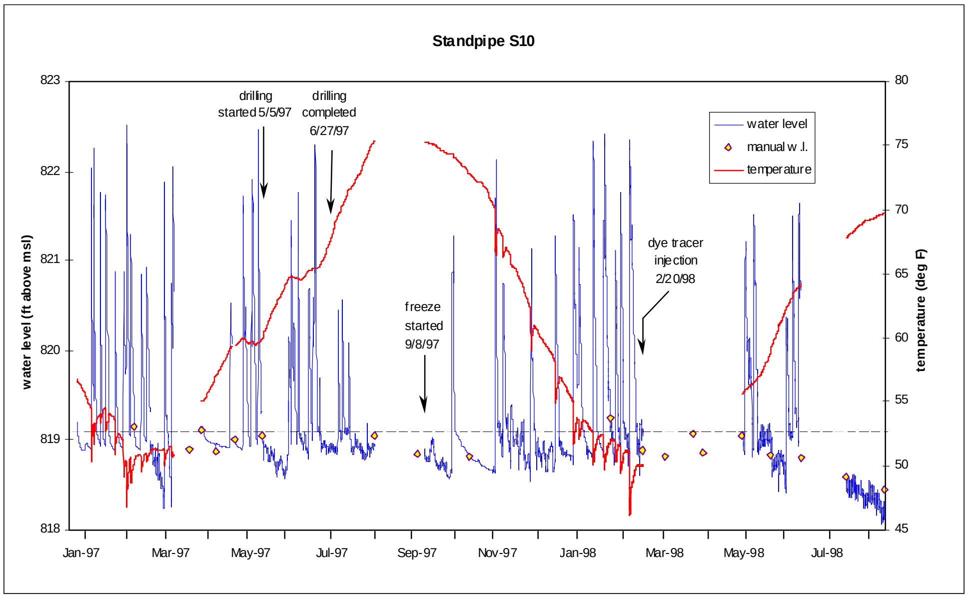

Figure B-2. Hydrograph for Monitoring Point S10

Monitoring Point S5 (Figure B-3): This well represents a downgradient response to emplacement of the barrier. There is an overall drop of around 5 feet, presumably as water is diverted around the barrier. There is also a significant drop in the winter low temperature as compared to the winter before the barrier was in place. The storm response returns after the water level stabilizes to a new average, and is probably caused by water moving rapidly along the original drainage features surrounding the impoundment which would now be subsurface preferential flow pathways.

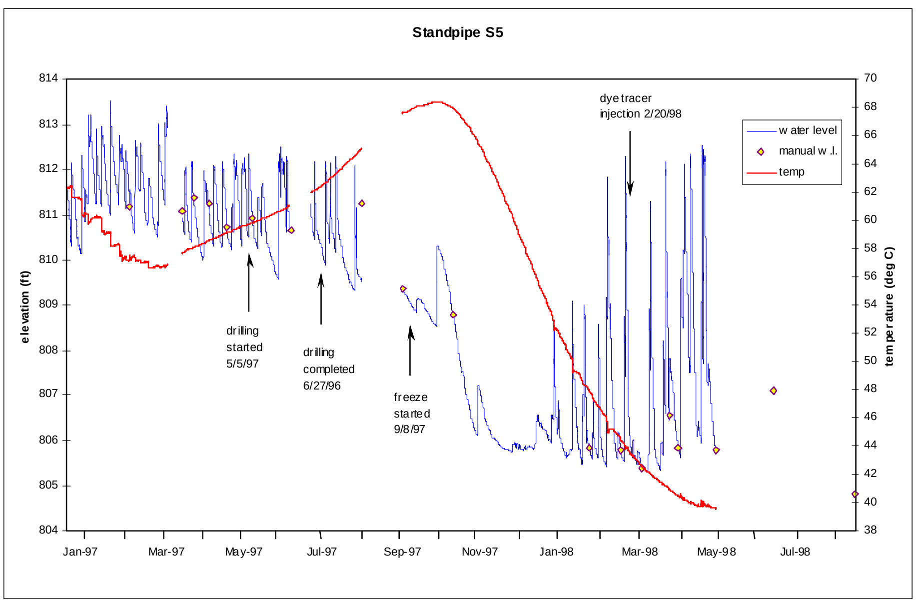

Figure B-3. Hydrograph for Monitoring Point S5