EPA United States Environmental Protection Agency

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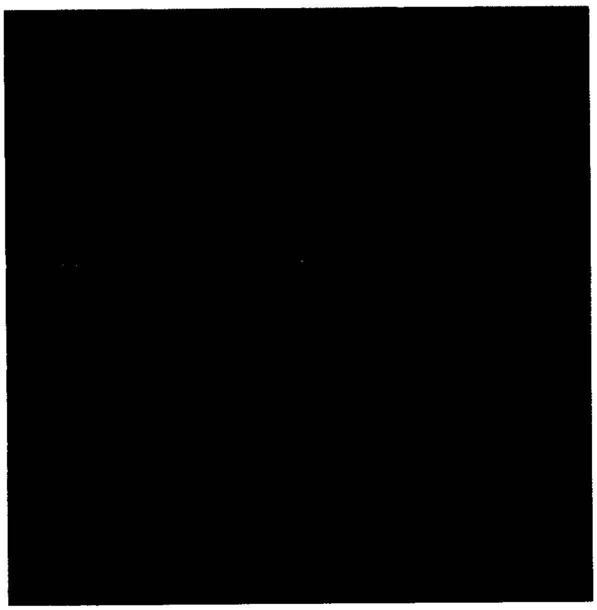
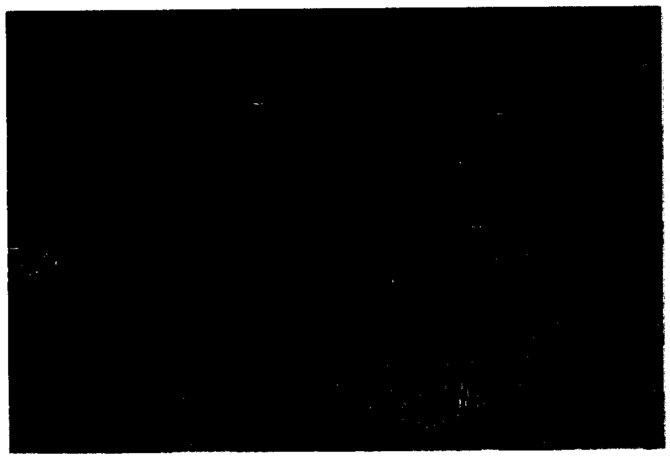
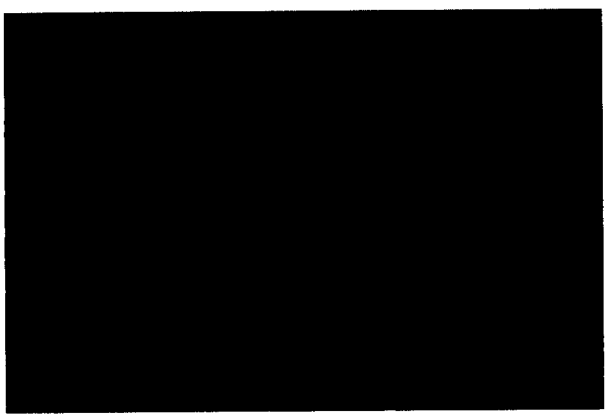
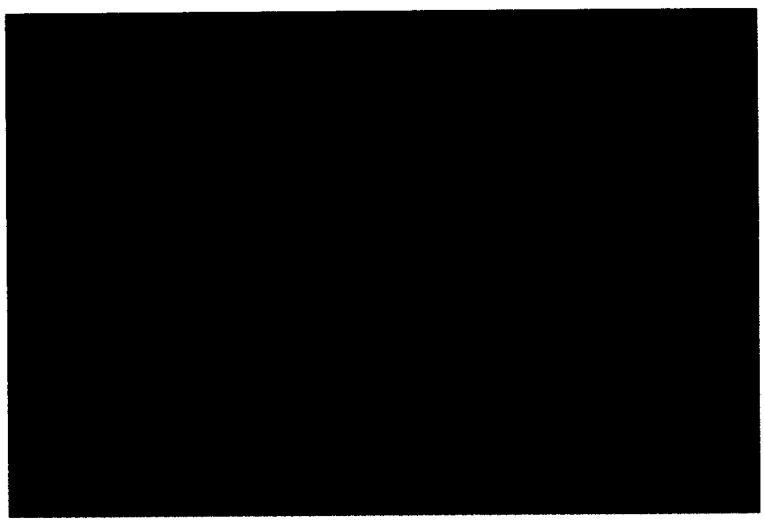
Arctic Foundations, Inc. Freeze Barrier Technology

Innovative Technology Evaluation Report









SITE

SUPERFUND INNOVATIVE TECHNOLOGY EVALUATION

SM-X7

EPA/540/R-03/508
September 2004

Arctic Foundations, Inc.
Freeze Barrier Technology

Innovative Technology Evaluation Report

National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

Notice

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Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and groundwater; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Larry Rieter, Acting Director
National Risk Management Research Laboratory

Abstract

Arctic Foundations, Inc. (AFI), of Anchorage, Alaska has developed a freeze barrier technology designed to prevent the migration of contaminants in groundwater by completely isolating contaminant source areas until appropriate remediation techniques can be applied. With this technology, contaminants are contained in situ with frozen native soils serving as the containment medium. The U.S. Environmental Protection Agency's (EPA) Superfund Innovative Technology Evaluation (SITE) Program evaluated the technology at the U.S. Department of Energy's (DOE) Oak Ridge National Laboratory facility in Oak Ridge, Tennessee from September 1997 to July 1998.

For the evaluation, an array of freeze pipes called "thermoprobes" were installed in a box-like structure around a former waste collection pond. The thermoprobes were installed vertically to a depth of 32 feet below ground surface and anchored in bedrock. The thermoprobes were connected to a refrigeration system by a piping network. A cooled refrigerant (R404A) was circulated through the system to remove heat from the soil. When the soil matrix next to the pipes reached 0 °C, soil particles bonded together as the soil moisture froze. Cooling continued until an impermeable frozen soil barrier was formed.

After the barrier wall reached its design thickness of 12 feet, the groundwater level within the former pond dropped, indicating that the barrier wall was effective in impeding recharge into the former pond. Further, water levels collected from within the former pond did not respond to storm events compared to water levels collected from locations outside the containment area, indicating that the barrier wall was effective in impeding horizontal groundwater flow through the former pond. Finally, a 1996 groundwater tracing investigation showed groundwater transport from the former pond area in a radial pattern which was not the case during the demonstration groundwater tracing investigation.

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Appendix

Attachment

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Figures (Cont'd.)

Tables

Acronyms, Abbreviations and Symbols

ARAR	Applicable or relevant and appropriate requirement
AEA	Atomic Energy Act
AFI	Arctic Foundations, Inc.
bgs	Below ground surface
CAA	Clean Air Act
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
Cs	Cesium
CWA	Clean Water Act
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
HRE	Homogeneous reactor experiment
HVAC	Heating, ventilation, and air conditioning
ITER	Innovative Technology Evaluation Report
kWh	Kilowatt-hour
MCL	Maximum contaminant level
MCLG	Maximum contaminant level goal
Means	R.S. Means Company, Inc.
mg/kg	Milligrams per kilogram
Mrad/hour	Milliradian per hour
MSE	MSE Technology Applications, Inc.
MSL	Mean sea level
NPDES	National Pollutant Discharge Elimination System
NPV	Net Present Value
NRC	Nuclear Regulatory Commission
NRMRL	National Risk Management Research Laboratory
O&M	Operation and maintenance
ORD	U.S. EPA Office of Research and Development

Acronyms, Abbreviations and Symbols (Cont'd.)

ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Act
OSWER	Office of Solid Waste and Emergency Response
POTW	Publicly owned treatment works
ppb	parts per billion
PPE	Personal protective equipment
QAPP	Quality assurance project plan
QA/QC	Quality assurance/quality control
RCRA	Resource Conservation and Recovery Act
RTD	Resistance temperature detector
SARA	Superfund Amendments and Reauthorization Act
SITE	Superfund Innovative Technology Evaluation
Sr	Strontium
TDEC	Tennessee Department of Environmental Conservation
UIC	Underground injection control
VOC	volatile organic compound

Conversion Factors

	To Convert From	*To*	*Multiply By*
Length:	inch	centimeter	2.54
	foot	meter	0.305
	mile	kilometer	1.61
Area:	square foot	square meter	0.0929
	acre	square meter	4,047
Volume:	gallon	liter	3.78
	cubic foot	cubic meter	0.0283
Mass:	pound	kilogram	0.454
Energy:	kilowatt-hour	megajoule	3.60
Power:	kilowatt	horsepower	1.34
Temperature:	(°Fahrenheit - 32)	°Celsius	0.556

Acknowledgments

This report was prepared for U.S. Environmental Protection Agency's (EPA) Superfund Innovative Technology Evaluation (SITE) Program by Tetra Tech EM Inc. (*formerly PRC Environmental Management, Inc.*) under the direction and coordination of Mr. Steve Rock, project manager for the SITE Program in the National Risk Management Research Laboratory, Cincinnati, Ohio.

Special acknowledgment is given to Mr. Ed Yarmak of Arctic Foundations, Inc.; Ms. Elizabeth Phillips and Dr. Gerilynn Moline of the U.S. Department of Energy; Gareth Davies of Cambrian Groundwater Company; and Dr. Sidney Jones and Mr. John Sebastian of the Tennessee Department of Environmental Conservation for their cooperation and support during the SITE Program demonstration and during the development of this report.

EXECUTIVE SUMMARY

Arctic Foundations, Inc. (AFI), originally developed the freeze barrier technology to give load-bearing strength to soils during excavation activities and construction of subsurface structures. The technology of freezing soils has just recently been considered for use as a containment technology to isolate a contaminant source area. AFI's freeze barrier technology was demonstrated under the U.S. Environmental Protection Agency's (EPA) Superfund Innovative Technology Evaluation (SITE) Program from September 1997 to July 1998 at the U.S. Department of Energy's (DOE) Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee.

The purpose of this Innovative Technology Evaluation Report (ITER) is to present information that will assist Superfund decision-makers in evaluating the freeze barrier technology for application at a particular hazardous waste site. The report provides an introduction to the SITE Program and the freeze barrier technology and discusses the demonstration objectives and activities (Section 1); evaluates the technology's effectiveness (Section 2); analyzes key factors pertaining to application of this technology (Section 3); analyzes the costs of using the technology to impede waterborne contaminants (Section 4); summarizes the technology's current status (Section 5); and presents a list of references (Section 6). Analytical data for groundwater and surface water samples collected during the demonstration are included in the appendix. Vendor's claims are included in the attachment.

This executive summary briefly summarizes the information discussed in the ITER and evaluates the technology with respect to the nine criteria used in Superfund feasibility studies.

Technology Description

The use of frozen barrier technology as a hazardous waste control/containment technology typically involves the installation of an array of freeze pipes (thermoprobes) around and often beneath a contaminant source area in an effort to seal off a hazardous waste area, thereby preventing further migration of contaminants. Thermoprobes are typically installed in a "V" or "U" configuration to ensure complete encapsulation and isolation of a waste source. This type of installation is accomplished by placing the thermoprobes within closely spaced, directional boreholes. Standard drilling techniques are normally used to create boreholes that house the thermoprobes. A "V" or "U" configuration is not always necessary or possible. In certain geological settings, where downward migration of contaminants is limited by a lithologic unit that is characterized by very low permeability, and when such a unit occurs at a shallow depth, thermoprobes may be installed in a vertical position, with the bottoms of the thermoprobes anchored in the unit. The arrangement of the thermoprobes to create a frozen barrier wall ultimately depends on the topography and underground disposition of the waste to be contained. For the freeze barrier wall to be effective, the waste source must be completely surrounded by the frozen soil barrier, or a combination of the frozen barrier and other impermeable features, limiting and perhaps preventing groundwater movement into and out of the waste source. To limit hydraulic loading due to direct infiltration of precipitation, the surface of the enclosed waste area is typically sealed. AFI claims that the technology can contain most known biological, chemical, and radioactive contaminants.

Once installed, the thermoprobes are connected to a refrigeration system through a piping network. A two-phase refrigerant is circulated through the system to remove heat from the soil, with the heat being dissipated to the air. When the soil matrix next to the pipes reaches 0 °C, soil particles are bonded together as soil moisture freezes. Cooling is continued until the frozen region around each thermoprobe begins to expand and build outward, coalescing with frozen regions developed around other thermoprobes until a continuous impermeable, frozen soil barrier is formed.

Overview of the Freeze Barrier Technology SITE Demonstration

The SITE demonstration of the freeze barrier technology occurred between September 1997 and July 1998. The demonstration site was a former surface impoundment known as the Homogeneous Reactor Experiment (HRE) Pond in Waste Area Grouping 9 at ORNL. The HRE pond's surface measured roughly 75 feet by 80 feet with sides sloping to a bottom measuring 45 feet by 50 feet. The HRE pond served as a retention/settling basin and received low-level radioactive liquid wastes. The HRE pond also received high levels of fission products and shield water from a chemical processing system. Past sediment and groundwater samples collected from the HRE pond area indicate the presence of radioactive contaminants including cesium^{137}, strontium^{90}, and tritium.

For the SITE Program demonstration, a ground freezing system was constructed around the former pond to determine the effectiveness of the technology in impeding groundwater flow into and out of the former pond. The system incorporated an array of thermoprobes that were installed in oversized drill holes, spaced about 6 feet apart, to form a 75 foot by 80 foot box-like structure around the former pond. The thermoprobes were installed vertically to a depth of 30 feet below ground surface and anchored in bedrock.

The thermoprobe is an innovative closed, two-phase system that can be used in both an active and passive mode. This active-passive system, called a "hybrid thermosyphon," is commonly used in temperate locations where reliance on low ambient temperatures (the passive mode application) is not feasible. The hybrid thermosyphon system consists of multiple thermoprobes, an active powered refrigeration unit, a two-phase active/passive refrigerant, a piping system, and a control system. Once installed, the thermoprobes were connected to the refrigeration unit, where the working fluid was circulated within the closed system to remove heat from the thermoprobe. For the demonstration, R-744 (carbon dioxide) was used as the passive refrigerant and R-404A (carbon dioxide) was used as the active refrigerant in the system. To monitor progress of the freeze barrier wall, a series of subsurface temperature monitoring points were installed at strategic locations.

The primary objective of the SITE demonstration was as follows:

- Determine the effectiveness of the freeze barrier wall in preventing horizontal groundwater flow beyond the limits of the frozen soil barrier through the performance of a groundwater tracing investigation using a fluorescent dye

The secondary objectives of the demonstration were as follows:

- Verify whether flow pathways outside the former pond are still open after placement of the frozen soil barrier
- Evaluate hydrogeologic isolation of the enclosed area before and after placement of the frozen soil barrier
- Monitor development of the frozen soil barrier
- Document installation and operating parameters of the freeze barrier wall

Prior to conducting the groundwater tracing investigation, a background study was conducted to determine if any dyes still remained in the groundwater system from previous tracer studies and to identify natural background fluorescence. Following the background study, the dye phloxine B was injected into a standpipe located in the center of the former pond. Groundwater and surface samples were collected and analyzed for phloxine B from February through July 1998. Samples were also collected and analyzed for the dye eosine OJ which was injected into an upgradient monitoring well. Groundwater and surface water samples were collected from the same dye recovery points that were used during a groundwater tracing investigation conducted by EPA Headquarters in 1996. These recovery points included a series of monitoring wells, piezometers, standpipes, springs, and a nearby tributary. Field measurements of subsurface soil temperatures and groundwater elevations were also performed to evaluate system performance.

SITE Demonstration Results

The following items summarize the significant results of the SITE demonstration:

- The frozen soil barrier reached its design thickness of 12 feet about 18 weeks following system startup and was maintained at an average power consumption rate of about 300 kilowatt-hours per day. Subsurface temperature data collected from temperature monitoring points demonstrated that the soil was frozen from the ground surface down to a depth of about 30 feet. The total volume of soil frozen is estimated at about 134,000 cubic feet and the total volume of soil isolated within the area enclosed by the barrier at about 180,000 cubic feet.

- Following establishment of the frozen soil barrier, water level data collected from within the barrier wall showed a drop in the water table elevation and a lack of response to storm events compared to locations outside the former pond, indicating that the barrier wall was effective in impeding recharge into the former pond.

- Tracer data collected during the demonstration show that the barrier was effective in impeding horizontal groundwater flow, with the exception of a breach in the northwest corner likely attributed to a subsurface pipe left in place after the former pond was closed or fractured bedrock.

- The barrier can be expected to maintain its integrity for several weeks following a loss of power or refrigeration as demonstrated during the technology demonstration.

- Results of the SITE demonstration show that subsurface engineering structures may interfere with the formation of a frozen soil barrier and preclude the use of this technology at some sites.

Economics

Using information from the SITE demonstration, AFI, and other sources, an economic analysis was conducted that examined 12 cost categories for two different applications of the freeze barrier technology. The first case (Case 1) presents a cost estimate for extending the use of the freeze barrier technology at the HRE pond site over a 5-year period. The second case (Case 2) is based on applying the freeze barrier technology to a Superfund site over a 10-year period. The cost estimate for Case 2 assumes that site conditions and contaminants were similar to those encountered at the HRE pond site, with the exception of the size of the containment area. Case 2 assumes that the area requiring containment is about 900,000 cubic feet. Based on these assumptions, the total cost per unit volume of frozen soil was about $8.30 per cubic foot for Case 1 and $8.50 per cubic foot for Case 2. The cost per unit volume of waste isolated decreased with increased size of the containment area which was about $6.50 per cubic foot for Case 1 and $2.80 per cubic foot for Case 2. Costs for applications of the freeze barrier technology may vary significantly from these estimates, depending on site-specific factors.

Superfund Feasibility Study Evaluation Criteria for the Freeze Barrier Technology

Table ES-1 briefly discusses an evaluation of the freeze barrier technology with respect to the nine evaluation criteria used for Superfund feasibility studies when considering remedial alternatives at Superfund sites (EPA 1988b).

TABLE ES-1

SUPERFUND FEASIBILITY STUDY EVALUATION CRITERIA [a] FOR THE FREEZE BARRIER TECHNOLOGY

Criterion	Discussion
Overall Protection of Human Health and the Environment	• The technology is expected to protect human health and the environment by preventing the further spread of waterborne contaminants until appropriate remediation techniques can be applied. • Requires measures to protect workers during drilling and installation activities.
Compliance with Applicable or Relevant and Appropriate Requirements (ARAR)	• Requires compliance with RCRA storage and disposal regulations for hazardous waste and pertinent Atomic Energy Act, DOE, and Nuclear Regulatory Commission requirements for radioactive or mixed waste. • Drilling, construction, and operation of a ground freezing system may require compliance with location-specific ARARs.
Long-Term Effectiveness and Permanence	• The treatment provides containment of wastes for as long as freezing conditions are maintained or until remediation techniques can be applied. • Periodic review of ground freezing system performance is needed because application of this technology to hazardous waste sites with contaminated groundwater is relatively recent.
Reduction of Toxicity, Mobility, or Volume Through Treatment	• A properly installed frozen soil barrier can isolate a contaminant source area without excavation, decreasing the potential for waste mobilization.
Short-Term Effectiveness	• The speed of development of the barrier wall may vary depending on site hydrogeology, topography, soil moisture content, soil type, and climate.
Implementability	• Hydrogeologic conditions should be well-defined prior to implementing this technology. The technology is most easily implemented at shallow depths; however, companies that employ this technology claim that barriers can be established to depths of 1,000 feet or more and can be used in both vadose and saturated zones. • The site must be accessible to standard drilling and other heavy equipment and delivery vehicles. • The actual space requirements depend on the size of the containment area and thickness of the barrier wall.

TABLE ES-1 (Continued)

SUPERFUND FEASIBILITY STUDY EVALUATION CRITERIA [a] FOR THE FREEZE BARRIER TECHNOLOGY

Criterion	Discussion
	• Ice does not degrade or weaken over time and is repairable in situ. The barrier wall is simply allowed to melt upon completion of containment needs and thermoprobes are removed. • Subsurface structures may interfere with the formation of a frozen soil barrier. • The formation of a frozen soil barrier in arid conditions may require a suitable method for adding moisture to the soils to achieve saturated conditions prior to barrier wall development.
Cost	• For a frozen soil barrier applied to a site that is 150 feet by 200 feet in size and operating for 10 years under some of the same general conditions observed at the HRE pond site, total estimated fixed costs are estimated to be about $1,903,700. Annual operating and maintenance costs, including those for utilities, supplies, analytical services, labor, and equipment maintenance are estimated to be about $63,200.
Community Acceptance	• This criterion is generally addressed in the record of decision (ROD) after community responses are received during the public comment period. However, because communities are not expected to be exposed to harmful levels of contaminants, noise, or fugitive emissions, community acceptance of the technology is expected to be high.
State Acceptance	• This criterion is generally addressed in the ROD; state acceptance of the technology will likely depend on the long-term effectiveness of the technology.

Note:

[a] EPA. 1988b. CERCLA *Compliance with Other Environmental Laws: Interim Final.* OSWER. EPA/540/G-89/006. August.

1.0 INTRODUCTION

This section describes the Superfund Innovative Technology Evaluation (SITE) Program and the Innovative Technology Evaluation Report (ITER); provides an overview and application of frozen soil barriers; presents background information on the Arctic Foundations, Inc. (AFI), freeze barrier technology; provides an overview and objectives of the SITE demonstration; and lists key contacts.

1.1 DESCRIPTION OF SITE PROGRAM AND REPORTS

This section provides information about (1) the purpose, history, and goals of the SITE Program, and (2) the reports used to document SITE demonstration results.

1.1.1 Purpose, History, and Goals of the SITE Program

The primary purpose of the SITE Program is to advance the development and demonstration, and thereby establish the commercial availability, of innovative treatment technologies applicable to Superfund and other hazardous waste sites. The SITE Program was established by the U.S. Environmental Protection Agency (EPA) Office of Solid Waste and Emergency Response (OSWER) and Office of Research and Development (ORD) in response to the Superfund Amendments and Reauthorization Act of 1986 (SARA), which recognizes the need for an alternative or innovative treatment technology research and demonstration program. The SITE Program is administered by ORD's National Risk Management Research Laboratory (NRMRL) in Cincinnati, Ohio. The overall goal of the SITE Program is to carry out a program of research, evaluation, testing, development, and demonstration of alternative or innovative treatment technologies that can be used in response actions to achieve more permanent protection of human health and welfare and the environment.

The SITE Program consists of four component programs: (1) the Demonstration Program, (2) the Emerging Technology Program, (3) the Monitoring and Measurement Technologies Program, and (4) the Technology Transfer Program. This ITER was prepared under the SITE Demonstration Program. The objective of the Demonstration Program is to provide reliable performance and cost data on innovative technologies so that potential users can assess a given technology's suitability for a specific site cleanup. To produce useful and reliable data, demonstrations are conducted at hazardous waste sites or under conditions that closely simulate actual waste site conditions. The program's rigorous quality assurance/quality control (QA/QC) procedures provide for objective and carefully controlled testing of field-ready technologies. Innovative technologies chosen for a SITE demonstration must be pilot- or full-scale applications and must offer some advantage over existing technologies.

Implementation of the SITE Program is a significant, ongoing effort involving ORD, OSWER, various EPA regions, and private business concerns, including technology developers and parties responsible for site remediation. Cooperative agreements between EPA and the innovative technology developer establish responsibilities for conducting the demonstrations and evaluating the technology. The developer is typically responsible for demonstrating the technology at the selected site and is expected to pay any costs for the transport, operation, and removal of related equipment. EPA is typically responsible for project planning, site preparation, technical assistance support, sampling and analysis, QA/QC, report preparation, information dissemination, and transport and disposal of treated waste materials.

1.1.2 Documentation of SITE Demonstration Results

The results of each SITE demonstration are reported in an ITER. Information presented in the ITER is intended to assist Superfund decision-makers in evaluating specific technologies for a particular clean-up situation. The ITER represents a critical step in the development and commercialization of a technology. The ITER discusses the effectiveness and applicability of the technology, summarizes the overall data quality, and analyzes costs associated with its application. The technology's effectiveness is evaluated based on data collected during the SITE demonstration and from other case studies. The applicability of the technology is discussed in terms of waste and site characteristics that could affect technology performance, material handling requirements, technology limitations, and other factors for application of the technology.

1.2 OVERVIEW AND APPLICATION OF FROZEN SOIL BARRIERS

Artificially frozen soil barriers have been used for over 100 years in the mining and construction industries (AFI 1998). The technology has been used in a variety of settings, including dam, tunnel, and highway construction. The process has recently been considered as a control and containment technology in the hazardous waste remediation industry. With this type of application, contaminants are contained in situ with native soils serving as a subsurface barrier. In theory, a frozen soil barrier is impermeable to aqueous phase waste and can thus provide subsurface containment for a variety of sites, including underground tanks, nuclear waste sites, groundwater plumes, burial trenches, in situ waste treatment areas, and ponds. Each application is site-specific and must take into account a number of factors that include, but are not limited to, waste type, topography, overall site hydrogeology, soil moisture content, subsurface structures, soil types, and thermal conductivity.

Thermoprobes may be installed in a "V" or "U" configuration to ensure complete encapsulation and isolation of a waste source (AFI 1998). This type of installation is accomplished by placing the thermoprobes within closely spaced directional boreholes. Standard drilling techniques are normally used to create boreholes that house the thermoprobes. In certain geological settings, where downward migration of contaminants is limited by a very low permeability clay or bedrock unit, and when such a unit occurs at a shallow depth, thermoprobes can be installed in a vertical position with the bottoms of the pipes anchored in the unit, which acts as a basal bottom confining layer.

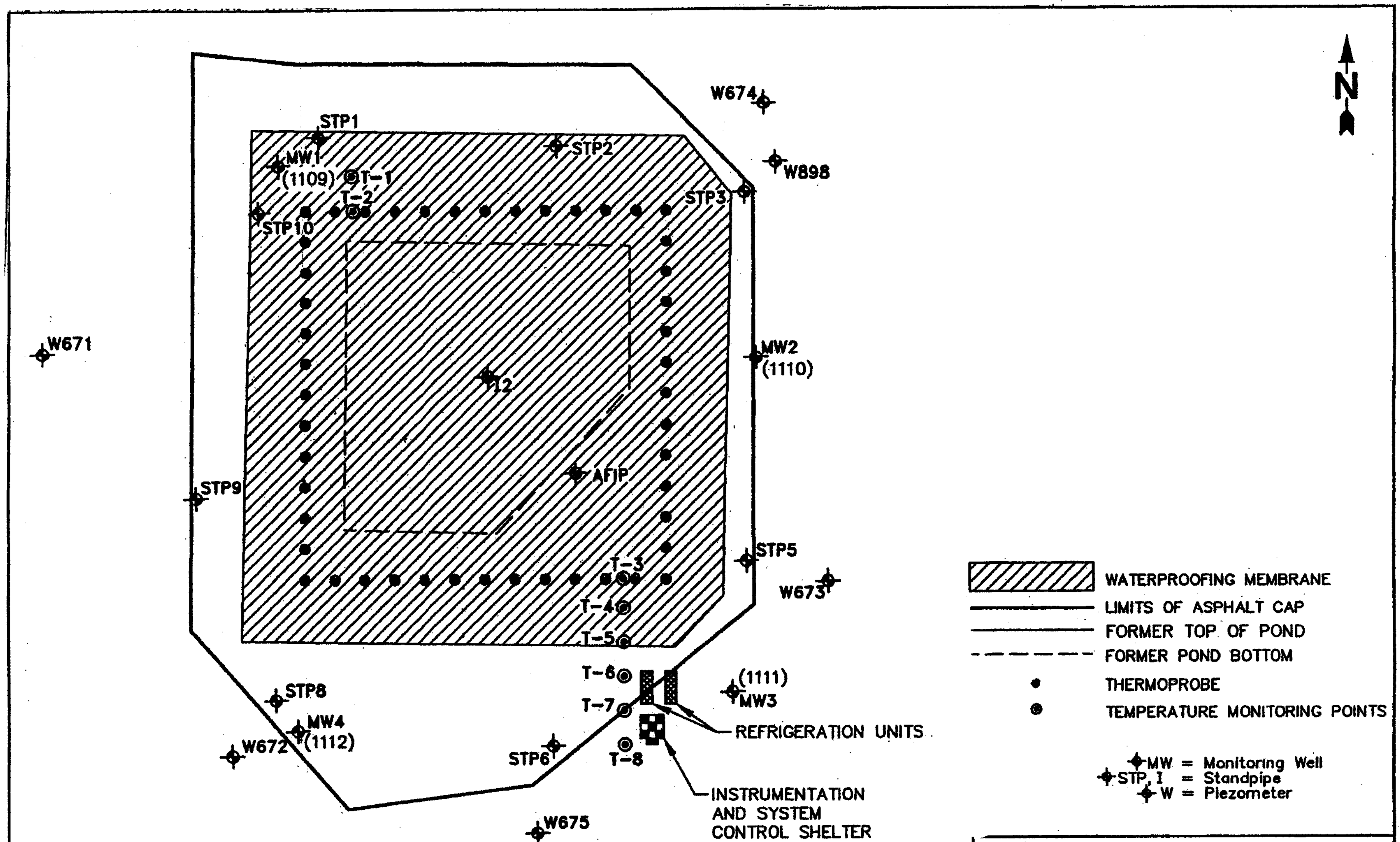
The arrangement of the thermoprobes to create a frozen barrier wall ultimately depends on the topography and underground disposition of the waste material. For a freeze barrier wall to be effective, the waste source must be completely surrounded by the frozen soil barrier, thereby preventing groundwater movement into and out of the waste source. To limit hydraulic loading due to direct infiltration of precipitation, the surface of the enclosed waste area is sealed. Once installed, the thermoprobes are connected to a refrigeration system by a distributive manifold. A two-phase refrigerant is circulated through the system to remove heat from the soil, with the heat being dissipated to the air. When the soil matrix next to the pipes reaches 0 °C, soil particles are bonded together as soil moisture freezes. Cooling is continued until the frozen region around each pipe begins to expand and build outward, coalescing with frozen regions developed around other pipes until a continuous, impermeable frozen soil barrier is formed. Barrier wall thickness and temperature will vary depending on site conditions.

1.3 AFI FREEZE BARRIER TECHNOLOGY

For the SITE demonstration, AFI used an innovative thermoprobe to demonstrate the capabilities of its freeze barrier technology. A standard AFI thermoprobe removes heat from the soil by acting as a thermosyphon. A thermosyphon removes heat passively, which means that soil can be frozen or maintained in the frozen state without the need for an external supply of energy or power. The thermosyphons function using a two-phase working fluid. The working fluid is contained in the thermoprobe, which is partially buried. In cold climates, particularly in permafrost regions, thermosyphons are used to maintain a frozen subgrade for foundation stability purposes. In these situations, the thermosyphons operate in a passive mode. In this case, the aboveground portion is subjected to cold ambient air, which cools and condenses the working fluid. The condensate flows by gravity to below ground level, where it encounters a warmer regime, warms, vaporizes and rises upward again to repeat the cycle.

AFI used a closed two-phase system that can be used in an active-passive mode and is applicable when the ambient air temperature is above freezing. Such active-passive systems are called "hybrid thermosyphons" and are often used in more temperate locations where reliance on low ambient air temperatures (passive mode application) is not feasible. AFI's ground freezing system deployed at the U.S. Department of Energy's (DOE) Oak Ridge National Laboratory (ORNL) homogeneous reactor experiment (HRE) pond site included 50 thermoprobes; two above-grade, 30-horsepower refrigeration units; a two-phase working fluid; an interconnecting piping network; and an instrument control system. The ground freezing system used during the SITE demonstration is shown in Figure 1-1.

For the "active/passive" operating thermoprobes, carbon dioxide in the bottom of each thermoprobe functions as the two-phase working fluid to move heat against gravity. As the surrounding soil warms the thermoprobe walls, the liquid phase of the carbon dioxide boils and the vapor rises to the top of the thermoprobe. At the top of the thermoprobe, a heat exchanger coil connected to an abovegrade



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OAK RIDGE, TENNESSEE

FIGURE 1-1
SITE DEMONSTRATION SYSTEM
LAYOUT AT HRE POND

Tetra Tech EM Inc.

NOT TO SCALE

SOURCE: MODIFIED FROM EPA QAPP 1998

refrigeration unit through a copper piping network 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. Thermal expansion valves at each thermoprobe modulate to allow flow of carbon dioxide from the refrigeration unit, through the heat exchanger coil. 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 -32 °C. There are no other moving components in the thermoprobe structure.

Each refrigeration unit consists of two motor/compressors in parallel and two fan coils in parallel. During the initial freeze-down, both units operated simultaneously to increase heat removal from the soil surrounding the thermoprobes. Once the frozen soil barrier reached an average thickness of 12 feet, the units were set up to operate for alternating periods of 24 hours each, sufficient to maintain barrier design thickness.

1.4 OVERVIEW AND OBJECTIVES OF THE SITE DEMONSTRATION

This section provides site background, site topography and geology, hydrogeology, system construction, SITE Program demonstration objectives, and predemonstration and demonstration activities.

1.4.1 HRE Pond Site Background

The SITE Program demonstration of the freeze barrier technology was conducted over a 5-month period from February to July 1998. The technology was demonstrated at DOE's ORNL Waste Area Grouping 9 area in Oak Ridge, Tennessee. A former unlined surface impoundment known as the HRE pond was the specific location for the technology demonstration. When it was operational, the HRE pond's surface measured about 75 feet by 80 feet, with sides sloping to a bottom measuring 45 feet by 50 feet (EPA 1998). The bottom of the HRE pond was reportedly about 15 feet below ground surface (bgs) (EPA 1998). Figure 1-2 shows the original engineering diagram for the HRE pond.

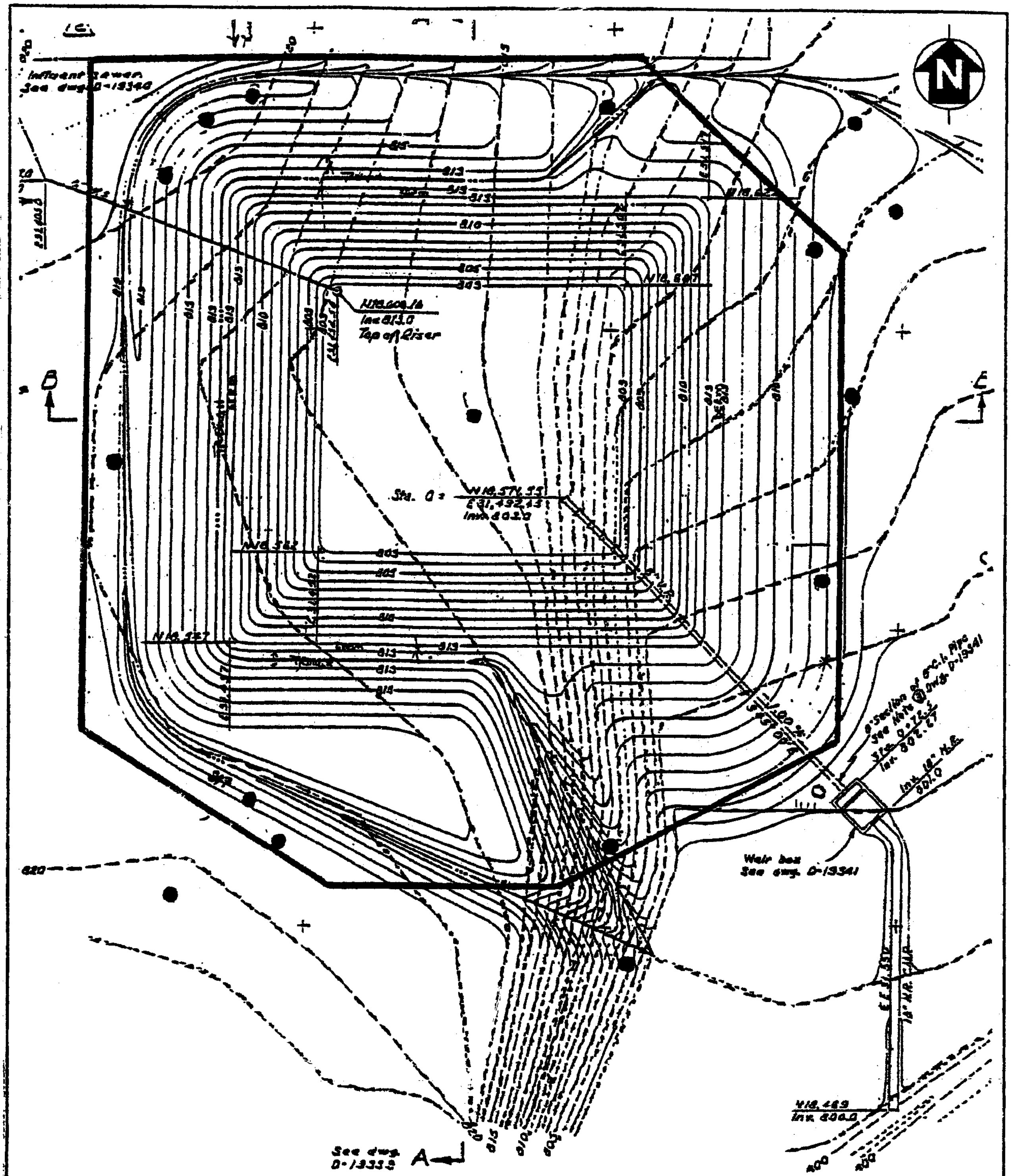

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FIGURE 1-2
ENGINEERING DRAWING OF HRE POND SHOWING INFLUENT AND EFFLUENT PIPES AND DRAINAGE DITCHES

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SOURCE: MODIFIED FROM DOE 1998a

From 1958 through 1961, the HRE pond served as a retention/settling basin for low-level radioactive liquid wastes with a radioactivity level equal to or less then 1,000 counts per minute (cpm). High levels of fission products from a chemical processing system and shield water containing about 340 curies (Ci) of beta-gamma activities were generated in a reactor tank in the HRE Building (7561); an influent line carrying these wastes reportedly entered the northwest corner of the HRE pond (DOE 1984). Contaminants from these waste streams were flocculated in the HRE pond, and treated water from the pond was piped and discharged to a weir box located about 40 feet southeast of the pond. The water was then released from the weir box to a small nearby tributary. A series of drainage ditches were also located on the north, south, and west sides of the HRE pond to contain any overflow from the waste streams (DOE 1998a; EPA 1998). In 1970, the HRE pond was (1) closed and backfilled with off-site soil containing shale fragments, (2) combined with sodium borate, and (3) capped with 8 inches of crushed limestone followed by an asphalt cap (EPA 1998). Figure 1-2 shows the influent and effluent lines along with the drainage ditches, which are identified as troughs.

In 1986, DOE conducted a soil and groundwater characterization study in and around the former pond to determine the concentrations of radiological contaminants (DOE 1986). As part of these activities, six soil borings were advanced and a series of monitoring wells, piezometers, and standpipes were installed (see Figure 1-3). The monitoring wells, piezometers, and standpipes were installed at depths ranging from 10 to 40 feet bgs. The standpipes are 3-inch-diameter steel pipes with 1-inch-diameter holes drilled along the length of the pipe. Analytical data from the soil borings indicated that the primary radiological contaminants detected in the former pond were cesium^{137} (Cs) and strontium^{90} (Sr). A soil boring installed in the northwest corner of the former pond yielded the highest radiological level, with a portion of the core reading about 100 millirems at a depth near the top of the former pond (DOE 1998a). Similar soil patterns were encountered in each borehole installed within the former pond. The stratification of each borehole consisted of about 4 inches of asphalt at the surface, about 1 foot of crushed limestone below the asphalt cap, followed by 13 feet of clay and shale fragments mixed with fill material down to an elevation of 803 feet above mean sea level (MSL), which is consistent with the bottom of the former pond (DOE 1998b). A plan view of the HRE pond showing site topography and on-site monitoring wells, standpipes, and piezometers is shown in Figure 1-3.

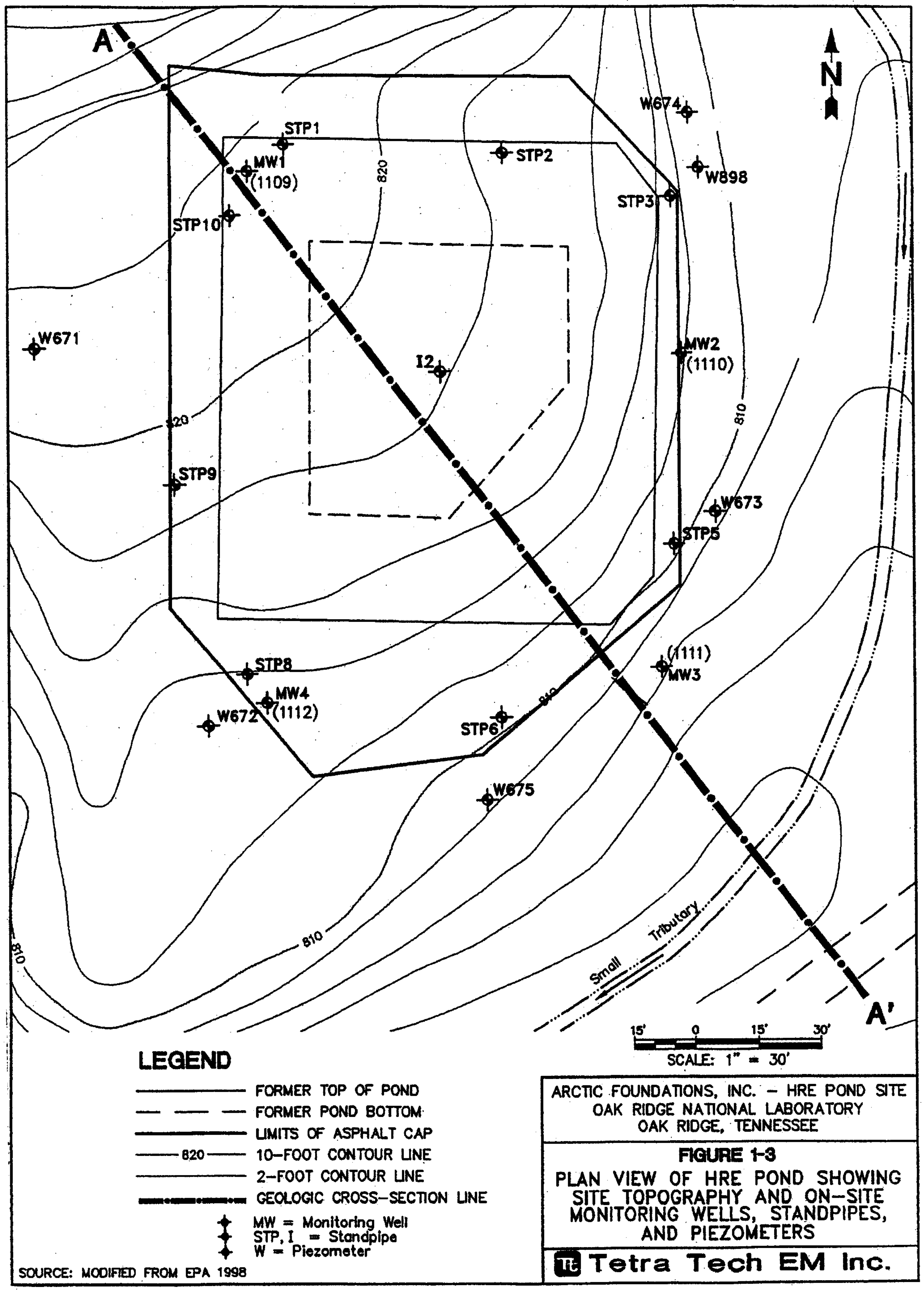

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FIGURE 1-3

PLAN VIEW OF HRE POND SHOWING SITE TOPOGRAPHY AND ON-SITE MONITORING WELLS, STANDPIPES, AND PIEZOMETERS

Tetra Tech EM Inc.

1.4.2 Site Topography and Geology

The site is located in Melton Valley about 2,000 feet southeast of the Copper Creek fault. The HRE pond was excavated in clay and weathered sedimentary rock of the Conasauga Group. Figure 1-4 (cross-section line A-A' from Figure 1-3) shows that the former pond is situated on a fairly steep slope. The weathered sedimentary rock is underlain by bedrock units of the Conasauga Group at an elevation about 790 feet above MSL. The two units include the Rogersville shale and the underlying Friendship formation. The Rogersville shale consists of interbedded mudstones and calcareous and noncalcareous siltstones. The Friendship formation is characterized by interbedded limestone and shale. Regional strike in the area is 45 to 60 degrees east of north. Bedding dips locally from 30 to 40 degrees to the southeast (DOE 1986; 1998b).

The thickness of the overlying soil ranges from less then 1 foot to 9 feet and includes clayey soil mixed with shale fragments introduced by backfill material. Beneath the soil is a leached saprolitic zone that extends down to the water table in the site vicinity. A generalized geologic cross-section of the HRE pond is presented in Figure 1-4.

1.4.3 Site Hydrogeology

The hydraulic gradient in the vicinity of the HRE pond trends south to southeast toward the on-site tributary that flows to Melton Branch. However, available information indicates that bedrock is fractured and that fractures in part control groundwater flow in the former pond area (DOE 1998b). Past studies at ORNL also indicate that the direction of groundwater movement is affected by the intrinsic permeability of the strata in bedrock. The Conasauga Group is reportedly anisotropic with respect to hydraulic conductivity. Therefore, groundwater flow is expected to occur at some acute angle to the hydraulic gradient and strongly affected by bedding planes and joint orientations. Past studies at other ORNL sites suggest that groundwater flow in the overlying saprolite is also controlled in part by fractures. DOE has reported that groundwater flow may be controlled by the gravel layer underlying the asphalt cap that covers the former pond during periods of high groundwater elevation. The groundwater transport zones are also reportedly in hydraulic communication. Other anthropogenic conditions may also affect groundwater flow on site. Water level data collected from on-site standpipes, piezometers, and monitoring wells indicate that groundwater at the site exhibits significant

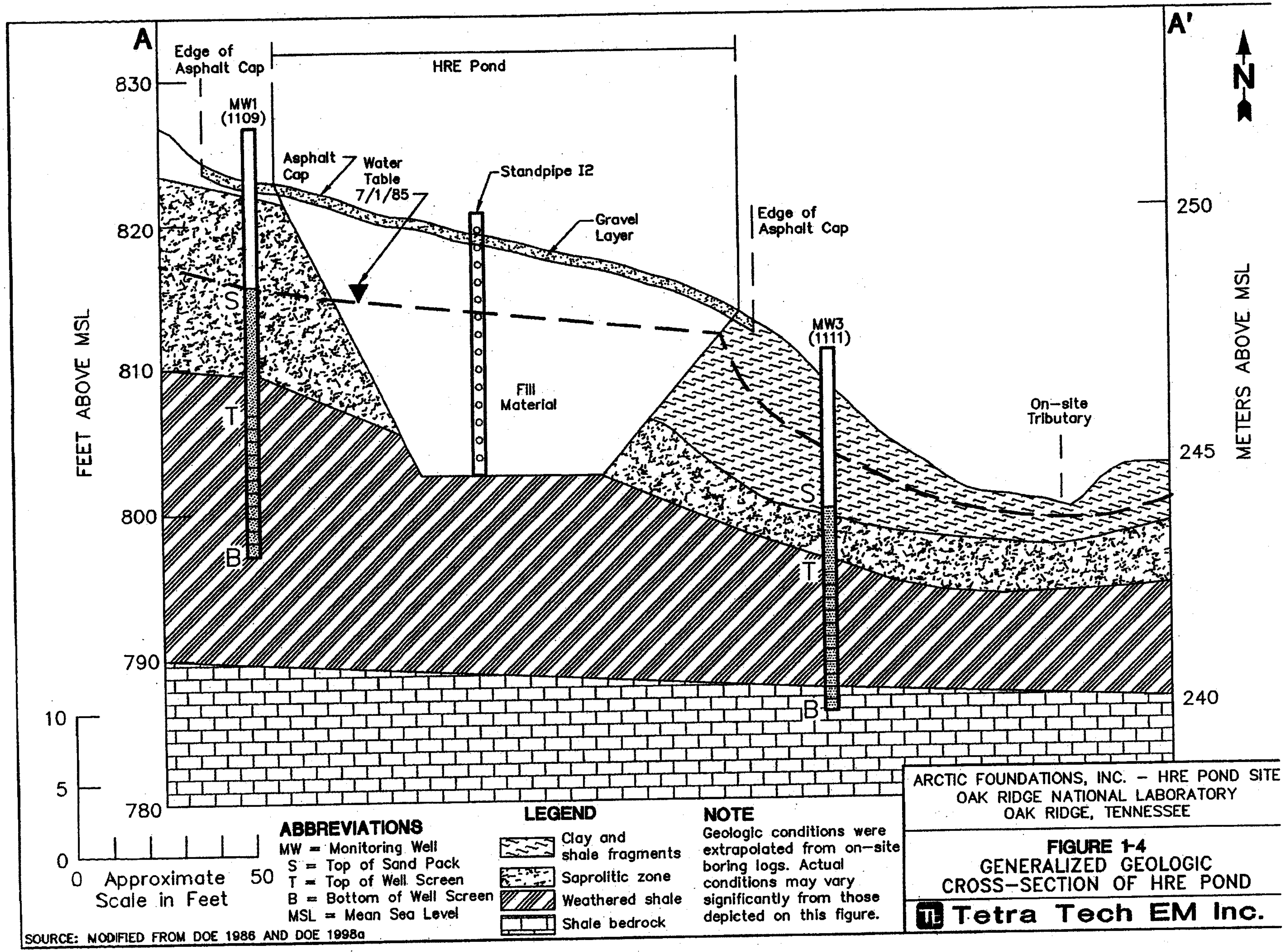


FIGURE 1-4
GENERALIZED GEOLOGIC CROSS-SECTION OF HRE POND

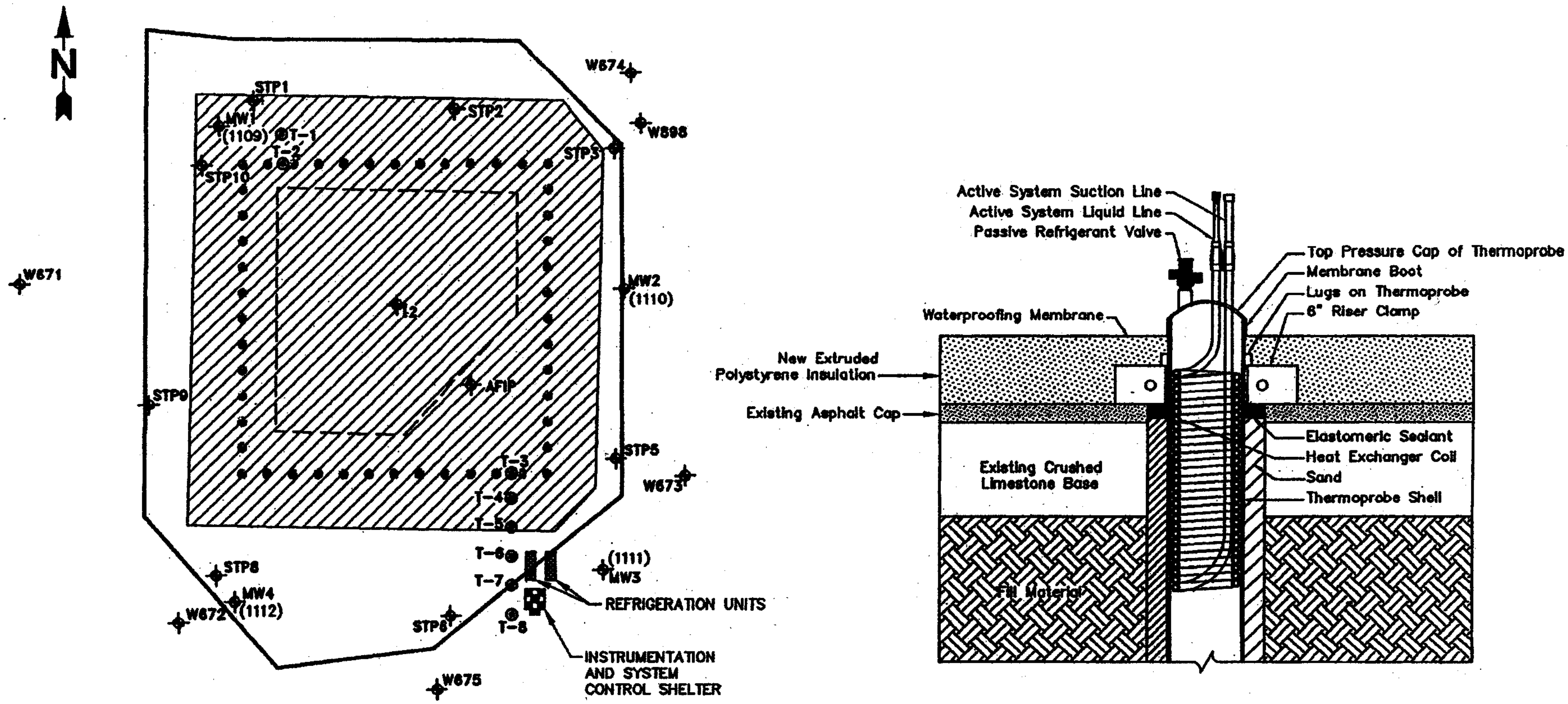
responsiveness to rainfall and storm events. The average depth to groundwater is about 6 to 10 feet bgs in the site vicinity (DOE 1986; EPA 1998).

1.4.4 System Construction

Prior to system construction, an electromagnetic geophysical survey of the former pond was conducted to identify objects that could potentially disrupt drilling and installation activities. The survey identified three anomalies, one of which extended through the northwest portion of the former pond that was consistent with a subsurface pipe, as shown in Figure 1-2. The two other anomalies were interpreted as possible buried scrap metal in the northwest and southeast corners of the former pond (DOE 1996; 1998b). AFI's ground freezing system was constructed from May through September 1997. The system was constructed around the top of the former pond, just southeast of the HRE building (building 7500). A categorical exclusion was granted under the National Environmental Policy Act for construction of the freeze barrier system, indicating that the project would not significantly affect the surrounding environment.

A total of 58 boreholes were drilled vertically, using solid-stem auger and air rotary drilling methods, to a depth of about 30 feet bgs into the underlying bedrock (DOE 1998a). Fifty thermoprobes, spaced about 6 feet apart, were installed into the boreholes with the base of each thermoprobe anchored in bedrock. The annular space around each thermoprobe was then filled with quartz sand. AFI also installed a piezometer, identified as AFIP on Figure 1-5, at a depth of about 7 feet bgs within the confines of the barrier wall, just southeast of standpipe I2. Figure 1-5 shows the system configuration in plan view and a profile view of AFI's thermoprobe.

Eight temperature monitoring points (T-1 through T-8) were installed in the remaining eight boreholes. using the same general procedures used to install the thermoprobes. The temperature monitoring points were placed at strategic locations to monitor development of the frozen barrier wall (see Figure 1-5). Temperature monitoring points were set inside protective casings to protect the instruments and allow



PLAN VIEW OF SYSTEM CONFIGURATION
NOT TO SCALE

PROFILE VIEW OF THERMOPROBE
NOT TO SCALE

LEGEND

- WATERPROOFING MEMBRANE
- LIMITS OF ASPHALT CAP
- FORMER TOP OF POND
- FORMER POND BOTTOM
- THERMOPROBE
- TEMPERATURE MONITORING POINTS
- MW = Monitoring Well
- STP, I = Standpipe
- W = Piezometer

SOURCE: MODIFIED FROM EPA 1998

NOT TO SCALE

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FIGURE 1-5
PLAN VIEW OF SYSTEM CONFIGURATION AND PROFILE VIEW OF THERMOPROBE

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replacement without having to redrill. The temperature sensors used for the temperature monitoring points are thermistors, which are reportedly stable resistance thermometers commonly used for soil temperature monitoring. Temperature monitoring points T-1 through T-4 have eight sensors each and are positioned to collect temperature readings at the top and bottom of the insulation material. Points T-1 through T-4 were installed following installation of the thermoprobes and have sensors positioned to collect temperature readings at 2.5, 7.5, 12.5, 17.5, 22.5, and 30.0 feet bgs. Temperature monitoring points T-5 through T-8 have seven sensors each, positioned to collect temperature readings at ground surface, 2.5, 7.5, 12.5, 17.5, 22.5, and 30.0 feet bgs.

Additional subsurface temperature data were collected from platinum resistance temperature detectors (RTD) that were installed on the external surface about midway down (15 feet bgs) each thermoprobe. The RTDs provide an indication of the operating temperature of each thermoprobe, and thus provided a means for AFI to evaluate thermoprobe performance. AFI then wired each thermistor and RTD to a datalogger for continuous collection of subsurface temperature data. The stored data were accessed either remotely by modem or were downloaded with a portable computer. Subsurface temperature data are discussed in detail in Section 2.1.4.

Following placement of thermoprobes and temperature monitoring points, cracks and voids in the asphalt cap were filled with an asphalt patching material. An extruded polystyrene insulation material was then placed over the asphalt surface extending 10 feet on each side of the centerline of the thermoprobes, and cut to fit securely around the thermoprobes and temperature monitoring points. A waterproofing membrane was placed over the insulation to prevent infiltration of rain or surface water. Concrete pavers were placed along the perimeter of the membrane and on other centralized locations to prevent uplift from wind. Once the waterproof membrane cured, the two refrigeration units, an abovegrade copper piping network, and the electrical connection were installed.

The two refrigeration units, each connected to 25 thermoprobes, were configured so that every other thermoprobe in the array surrounding the former pond was plumbed to the same refrigeration unit. Before the system was charged with two-phase refrigerant, the system underwent pressure testing to ensure that there were no leaks or blockages. The ground freezing system was activated in mid-

September 1997 and the frozen soil barrier reached its design thickness of 12 feet about 18 weeks following system startup.

1.4.5 SITE Demonstration Objectives

EPA established primary and secondary objectives for the SITE demonstration of the freeze barrier technology. The objectives were based on EPA's understanding of the freeze barrier technology, SITE demonstration program goals, and input from AFI. The objectives were selected to provide overlapping evaluation capacity and to provide potential users of the freeze barrier technology with technical information to determine if the technology is applicable to other contaminated sites. The SITE demonstration was designed to address one primary objective and four secondary objectives for evaluation of the freeze barrier technology.

Primary Objective

The following was the primary (P) objective of the technology demonstration:

- P1 - Determine the effectiveness of the freeze barrier technology in preventing horizontal groundwater flow beyond the limits of the frozen soil barrier through the performance of a groundwater tracing investigation using a fluorescent dye

The primary objective was established to evaluate the frozen soil barrier's ability to control hydrogeologic conditions in the former pond. The barrier wall was evaluated through the performance of a groundwater tracing investigation that included injecting a fluorescent dye into standpipe I2, located in the center of the former pond, and monitoring for the dye at groundwater and surface water recovery points located within and outside the former pond.

Secondary Objectives

The following were the secondary (S) objectives of the demonstration:

- S1 - Verify whether flow pathways outside the former pond were still open after placement of the freeze barrier wall
- S2 - Evaluate the hydrogeologic isolation of the enclosed former pond area before and after placement of the freeze barrier wall

- S3 - Monitor development of the freeze barrier wall
- S4 - Document installation and operating parameters of the freeze barrier wall

Secondary objective S1 was evaluated through the performance of a second groundwater tracing investigation that included adding a second fluorescent dye to upgradient monitoring well MW1 (1109) and monitoring for its presence at groundwater and surface water recovery points within and outside the barrier wall. Objective S2 was evaluated through a comparison of water level data obtained from standpipe I2 and monitoring wells MW1 (1109) and MW2 (1110). Objective S3 was evaluated by collecting subsurface temperature data from a series of temperature monitoring points located within and outside the barrier wall in the southeast corner of the containment area. Objective S4 was established to provide data for estimating costs associated with use of the freeze barrier technology, and was based on observations made during the demonstration, demonstration data, and data provided by AFI.

1.4.6 Predemonstration Activities at the HRE Pond

Predemonstration activities at the HRE pond site, which included a groundwater tracing investigation conducted by EPA in 1996 and two helium gas tracer studies conducted by DOE in 1996 and 1997, are discussed below.

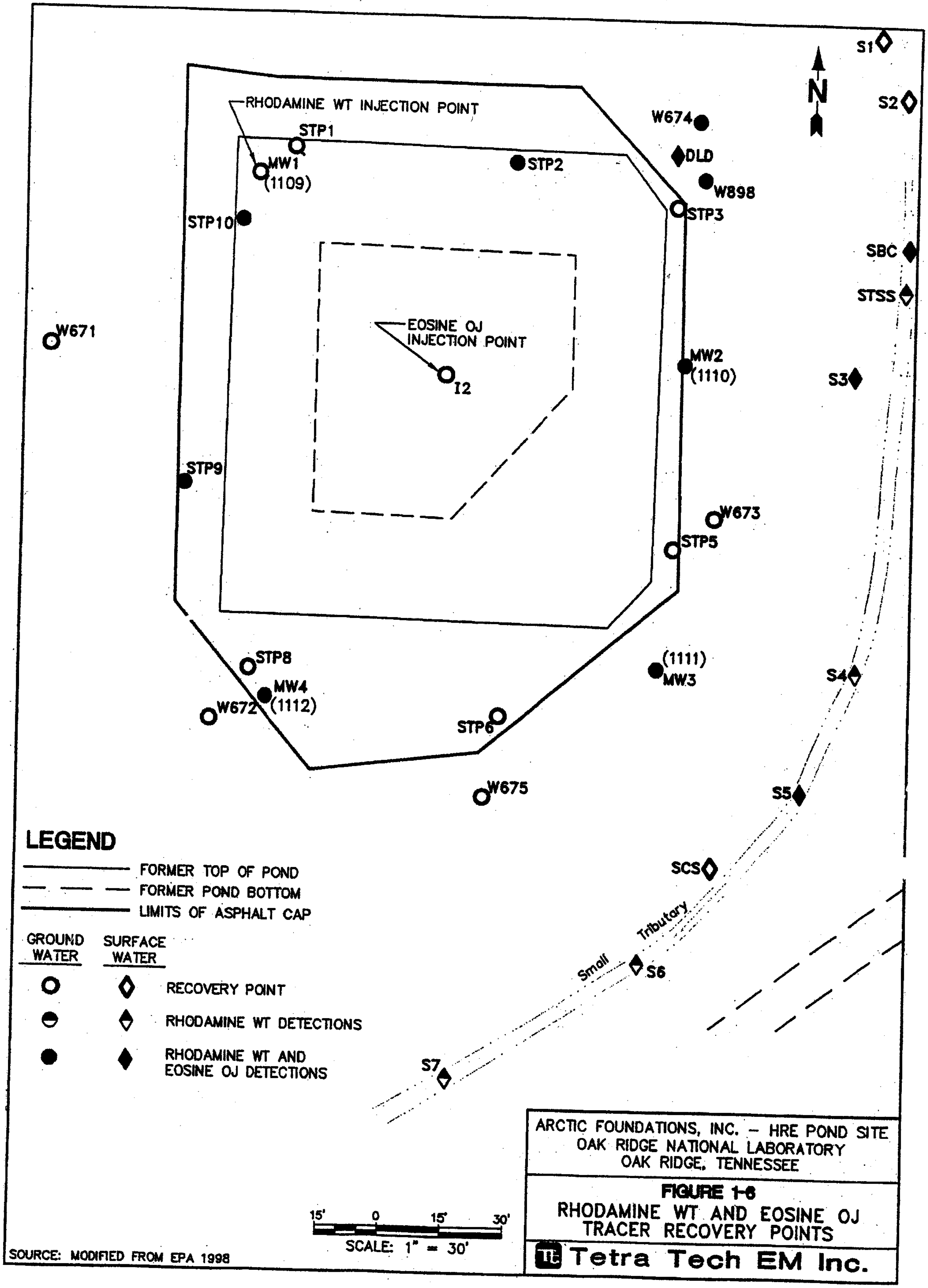
1996 EPA Groundwater Tracing Investigation

EPA conducted a groundwater tracing investigation at the HRE pond site between June 6 and August 16, 1996. The investigation was conducted to validate (1) the suitability of the two injection points (monitoring well MW1 [1109] and standpipe I2) proposed for use during the demonstration groundwater tracing investigation; (2) the functionality of the dyes prior to establishment of the barrier wall; and (3) to identify viable groundwater and surface water sampling locations for the demonstration groundwater tracing investigation. The investigation was also used as a baseline for comparing dye transport patterns to those observed during the demonstration groundwater tracing investigation after the barrier wall was in place.

Prior to the investigation, EPA initiated a background study to determine if the fluorescent dyes under consideration for the groundwater tracing investigation already occurred at detectable concentrations in the vicinity of the former pond. Dyes exhibiting characteristics similar to natural background fluorescence, or commercial dyes detected in the groundwater system would not be used for the groundwater tracing investigation. A background study was initiated on May 17, 1996, and included collection of water and charcoal samples at 20 surface water and monitoring well recovery points in the vicinity of the HRE pond. Figure 1-6 shows the specific groundwater and surface water recovery points selected for the study. The background study took place over a 3-week period so that three samples were collected from each location. After collection, the samples were analyzed for detectable concentrations of frequently used fluorescent dyes and natural background fluorescence. The dye uranine was detected at the following recovery points: S1, S3, S4, S5, S6, and S7 (EPA 1996).

Two dyes, rhodamine WT and eosine OJ, were selected for use during the groundwater tracing investigation because the dyes were not detected in samples collected during the background study. On June 7, 1996, 9.01×10^2 grams of rhodamine WT dye was injected into monitoring well MW1 (1109) located in the northwest corner of the pond, and 9.89×10^2 grams of eosine OJ dye was injected into standpipe I2 located near the center of the asphalt cap covering the former pond (see Figure 1-6). Both dyes were flushed into the surrounding aquifer by a slow injection of deionized water over a 5-day period. A few days after dye injection, Oak Ridge received several inches of rain, which also helped to mobilize the dyes (EPA 1996).

During the groundwater tracing investigation, charcoal packets and water samples were collected from the same locations used during the background study. Rhodamine WT was detected at 16 recovery points and eosine OJ was detected at 12 recovery points (EPA 1996). Recovery points DLD, SBC, S3, S4, S5, S6, and S7 showed detectable concentrations of rhodamine WT tracer between 2 and 5 days following dye injection. Transport of rhodamine WT was also evident at locations MW2 (1110), MW3 (1111), and MW4 (1112) 15 days following dye injection. Rhodamine WT was detected at recovery point STSS 22 days after dye injection. At recovery points STP2, STP9, STP10, W898, and W674,


RHODAMINE WT INJECTION POINT
STP1
MW1
(1109)
STP2
W674
DLD
W898
STP3
STP10
S1
S2
N
SBC
STSS
W671
EOSINE OJ
INJECTION POINT
I2
MW2
(1110)
S3
STP9
W673
STP5
(1111)
MW3
STP8
MW4
(1112)
W672
STP6
S4
W675
S5
SCS
Small Tributary
S6
S7
LEGEND
FORMER TOP OF POND
FORMER POND BOTTOM
LIMITS OF ASPHALT CAP
GROUND WATER
SURFACE WATER
RECOVERY POINT
RHODAMINE WT DETECTIONS
RHODAMINE WT AND EOSINE OJ DETECTIONS
15' 0 15' 30'
SCALE: 1" = 30'
SOURCE: MODIFIED FROM EPA 1998
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OAK RIDGE, TENNESSEE
FIGURE 1-6
RHODAMINE WT AND EOSINE OJ
TRACER RECOVERY POINTS
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rhodamine WT was detected at times ranging between 39 and 50 days following dye injection (EPA 1996). Figure 1-6 shows the locations where rhodamine WT was recovered. Table 1-1 presents elapsed time data for rhodamine WT at each recovery point and the initial concentration.

Eosine OJ tracer was detected at times ranging from 15 to 22 days following dye injection at recovery points MW2 (1110), MW3 (1111), and MW4 (1112). Thirty-nine to 50 days following dye injection, transport of eosine OJ was also evident at recovery points STP2, STP9, STP10, SBC, W898, and W674. At recovery points S3, S5, and DLD, eosine OJ arrived at times ranging from 50 to 56 days following dye injection (EPA 1996). Figure 1-6 shows the locations where eosine OJ was recovered. Table 1-2 presents elapsed time data for eosine OJ at each recovery point and the initial concentration. Days to peak concentration and the peak concentration value also are provided. The eosine OJ results suggested that a preferential pathway may exist on the north side of the former pond because eosine OJ was detected in water samples collected from the small tributary sooner then the recovery points closest to the eosine OJ injection point, MW1 (1109). The eosine OJ bypassed on-site monitoring wells, standpipes, and piezometers and discharged directly into the tributary within 2 to 4 days following injection. The 1996 groundwater tracing investigation also showed that groundwater transport out of the former pond occurs in a radially distributed pattern and that the pond is hydraulically connected to the surrounding soils.

DOE Helium Gas Tracing Investigations

Following EPA's groundwater tracing investigation, DOE conducted two independent gas tracing investigations using helium in the summer of 1996 and winter of 1997. The results of DOE's investigations confirmed that transport out of the former pond occurs in a radially distributed pattern. DOE also reported that transport out of the former pond occurs under ambient conditions and not just under forced-gradient conditions (water injection) as was the case with the groundwater tracing

TABLE 1-1

RESULTS OF THE 1996 GROUNDWATER TRACING INVESTIGATION FOR RHODAMINE WT

Recovery Point	Initial Detection (days)[a]	Peak Detection (days)[a]	Initial Concentration (ppb)	Peak Concentration (ppb)
SBC	2	7.81	1.20e-05	3.27e-01
S7	4	71.00	1.00e-01	2.15e+01
S6	4	14.91	1.06e-01	7.86e+00
S5	4	14.91	1.12e-01	5.41e+00
S3	4	14.91	2.95e-01	1.24e+01
S4	4	14.91	1.16e-01	9.09e+00
DLD	5	7.81	3.70e+01	8.36+01
MW2 (1110)	15	14.91	2.83e-01	2.83e-01
MW3 (1111)	15	71	6.48e-03	1.76e-02
MW4 (1112)	15	36.21	8.81e-03	1.20e-02
STSS	22	27.52	9.60e-04	5.50e-03
STP10	39-43	42.60	Not Determined[b]	4.90e-02
W674	43	63.90	8.45e-02	2.91e-01
W898	43	63.90	1.78e-01	3.38e-01
STP2	43	56.09	1.20e-05	1.59e-02
STP9	50	56.09	1.20e-07	3.63e-02

Notes:

ppb parts per billion
[a] Number of days following dye injection
[b] Initial concentration could not be determined due to the sampling frequency

TABLE 1-2

RESULTS OF THE 1996 GROUNDWATER TRACING INVESTIGATION FOR EOSINE OJ

Recovery Point	Initial Detection (days)[a]	Peak Detection (days)[a]	Initial Concentration (ppb)	Peak Concentration (ppb)
MW2 (1110)	15	42.6	1.10e-02	6.71e-02
MW4 (1112)	22	36.21	5.29e-03	2.68e+00
MW3 (1111)	22	42.6	4.04e-02	1.32e-01
W674	39-43	42.6	Not Determined[b]	1.25e+00
STP10	39-43	42.6	Not Determined[b]	1.79e-01
W898	39-43	42.6	Not Determined[b]	4.98e+00
STP2	43	63.9	1.10e-05	2.03e+00
SBC	43-50	49.7	Not Determined[b]	4.19e-01
STP9	50	63.9	1.10e-05	2.85e-02
S5	50-56	55.38	Not Determined[b]	5.67e+00
S3	50-56	55.38	Not Determined[b]	1.65e-01
DLD	56	71	1.64e+01	4.29e+01

Notes:

ppb parts per billion
[a] Number of days following dye injection
[b] Initial concentration could not be determined due to the sampling frequency

investigation (DOE 1998b). Based on available information, including the geology of the former pond area, the construction of the former pond, and the subsequent backfilling and capping of the former pond, it appears that multiple groundwater transport pathways from the former pond may exist. These transport pathways include transport from the bottom of the former pond through shallow fractured bedrock; transport through the fill material (clay and shale fragments) and gravel layer overlying the former pond; and transport through the walls of the former pond, by abandoned influent/effluent pipes (DOE 1998a).

1.4.7 Demonstration Activities at the HRE Pond

The effectiveness of AFI's freeze barrier technology was evaluated over an 11-month period by collecting independent data. In general, three types of data were obtained: (1) analytical tracer data from groundwater, surface water, and charcoal packet samples collected within and outside the freeze barrier wall; (2) water level data from on-site monitoring wells, standpipes, and piezometers; and (3) subsurface temperature data from eight temperature monitoring points. Data collection procedures for the demonstration were specified in (1) the EPA-approved quality assurance project plan (QAPP) written specifically for the freeze barrier technology demonstration, and (2) EPA's guidance for applying dye tracing techniques (EPA 1988c; 1998).

This SITE project incorporated the assistance and expertise of SITE Program individuals and participants outside the normal SITE Program umbrella. These participants included DOE and DOE's subcontractor, AFI, Cambrian Groundwater Company, and the Tennessee Department of Environment and Conservation (TDEC).

Demonstration Background Study

In January 1998, a demonstration background study was conducted to identify (1) detectable concentrations of residual dyes remaining in the groundwater system from EPA's initial groundwater tracing investigation conducted in 1996, and (2) natural background fluorescence that might interfere with the demonstration groundwater tracing investigation. During the demonstration background study, groundwater, surface water, and charcoal packet samples were collected from locations within and outside the barrier wall over a period of 21 days, as specified in the QAPP. The samples were analyzed for residual dyes and background fluorescence by spectrofluorophotometric analysis. The background sampling began after the barrier wall reached its design thickness of about 12 feet.

Demonstration Groundwater Tracing Investigation

Based on the demonstration background study results (see Section 2.1.1) two dyes, phloxine B and eosine OJ, were selected for use during the demonstration groundwater tracing investigation. The two dye injection points, standpipe I2 and monitoring well MW1 (1109), that were used during EPA's 1996 groundwater tracing investigation were retained for this investigation. The purpose of injecting dye into standpipe I2 was to evaluate the effectiveness of the barrier wall in controlling the horizontal flow of groundwater in the containment area. The purpose of injecting dye into monitoring well MW1 (1109) was to evaluate the effect of the barrier wall on the groundwater system outside the containment area by comparing the results to the 1996 groundwater tracing investigation data obtained prior to establishment of the barrier wall.

On February 20, 1998, field personnel injected about 1,800 grams of eosine OJ into monitoring well MW1 (1109) and about 450 grams of phloxine B into standpipe I2. Next, about 130 gallons of potable water was flushed into each injection point over a 5-day period to assist in mobilizing the two dyes. Dye was monitored by collecting groundwater and surface water samples and by sorption of dye onto particles of activated charcoal packets suspended in the flow of water, as specified in the QAPP. Charcoal packets were initially used, but later discontinued because water samples yielded more reliable fluorescence data. Table 1-3 describes each recovery point and the sampling method used at each location.

Field personnel collected samples from five additional locations identified as MH, KL, OF283, TCP, and FS in Table 1-3. The additional locations are also identified on Figure 2-1 in Section 2.1.3. When weather conditions warranted, the frequency of sample collection was sometimes modified to ensure that a slug of dye did not pass recovery points undetected. QA/QC samples were also prepared and submitted for analyses, as specified in the EPA-approved QAPP (EPA 1998). Samples were delivered to a local laboratory for spectrofluorophotometric analysis.

TABLE 1-3

RECOVERY POINTS AND SAMPLING METHODS

Recovery Point	Description	Sampling Method
MW1 (1109)	monitoring well/injection point	water grab samples
MW2 (1110)	monitoring well	automatic water sampler/charcoal packet
MW3 (1111)	monitoring well	water grab samples
MW4 (1112)	monitoring well	automatic water sampler/charcoal packet
I2	standpipe/injection point	water grab samples
STP1	standpipe	water grab samples
STP2	standpipe	water grab samples/charcoal packet
STP5	standpipe	water grab samples
STP6	standpipe	water grab samples
STP7	standpipe	water grab samples
STP8	standpipe	water grab samples
STP9	standpipe	water grab samples/charcoal packet
STP10	standpipe	water grab samples/charcoal packet
AFIP	piezometer	water grab samples
W898	piezometer	automatic water sampler/charcoal packet
SBC	stream below culvert	automatic water sampler/charcoal packet
STSS	Trivelpiece Spring	water grab samples/charcoal packet
MH	manhole south of pond	water grab samples
KL	Keller's Leak	water grab samples
DLD	Dale's Little Dipper Spring	water grab samples
OF283	Overflow 283	water grab samples
SCS	Steel Cylinder Spring	water grab samples
S1	small tributary	water grab samples/charcoal packet
S2	small tributary	water grab samples/charcoal packet
S7	small tributary	water grab samples/charcoal packet
TCP	terra cotta pipe	water grab samples
FS	Frank's Spring	water grab samples

In addition to samples collected for dye tracer analyses, water level data were supposed to be collected from standpipe I2 located in the center of the former pond, monitoring well MW1 (1109) located upgradient of the pond, and monitoring well MW2 (1110) located downgradient of the former pond, as specified in the QAPP. Due to complications with DOE's data logging equipment, however, pre-barrier water level data from upgradient well MW1 (1109) were not available; therefore, water level data from upgradient standpipe STP10 located directly adjacent to MW1 (1109) were used. Water level data were collected by DOE personnel using either a manual water level indicator or a field data logger in combination with a series of pressure transducers positioned belcw the water in each well or standpipe, as specified in the QAPP (EPA 1998).

Continuous subsurface temperature data were collected from a series of temperature monitoring points positioned at strategic locations to track the development of the barrier wall. AFI installed these points for operational monitoring purposes and, as such, set up the dataloggers and frequency of monitoring to best suit their objectives. Of particular interest to the SITE Program was the array installed near the southeast corner of the barrier (T-3 through T-8), which provided information on development of the barrier wall. Development of the freeze barrier wall is discussed further in Section 2.1.2.

1.5 KEY CONTACTS

Additional information on the freeze barrier technology, AFI, the SITE Program, and the DOE demonstration site is available from the following sources:

The Freeze Barrier Technology

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The SITE Program

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2.0 TECHNOLOGY EFFECTIVENESS ANALYSIS

This section addresses the effectiveness of the freeze barrier technology in preventing groundwater flow beyond the limits of the frozen soil barrier. The effectiveness of the freeze barrier technology in controlling the horizontal flow of groundwater through the former pond was the primary objective of the SITE demonstration. Some characteristics of the HRE pond site, such as shallow depth to groundwater, waste properties, and site topography and drainage appeared favorable for demonstrating the freeze barrier technology. Prior to the demonstration, participants identified several unconfirmed features, such as groundwater flow in fractured bedrock and subsurface features (pipes) in the former pond area with the potential to affect dye migration. For this reason, the SITE Program demonstration included objectives based on factors such as piezometric data and subsurface soil temperature data, in addition to the tracer studies, to evaluate system performance. The analysis of the technology's effectiveness presented in this section is based on the results of the SITE demonstration at the HRE pond site.

Tables summarizing the laboratory analytical data for groundwater and surface water samples collected during the demonstration are included in the appendix. AFI's claims regarding the effectiveness of the freeze barrier technology are presented in the attachment.

2.1 SITE DEMONSTRATION RESULTS

This section summarizes the methods and procedures used to collect and analyze samples for the critical parameters during the SITE demonstration, the results of the SITE demonstration, including the demonstration background study, the demonstration groundwater tracing investigations, water level measurements, subsurface soil temperature, installation and operating parameters, and quality control results.

2.1.1 Methods

Both the demonstration background study and groundwater tracing investigation employed the use of activated charcoal packets and grab sampling techniques for the collection of groundwater and surface water samples from potential dye recovery points. The potential dye recovery points were located downgradient and cross gradient from the two dye injection points (standpipe I2 and monitoring well MW1 [1109]). Charcoal packets were suspended in water at each recovery point using nylon cord and an anchor, so as to expose them to as much water as possible. Grab samples of water were collected using one of three techniques, depending on location: (1) decontaminated bailers, (2) ISCO® automatic water samplers, or (3) by lowering a clean sample vial into the well using nylon fishing line. The samples were collected in accordance with the methods required by the Freeze Barrier Technology Demonstration QAPP (EPA 1998).

The demonstration background study was conducted over a 21-day period in January 1998 after the frozen soil barrier reached its design thickness of 12 feet. A total of 22 charcoal packets and 114 grab samples of water were collected from the recovery points over the 21-day period. The samples were analyzed using a spectrofluorophotometer for any residual dyes from the 1996 groundwater tracing investigation or natural background fluorescence.

The demonstration groundwater tracing phase of the demonstration was conducted over a 5-month period after the background study was completed. Phloxine B and eosine OJ were injected at locations I2 and MW1 (1109), respectively. As before, each dye recovery point was monitored using activated charcoal packets and by collecting and analyzing frequent grab samples of groundwater and surface water. A total of 15 charcoal packets and 359 grab samples of water were collected from the recovery points, using the same general sample collection procedures as described above. As stated in Section 1.4.7, charcoal packets were initially used, but later discontinued because water samples provided more reliable fluorescence data. The frequency of sample collection at each recovery point for both phases of the SITE demonstration are included in the appendix.

The samples were analyzed for the two dyes phloxine B and eosine OJ, using a spectrofluorophotometer. The laboratory method, which used a synchronous scanning spectrofluorophotometer, enabled the evaluation of both excitation and emission spectra for the dyes. Each sample was placed in the cuvette or sample compartment; the appropriate wavelengths were selected; and the sample was scanned in the synchronous mode. Calculations comparing the emission spectra for the sample to known standard emission spectra were performed to identify the source of the fluorescence and determine sample concentrations. Dilutions were made as necessary to keep sample measurements within the range of the standards. All samples and standards were analyzed at room temperature with all other conditions being the same for all analyses performed.

2.1.2 Results of the Demonstration Background Study

Results of analysis of samples collected during the background study indicated the presence of residual concentrations of the dyes eosine OJ and rhodamine WT at the same recovery points where the two dyes were detected during the 1996 groundwater tracing investigation (see Section 1.4.6). According to the analytical laboratory, a green compound, which is a common derivative of rhodamine WT, was identified in samples collected from recovery points STP2, STP9, DLD, KL, and MW1 (1109). Analytical results also indicated that uranine was present in water samples collected from recovery points I2, SBC, STP9, AFIP, MW4 (1112), S1, and S2. Uranine also was present in samples collected from the same recovery points during the 1996 groundwater tracing investigation.

The highest concentration of fluorescence in background samples in the range of the emission spectra for phloxine B and eosine OJ was 1.30e-03 parts per billion (ppb). This background concentration for phloxine B and eosine OJ was used as a baseline for comparison to demonstration groundwater tracing investigation results. Therefore, phloxine B and eosine OJ detected above the highest background concentration was considered a detection at any recovery point.

During the demonstration background study, field personnel interviewed Mr. Marlin Ritchey, a Lockheed Martin Energy Systems, Inc., engineer in charge of sump pumps in the basement of the HRE building (7561), located northwest (upgradient) of the former pond. Mr. Ritchey was interviewed in an attempt to identify a source for the uranine. Mr. Ritchey stated that he had conducted a number of dye tracing experiments from the basement of the HRE building, using the dye uranine, during the period between the 1996 groundwater tracing investigation and the demonstration background study. After discovering a potential source for the uranine, it was unclear how uranine migrated from the HRE building to standpipe I2 and piezometer AFIP located within the containment area. Available information indicates that a number of pipes connected to the HRE building entered the former pond from the northwest and may have been left in place after the pond closed. A report of a geophysical survey conducted prior to the demonstration refers to a subsurface pipe that extends through the northwest wall of the former pond, inferring that a pathway could exist between the former pond and the HRE building (DOE 1996). However, it is unknown whether this pathway was open or closed after placement of the barrier wall.

2.1.3 Results of the Demonstration Groundwater Tracing Investigations

Tracing investigation results of the dye phloxine B injected into standpipe I2 located within the containment area and the dye eosine OJ injected into monitoring well MW1 (1109) located outside and northwest of the containment area are presented below. Figure 2-1 shows the recovery points where phloxine B and eosine OJ were detected during the demonstration groundwater dye tracing investigation.

Phloxine B Results

Phloxine B was detected in water samples collected outside the former pond at recovery points STP10, AFIP, STP1, STP2, STP9, and MW4 (1112). Figures 2-2 through 2-7 plot the concentration of phloxine B relative to days following dye injection for dye recovered at each recovery point. Phloxine B was first recovered about 16 days after dye injection at recovery point STP10, which is located upgradient of injection point I2. The concentration of phloxine B detected at recovery point STP10 was 3.20e-01 ppb, well above the highest concentration (1.30e-03 ppb) detected during the demonstration background study. The recovery pattern at STP10 shows a rapid increase in concentration of the emission peak for phloxine B over time, with a lower exponential decrease as shown in Figure 2-2. The second detection of phloxine B occurred at recovery point AFIP 10 weeks after dye injection. AFIP is located within the area surrounded by the freeze barrier wall, just southeast of injection point I2 (see Figure 2-3).

Based on the recovery of phloxine B at recovery point STP10, the probability that a series of pipes may exist in the northwest portion of the former pond cannot be discounted. The pathway from standpipe I2 to the area near standpipe STP10 is very close to the reported location and alignment of a geophysical anomaly, inferred to be a pipe, that was detected prior to the technology demonstration.

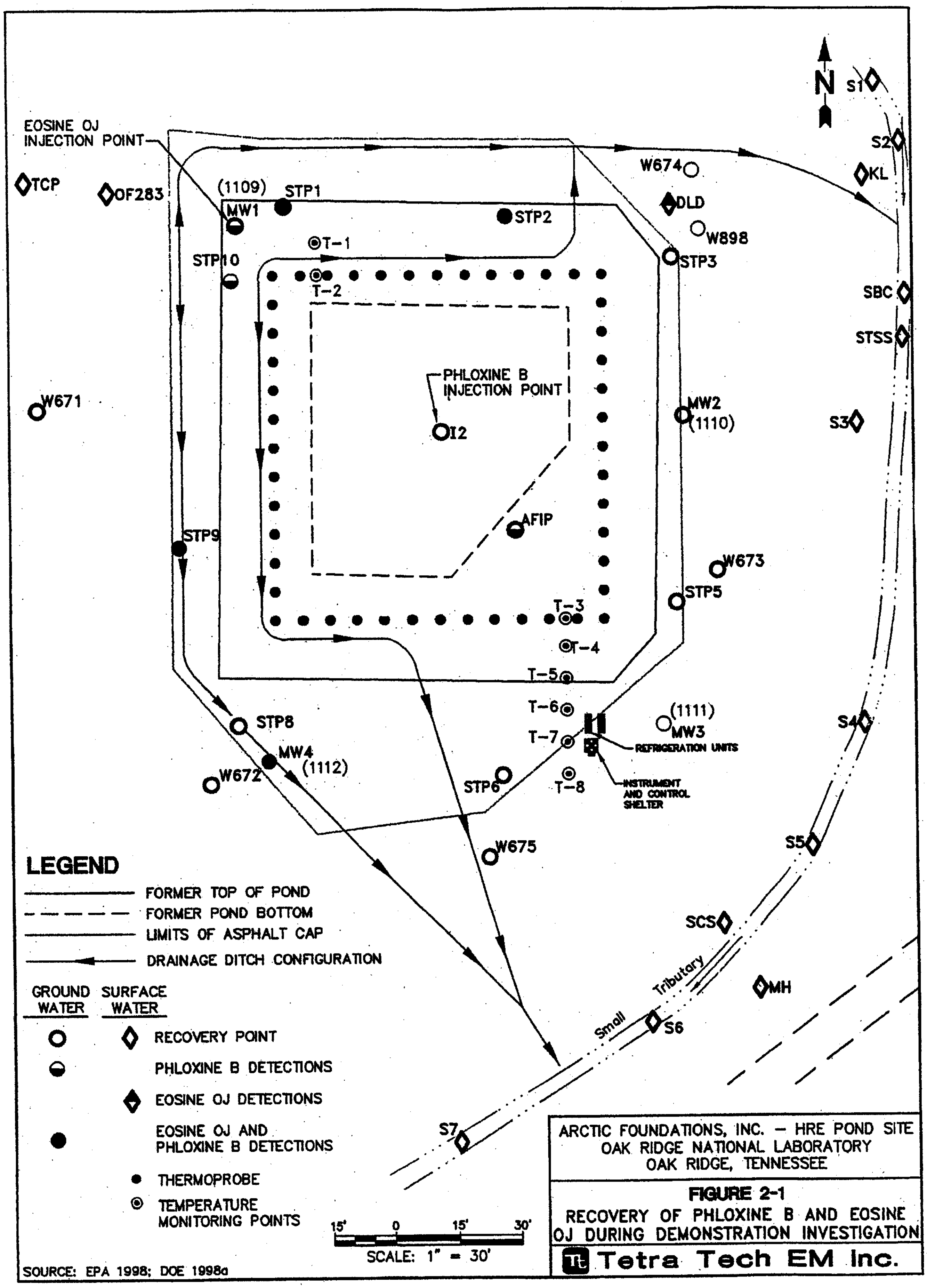

EOSINE OJ INJECTION POINT
TCP
OF283
(1109)
MW1
STP1
STP2
W674
DLD
W898
STP3
T-1
STP10
T-2
PHLOXINE B INJECTION POINT
I2
W671
MW2 (1110)
AFIP
STP9
W673
STP5
T-3
T-4
T-5
T-6
T-7
T-8
(1111) MW3
REFRIGERATION UNITS
INSTRUMENT AND CONTROL SHELTER
STP8
MW4 (1112)
W672
STP6
W675
S1
S2
KL
SBC
STSS
S3
S4
S5
SCS
MH
S6
S7
Small Tributary
LEGEND
FORMER TOP OF POND
FORMER POND BOTTOM
LIMITS OF ASPHALT CAP
DRAINAGE DITCH CONFIGURATION
GROUND WATER
SURFACE WATER
RECOVERY POINT
PHLOXINE B DETECTIONS
EOSINE OJ DETECTIONS
EOSINE OJ AND PHLOXINE B DETECTIONS
THERMOPROBE
TEMPERATURE MONITORING POINTS
15' 0 15' 30'
SCALE: 1" = 30'
SOURCE: EPA 1998; DOE 1998a
ARCTIC FOUNDATIONS, INC. – HRE POND SITE
OAK RIDGE NATIONAL LABORATORY
OAK RIDGE, TENNESSEE
FIGURE 2-1
RECOVERY OF PHLOXINE B AND EOSINE OJ DURING DEMONSTRATION INVESTIGATION
Tetra Tech EM Inc.

Figure 2-2
Concentrations of Phloxine B Versus Time
for Location STP10

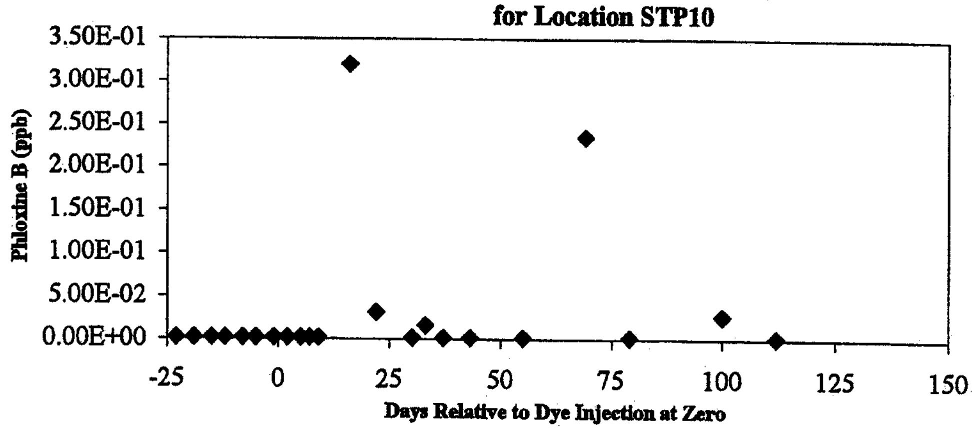


Figure 2-3
Concentrations of Phloxine B Versus Time
for Location AFIP

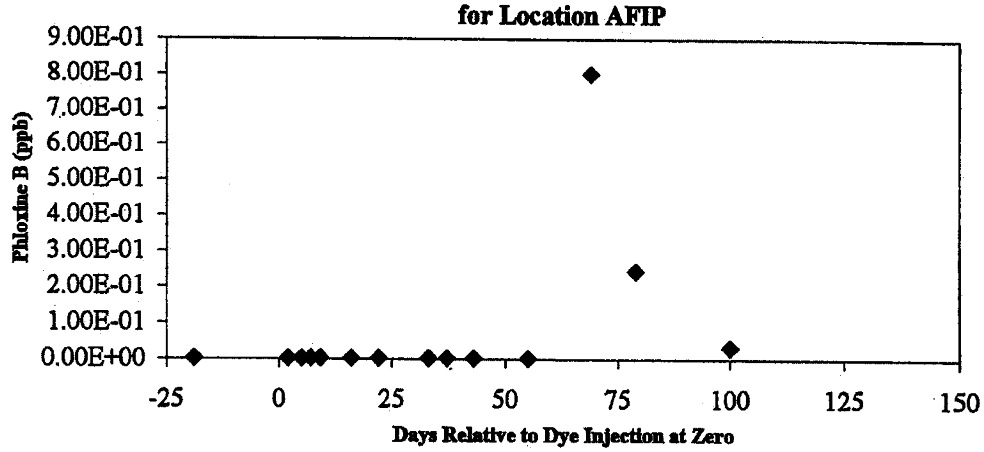


Figure 2-4
Concentrations of Phloxine B Versus Time
for Location STP1

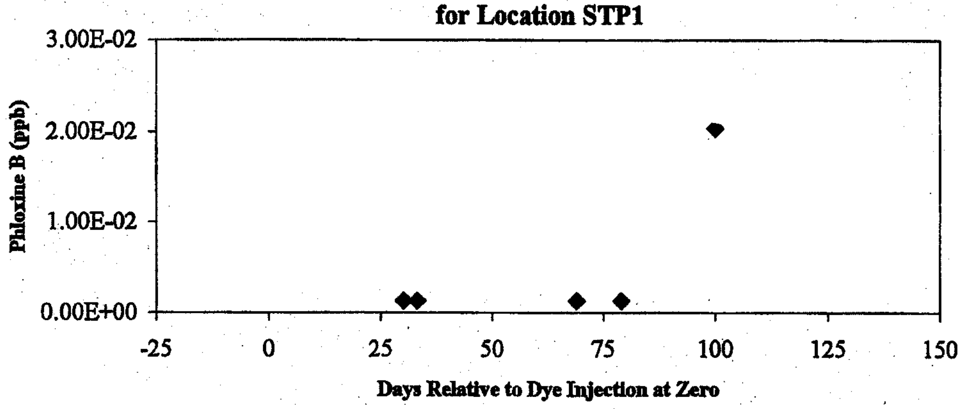


Figure 2-5
Concentrations of Phloxine B Versus Time
for Location STP2

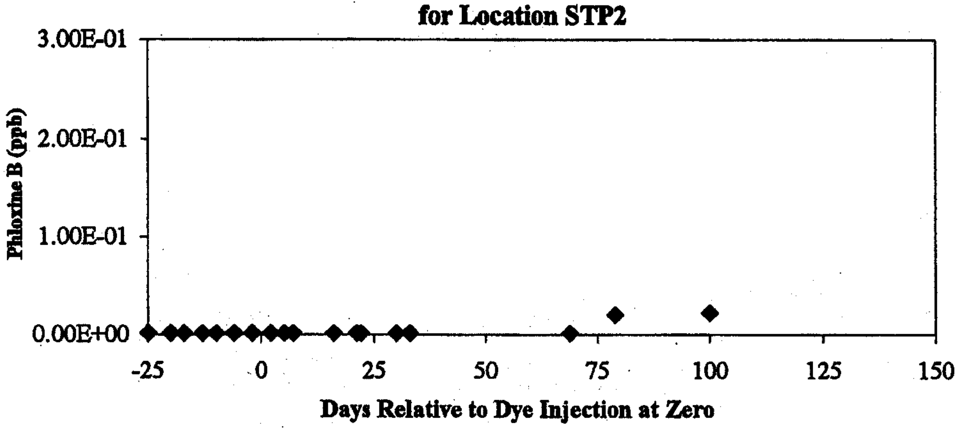


Figure 2-6
Concentrations of Phloxine B Versus Time
for Location STP9

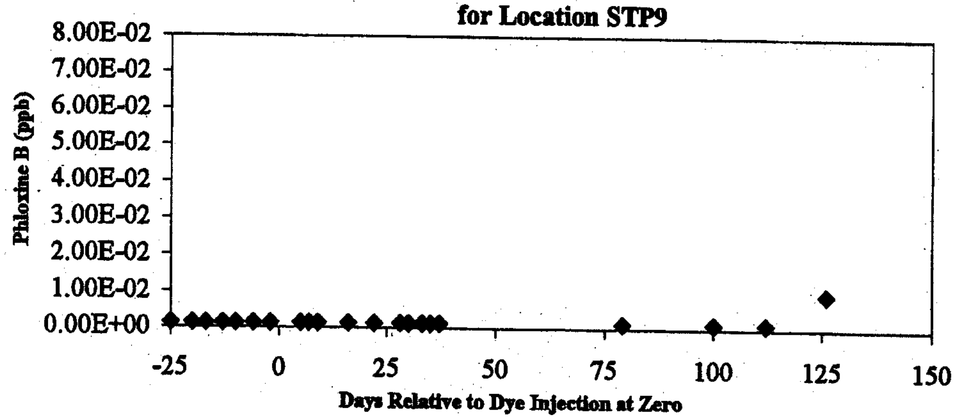
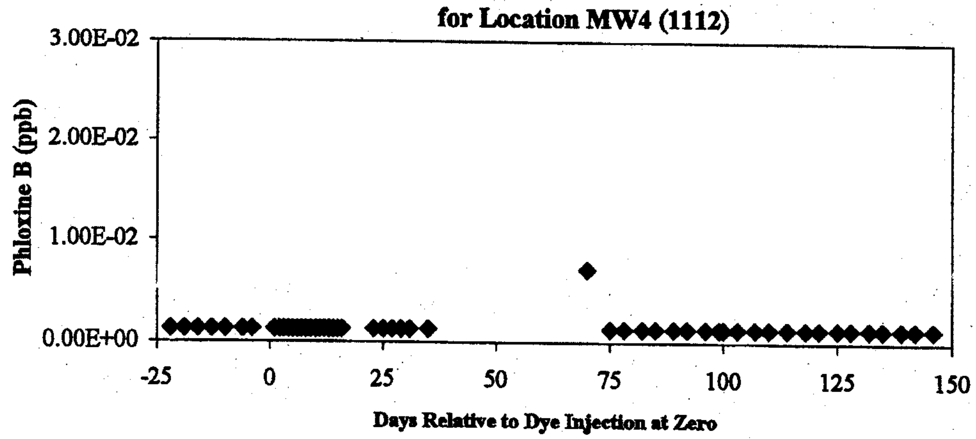


Figure 2-7
Concentrations of Phloxine B Versus Time
for Location MW4 (1112)



Although this is not the exact location for the inlet pipes shown in Figure 1-2, there are no as-built diagrams available to confirm the exact location of the pipes. Drilling activities associated with installation of the ground freezing system revealed the highest concentration of radionuclides in auger cuttings collected in the northwest corner of the former pond, close to where the geophysical anomaly was identified. This high concentration is most likely associated with either a leak in the influent pipe that extends from the HRE building to the former pond or where the pipe emptied into the pond (DOE 1998a).

Water level data collected from standpipes I2 and STP10, during water injection to mobilize the phloxine B dye, revealed that the groundwater elevation in standpipe I2 was higher compared to that in standpipe STP10 (DOE 1998b). The hydrograph for standpipe I2 shows a rapid water level increase and subsequent decrease during water injection to mobilize the phloxine B dye. According to DOE, this fluctuation was caused by groundwater mounding following water injection at standpipe I2. The water level data collected within and outside the area surrounded by the barrier wall also showed that the barrier wall inhibited groundwater recharge into the former pond area. This factor along with water injection at standpipe I2 likely created a temporary gradient reversal in the direction of STP10. This gradient reversal may have transported the phloxine B-laden groundwater laterally through the subsurface pipe to the area near standpipe STP10. Although the exact depth of the subsurface pipe is unknown, the pipe is assumed to be located close to where the highest concentrations of radionuclides were detected during installation of the freeze barrier system. The highest concentration of radionuclides were detected in the northwest corner of the former pond at depths ranging from 10 feet to 14 feet bgs, consistent with the water table which is found at an average depth of 6 to 10 feet bgs in the former pond area (DOE 1998a).

Phloxine B also was detected at concentrations above background at recovery points STP1, STP2, MW4 (1112), and STP9 between 69 and 126 days following dye injection, which was much later than the detection at STP10. Based on the timing of the recoveries and decreased concentrations with distance from recovery point STP10, it does not appear that phloxine B migrated directly to any other location. Available information also indicates that recovery points STP10, STP1, STP2, STP9, and MW4 (1112) may be located within the drainage ditches on the north and west sides of the former pond, outside the containment area. The drainage ditches, which are located around the perimeter of the former pond, were designed to contain any pond overflow and prevent release into the surrounding groundwater system. The ditches are also reportedly below the water table at an elevation of about 804 feet above MSL (DOE 1998a). The ditch locations and flow directions, based on information provided by DOE, are shown on Figure 2-1. The drainage ditches may have provided a preferential pathway to transport the phloxine B from STP10 to recovery points STP1, STP2, STP9, and MW4 (1112) which were located downgradient of STP10.

As previously discussed, the dye tracing investigation conducted in 1996 demonstrated that groundwater within the former pond is hydraulically active and connected to the surrounding soil. The tracer dye eosine OJ injected into center standpipe I2 was transported radially throughout the surrounding area to recovery points MW2 (1110), MW3 (1111), MW4 (1112), W674, STP10, W898, STP2, SBC, STP9, S3, S5, and DLD. This was not the case during the demonstration investigation using phloxine B as shown in Figure 2-1. Table 2-1 compares the results of the 1996 investigation with the demonstration investigation from tracer dye injection point standpipe I2.

During the technology demonstration, TDEC state regulators also collected surface water samples from the weir box located in the outfall about 40 feet southeast of the former pond, to compare radionuclide levels during and after development of the barrier wall. Surface water sampling results from July through September 1998 showed slightly lower levels of gross beta activity. However, sampling results should be qualified until long-term results are made available because the samples were collected during the dry season when gross beta activity is generally lower (TDEC 1998). See Figure 2-8 for surface water sampling results.

Eosine OJ Results

The tracer dye transport behavior of eosine OJ, injected into monitoring well MW1 (1109), observed during the demonstration dye tracing investigation differed from the dye tracing investigation conducted by EPA in 1996, suggesting that the barrier wall had an effect on horizontal groundwater flow in the former pond area. The 1996 investigation showed rhodamine WT dye tracer transport from injection point MW1 (1109) to most of the downgradient recovery points including DLD, SBC, MW2 (1110), MW3 (1111), MW4 (1112), STSS, STP2, STP9, STP10, W674, W898, and S3 through S7 (EPA 1996).

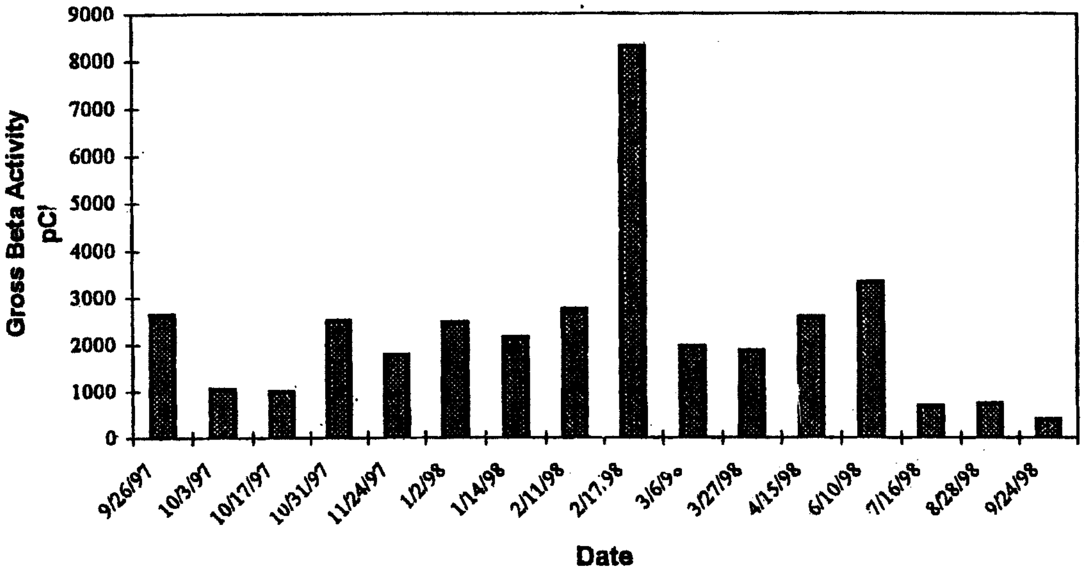
TABLE 2-1

COMPARISON OF ANALYTICAL RESULTS FROM THE 1996 INVESTIGATION WITH THE RESULTS OF THE DEMONSTRATION DYE TRACING INVESTIGATION FOR STANDPIPE I2

Recovery Point	Initial Detection (days)[a]	Initial Concentration (ppb)	Peak Detection (days)[a]	Peak Concentration (ppb)
1996 Investigation Using Eosine OJ				
MW2 (1110)	15	1.10e-02	43	6.71e-02
MW4 (1112)	22	5.29e-03	36	2.68e+00
MW3 (1111)	22	4.04e-02	43	1.32e-01
W674	39-43	Not Determined[b]	43	1.25e+00
STP10	39-43	Not Determined[b]	43	1.79e-01
W898	39-43	Not Determined[b]	43	4.98e+00
STP2	43	1.10e-05	64	2.03e+00
SBC	43-50	Not Determined[b]	50	4.19e-01
STP9	50	1.10e-05	64	2.85e-02
S5	50-56	Not Determined[b]	55	5.67e+00
S3	50-56	Not Determined[b]	55	1.65e-01
DLD	56	1.64+01	71	4.29e+01
Demonstration Investigation Using Phloxine B				
STP10	16	3.20e-01	16	3.20e-01
AFIP	69	7.99e-01	69	7.99e-01
MW4 (1112)	70	7.10e-03	70	7.10e-03
STP2	79	2.03e-02	100	2.24e-02
STP1	100	2.03e-02	100	2.03e-02
STP9	126	9.40e-03	126	9.40e-03

Notes:
[a] number of days following tracer dye injection
ppb parts per billion
[b] initial concentration could not be determined due to the sampling frequency

Figure 2-8
Gross Beta Activity in Surface Water Samples Collected From Weir Box



The demonstration dye tracing investigation only showed tracer dye (eosine OJ) transport from injection point MW1 (1109) to recovery points STP1, STP2, STP9, MW4 (1112), and DLD. This change in transport behavior is likely due to diversion of dye-laden groundwater around the barrier wall. This behavioral change is apparent in the eosine OJ analytical data for recovery point MW4 (1112), where the highest concentration detected during the investigation did not occur until 2 weeks prior to the end of the technology demonstration (Cambrian 1998). Figures 2-9 through 2-13 plot the concentration of eosine OJ against days relative to dye injection for dye recovered at each location.

Results from the 1996 dye tracing investigation also showed tracer dye transport to the furthest recovery points (from monitoring well MW1 [1109]) along the tributary (SBC and S3 through S7) sooner than the closest locations (STP2, W898, W674, and DLD) (EPA 1996). Tracer dye appeared to bypass the upgradient recovery points and discharge directly into the tributary, indicating that a preferential pathway may exist on the north side of the former pond. Tracer dye transport from injection point MW1 (1109) to the tributary was not observed during the demonstration dye tracing investigation, indicating that horizontal groundwater flow may have been impeded or retarded as a result of the barrier wall. Table 2-2 compares the results of the 1996 investigation with the demonstration investigation from tracer dye injection point MW1 (1109).

2.1.4 Groundwater Elevation Results

Information on water level results discussed in this section is based on data gathered by DOE and presented in a report entitled "HRE-Pond Cryogenic Barrier Technology Demonstration: Pre- and Post-Barrier Hydrologic Assessment" prepared by Dr. Gerilynn Moline, ORNL Environmental Sciences Division. Hydrographs plotting average water table elevations before, during, and after emplacement of the barrier wall for standpipes I2 and STP10 and monitoring well MW2 (1110) are included in Figures 2-14 through 2-16. The following sections describe the groundwater conditions encountered before and after establishment of the barrier wall in the former pond area.

Figure 2-9
Concentrations of Eosine OJ Versus Time for Location STP1

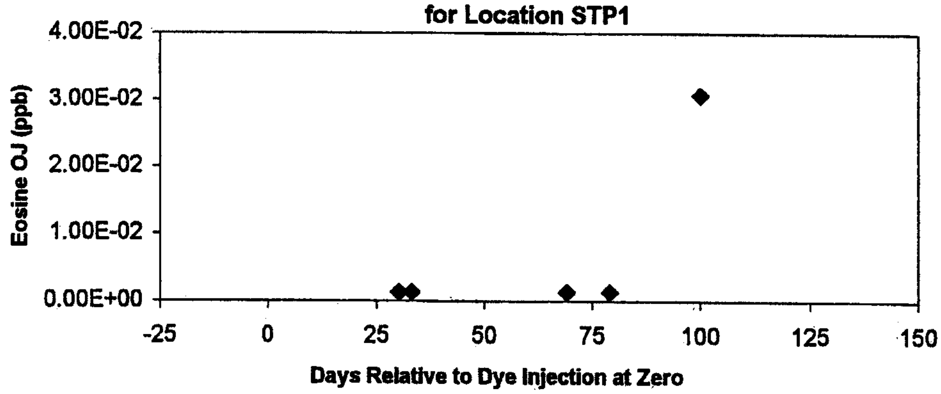
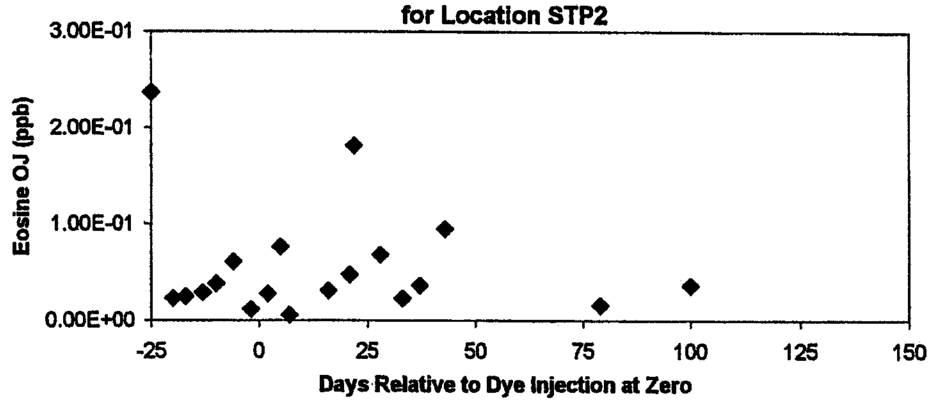


Figure 2-10
Concentrations of Eosine OJ Versus Time for Location STP2



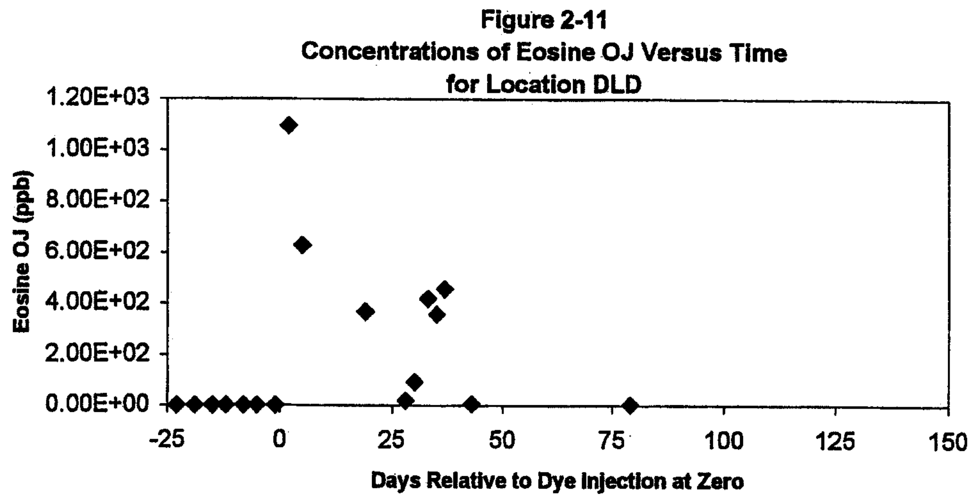


Figure 2-11
Concentrations of Eosine OJ Versus Time
for Location DLD
1.20E+03
1.00E+03
8.00E+02
6.00E+02
4.00E+02
2.00E+02
0.00E+00
Eosine OJ (ppb)
-25
0
25
50
75
100
125
150
Days Relative to Dye Injection at Zero

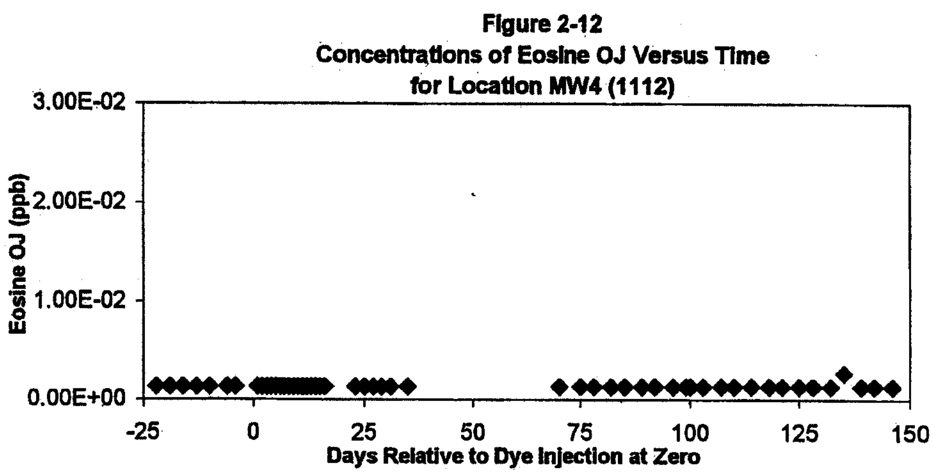


Figure 2-12
Concentrations of Eosine OJ Versus Time
for Location MW4 (1112)
3.00E-02
2.00E-02
1.00E-02
0.00E+00
Eosine OJ (ppb)
-25
0
25
50
75
100
125
150
Days Relative to Dye Injection at Zero

Figure 2-13
Concentrations of Eosine OJ Versus Time for Location STP9

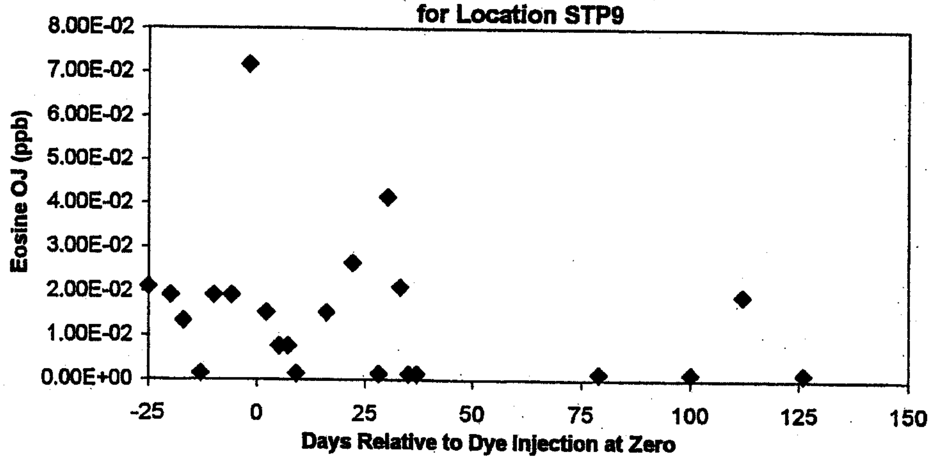


TABLE 2-2

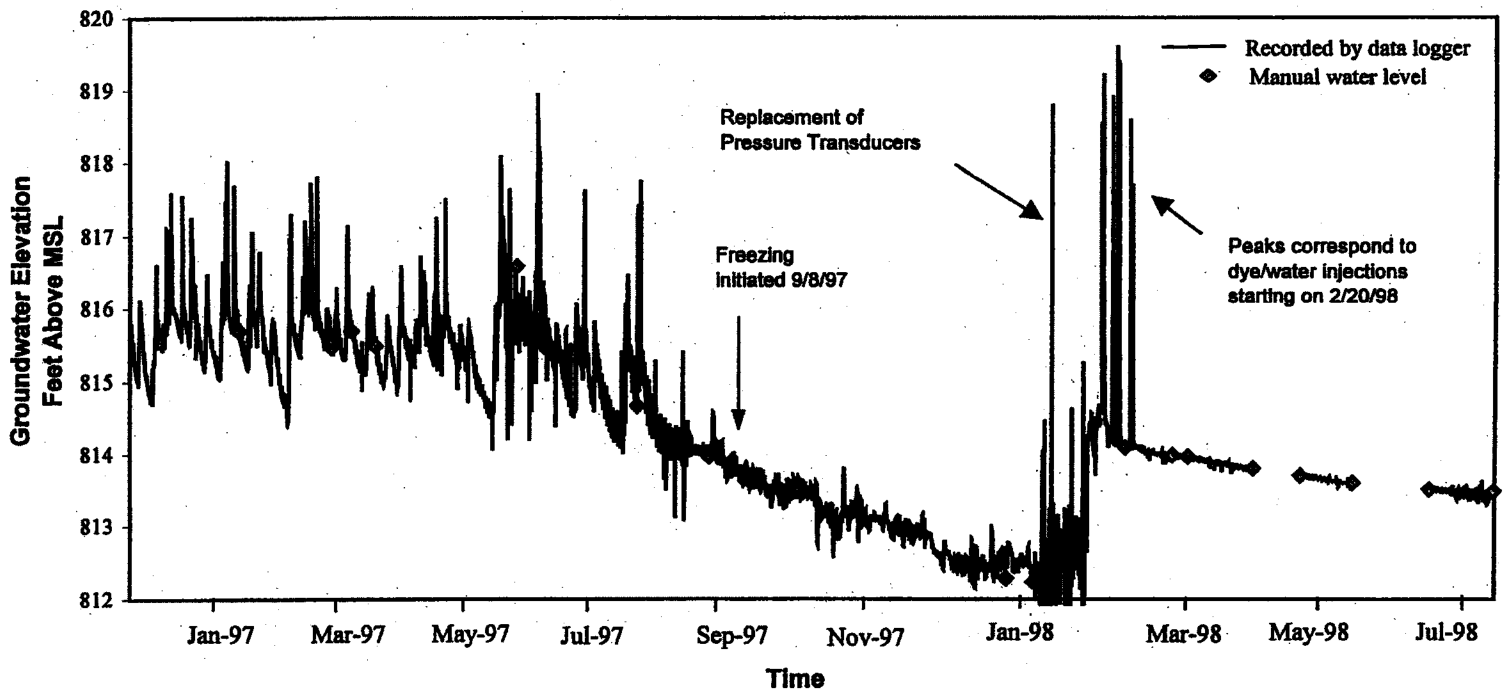
COMPARISON OF ANALYTICAL RESULTS FROM THE 1996 INVESTIGATION WITH THE RESULTS OF THE DEMONSTRATION DYE TRACING INVESTIGATIONS FOR MONITORING WELL MW1 (1109)

Recovery Point	Initial Detection (days)[a]	Initial Concentration (ppb)	Peak Detection (days)[a]	Peak Concentration (ppb)
1996 Investigation Using Rhodamine WT				
SBC	2	1.20e-05	8	3.27e-01
S7	4	1.00e-01	71	2.15e+01
S6	4	1.06e-01	15	7.86e+00
S5	4	1.12e-01	15	5.41e+00
S3	4	2.95e-01	15	1.24e+01
S4	4	1.16e-01	15	9.09e+00
DLD	5	3.70e+01	8	8.36+01
MW2 (1110)	15	2.83e-01	15	2.83e-01
MW3 (1111)	15	6.48e-03	71	1.76e-02
MW4 (1112)	15	8.81e-03	36	1.20e-02
STSS	22	9.60e-04	28	5.50e-03
STP10	39-43	Not Determined [b]	43	4.90e-02
W674	43	8.45e-02	64	2.91e-01
W898	43	1.78e-01	64	3.38e-01
STP2	43	1.20e-05	56	1.59e-02
STP9	50	1.20e-07	56	3.63e-02
Demonstration Investigation Using Eosine OJ				
STP1	97	3.07e-02	97	3.07e-02
STP2	3	2.75e-02	25	1.82e-01
STP9	2	1.52e-02	27	4.15e-02
MW4 (1112)	137	2.70e-03	137	2.70e-03
DLD	2	1.09+03	2	1.09+03

Notes:

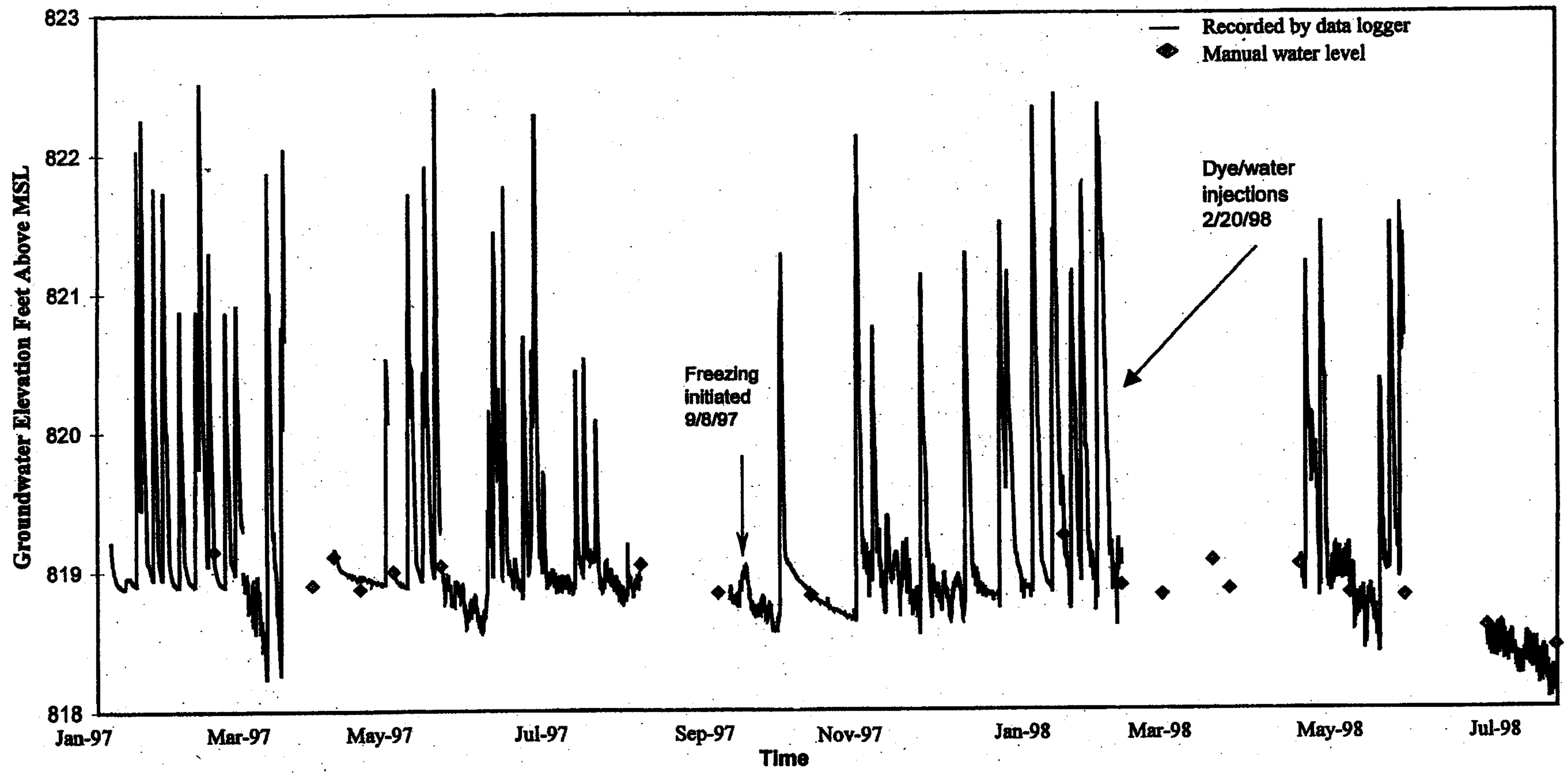
[a] number of days following tracer dye injection
ppb parts per billion
[b] initial concentration could not be determined due to the sampling frequency

Figure 2-14
Hydrograph for Standpipe I2



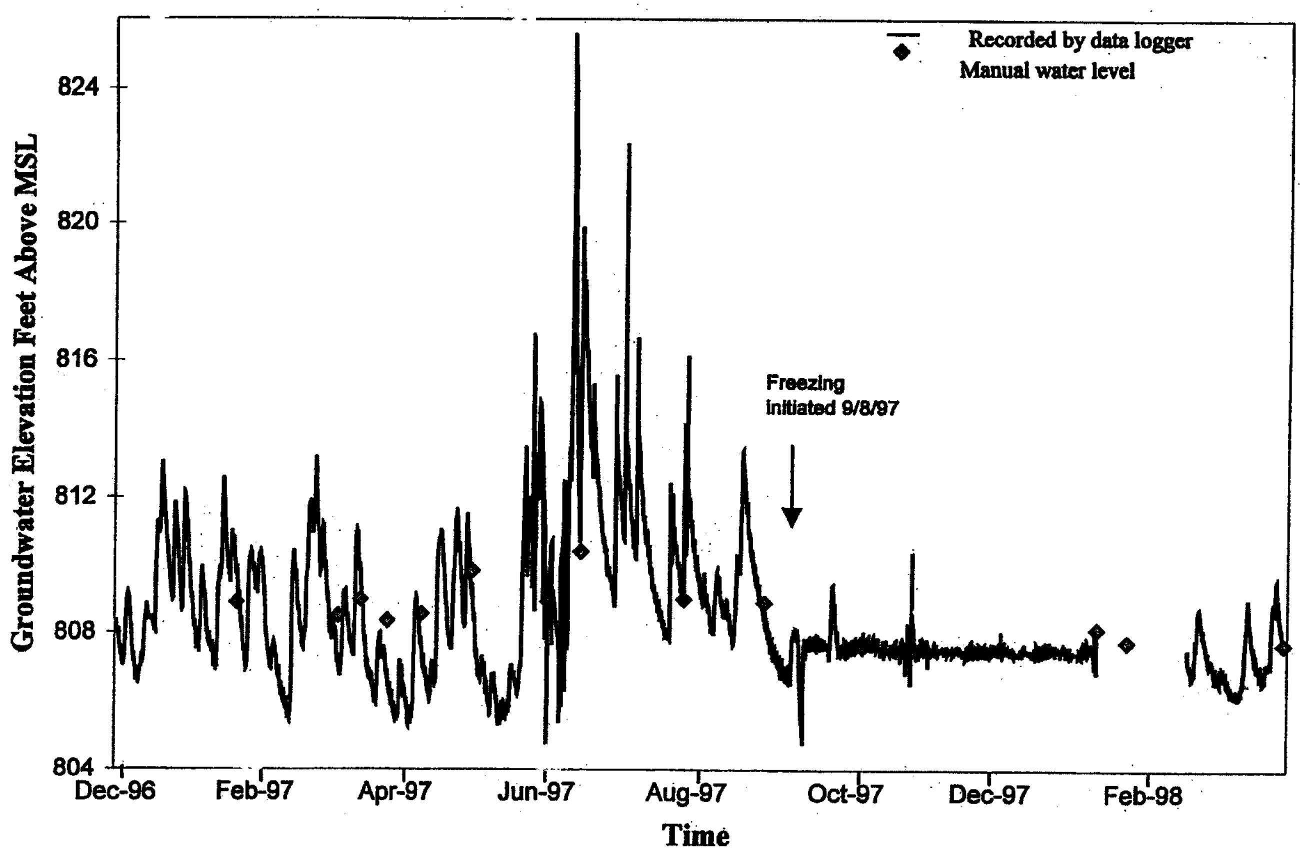
Source: DOE 1998b

Figure 2-15
Hydrograph for Standpipe STP10



Source: DOE 1998b

Figure 2-16
Hydrograph for Monitoring Well MW2 (1110)



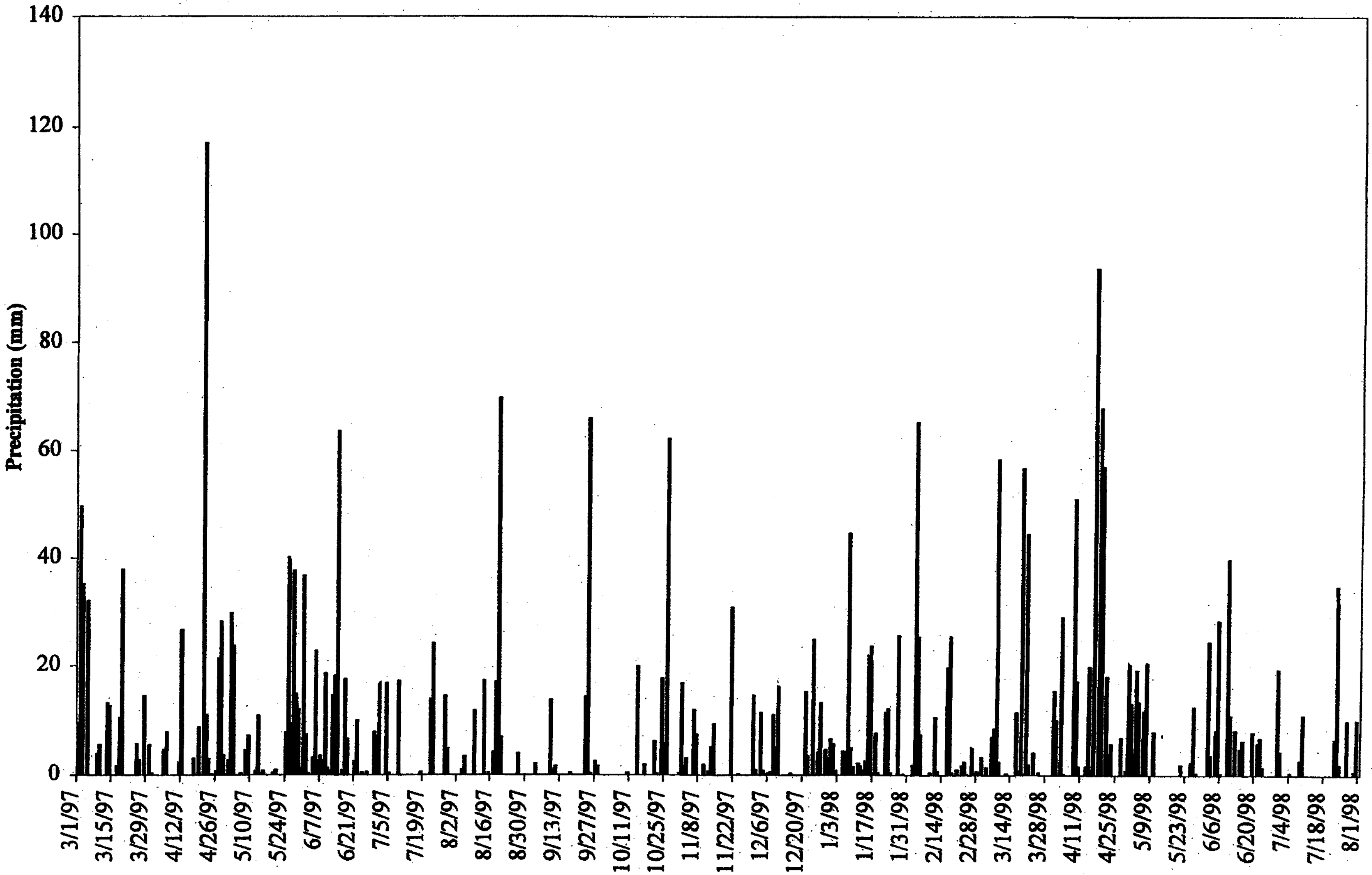
DOE 1998b

Pre-Barrier Groundwater Conditions

Water level data collected from monitoring locations I2, STP10, and MW2 (1110) compared to precipitation data presented in Figure 2-17 indicates that all three monitoring points were responsive to storm events prior to establishment of the frozen soil barrier. The data also show that all three monitoring locations exhibited similar water level fluctuations during storm events. The rapid rise in groundwater elevations at standpipe I2 during some storm events also suggests that the water table may intersect the gravel layer beneath the asphalt cap, thereby providing a pathway for migration of contaminants out of the former pond through this high permeable layer. This relationship can be seen in the hydrograph for standpipe I2, where the elevation from the top of the asphalt cap at standpipe I2 is 818.5 feet above MSL and the groundwater elevation at standpipe I2 frequently exceeded 817 feet above MSL during storm events. The cap is assumed to be 1 foot thick (DOE 1998b). Groundwater elevation data also show a hydraulic gradient in the direction of the tributary, located just east of the former pond, indicating that there is potential for contaminants to be transported through the shallow groundwater system, eventually discharging into the tributary.

The 1996 groundwater tracing investigation conducted by EPA, discussed in more detail in Section 1.4.6, also shows that groundwater within the former pond is hydraulically active and connected to the surrounding soils, as evidenced by the transport of tracers from within the pond to areas outside the pond. The dye eosine OJ, injected into center standpipe I2 under forced-gradient conditions during water injection, was transported radially throughout the area surrounding the former pond. The rhodamine WT dye injected into monitoring well MW1 (1109) showed that a preferential pathway may exist on the north side of the former pond between monitoring well MW1 (1109) and the tributary located just east of the pond. Rhodamine WT was transported directly to the tributary and bypassed on site recovery points directly in line with the tributary. DOE's study using helium gas demonstrated that transport out of the former pond also occurs under ambient conditions and is more frequent during the winter months when water levels are highest (DOE 1998b).

Figure 2-17
Oak Ridge Precipitation Data from March 1997 through July 1998



Source: DOE 1998b

Post-Barrier Groundwater Conditions

Groundwater measurement results showed that the water level within the former pond was significantly affected by the barrier wall. As demonstrated in the hydrograph for standpipe I2, the measured water table elevations gradually decreased over time and did not appear to respond to storm events (compared to locations outside the containment area) after freezing was initiated (see Figure 2-14). According to AFI, the slow decline in water levels at standpipe I2 is a result of soil moisture being drawn to the frozen soil barrier (AFI 1998). The slow decline also may have been a result of slow seepage through fractured bedrock in the base of the former pond, combined with the inhibited recharge induced by the barrier wall. The hydrograph for standpipe I2 also shows some distinct peaks just prior to the demonstration groundwater tracing investigation that do not reflect actual water table fluctuations that require some explanation. According to DOE, the water level monitoring system at standpipe I2 was not maintained due to budgetary problems, which resulted in moisture buildup in the pressure transducer. The pressure transducer was replaced just prior to initiation of the demonstration groundwater tracing investigation, which reportedly displaced the water level in standpipe I2, resulting in fluctuations in the hydrograph for standpipe I2. The only other water level responses seen in the hydrograph for standpipe I2 correspond to water injections that occurred for 5 days following dye injection, even though there were numerous storm events during this period as seen in the precipitation data presented in Figure 2-17 (DOE 1998b). As seen in the hydrograph for standpipe I2, there appeared to be a slow decline in water levels at standpipe I2 following the initial increase caused by dye and water injections.

Water table elevations downgradient of the former pond were also affected by the frozen soil barrier. DOE reported that the water level in standpipe STP5 dropped about 6.5 feet following barrier placement. DOE also reported that water levels at standpipe STP6 were not as responsive to storm events following barrier placement and that only large storms produced the type of response observed at STP6 prior to barrier placement. This effect also shows that horizontal groundwater flow through the former pond to these downgradient locations was impeded or that flow was diverted around the barrier wall, resulting in suppression of the water table at these locations (DOE 1998b).

2.1.5 Subsurface Soil Temperature Results

Continuous subsurface temperature data were collected from eight temperature monitoring points at various locations and distances from the Thermoprobes to monitor the development of the frozen soil barrier wall (see Figure 1-5). Six temperature monitoring points (T-3 through T-8) installed in the southeast corner of the containment area were used to monitor development of the barrier wall. Each temperature monitoring point was equipped with eight temperature sensors installed at various depths to provide a vertical profile of temperature conditions at each location. Figures 2-18 through 2-23 plot temperature at each sensor interval against time for temperature monitoring points T-3 through T-8 to show a vertical profile of temperature response with distance from the barrier. Temperature data from each sensor interval were averaged for each month to facilitate presentation of data in Figures 2-18 through 2-23.

The ground freezing system operated in three phases: initial freeze-down, freezing to design thickness, and maintenance freezing. During the freeze-down phase, which began in mid-September 1997, the two refrigeration units operated simultaneously, driving the 50 thermoprobes at temperatures below 0° C. Gradually, the soil temperature was reduced until the soil moisture around each thermoprobe was frozen and began coalescing, which occurred about mid-October 1997. According to AFI, this process was continued until the frozen soil region around each thermoprobe reached about 3 feet in thickness radially and completely joined at the surface of the asphalt pavement, which occurred around the first week of November 1997 (see Figure 2-18) (AFI 1998). This process, which is referred to as "freezing to closure," occurred about 7 weeks following system start-up.

Following closure, AFI reported that freezing was continued until the frozen soil wall reached the design thickness of 12 feet, which occurred in mid-January 1998, or about 18 weeks following system startup (AFI 1998). According to AFI, the design thickness was selected based on AFI's past experience using the thermoprobe placement configuration similar to that applied to the HRE pond site. As shown in Figure 2-18, subsurface temperatures at T-3 (located directly on the centerline of the barrier) from the bottom of the insulation to 30 feet bgs remained well below 0° C, from mid-January through mid-July 1998. According to AFI, the frozen soil barrier probably extended to a depth of about 36 feet bgs, into the bedrock. However, this claim cannot be confirmed because the deepest temperature sensors are set at about 30 feet bgs along the length of the temperature monitoring points.

Figure 2-18
Subsurface Temperature Data Over Time for T-3

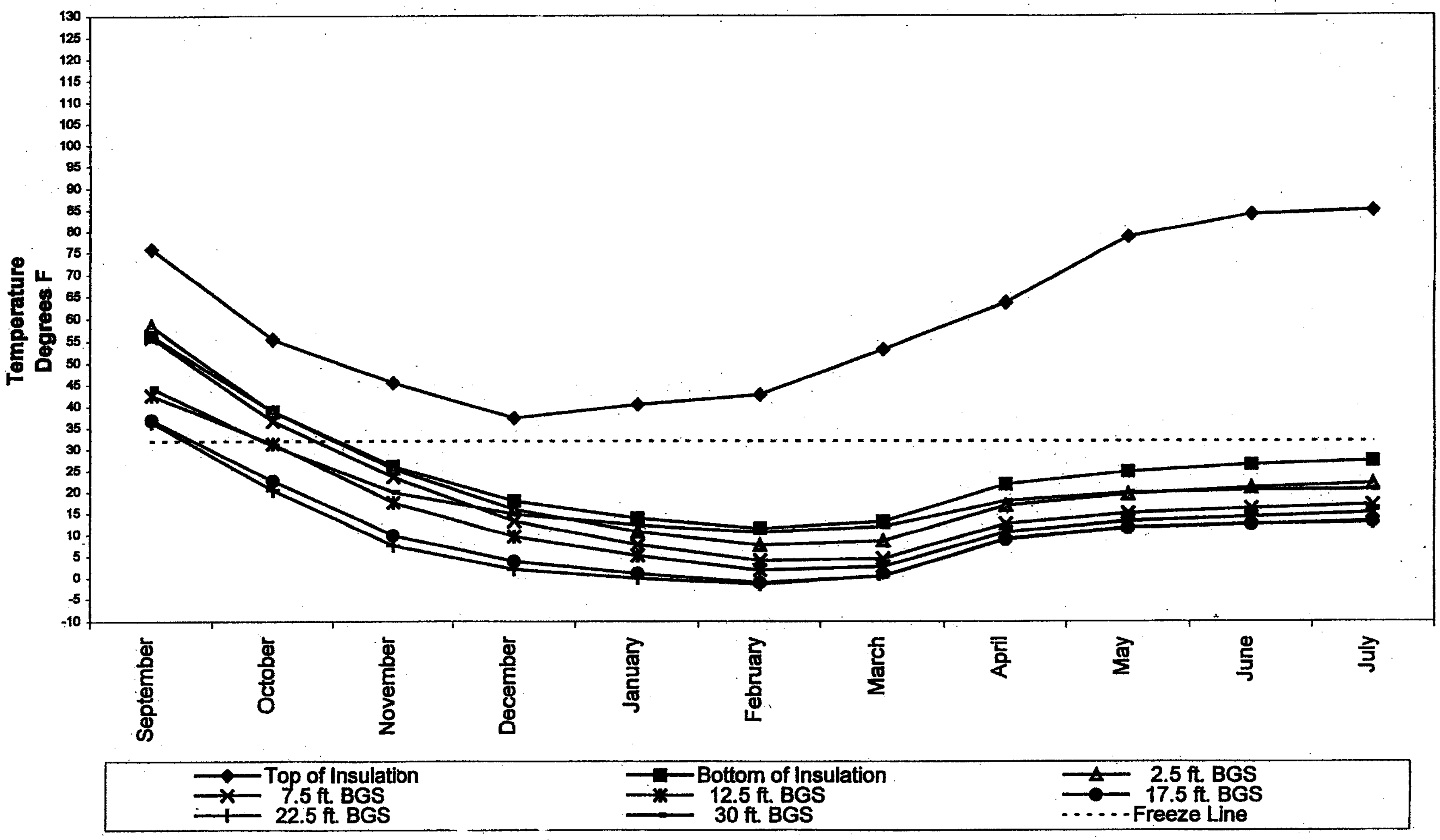


Figure 2-19
Subsurface Temperature Data Over Time for T-4

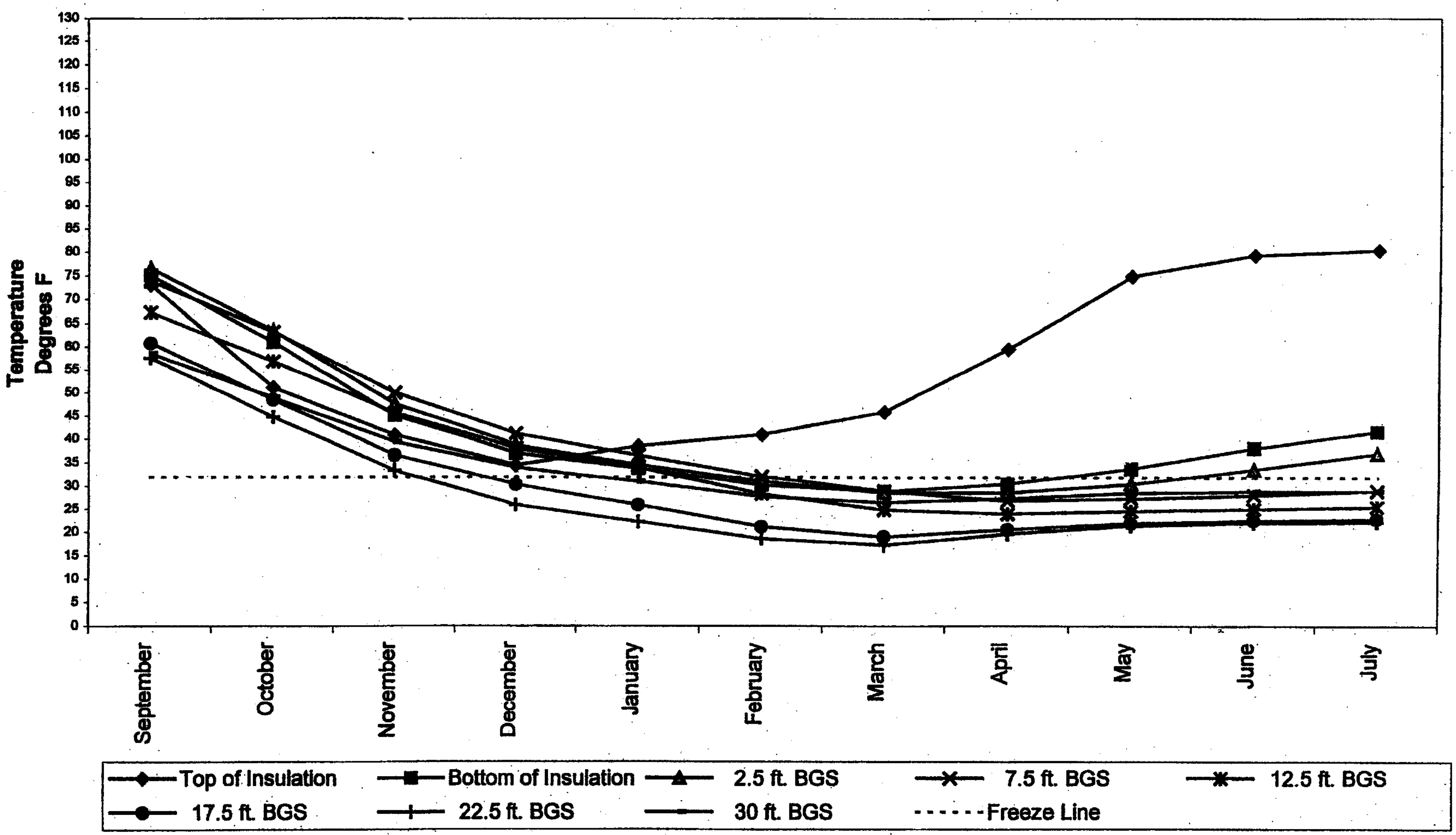


Figure 2-20
Subsurface Temperature Data Over Time for T-5

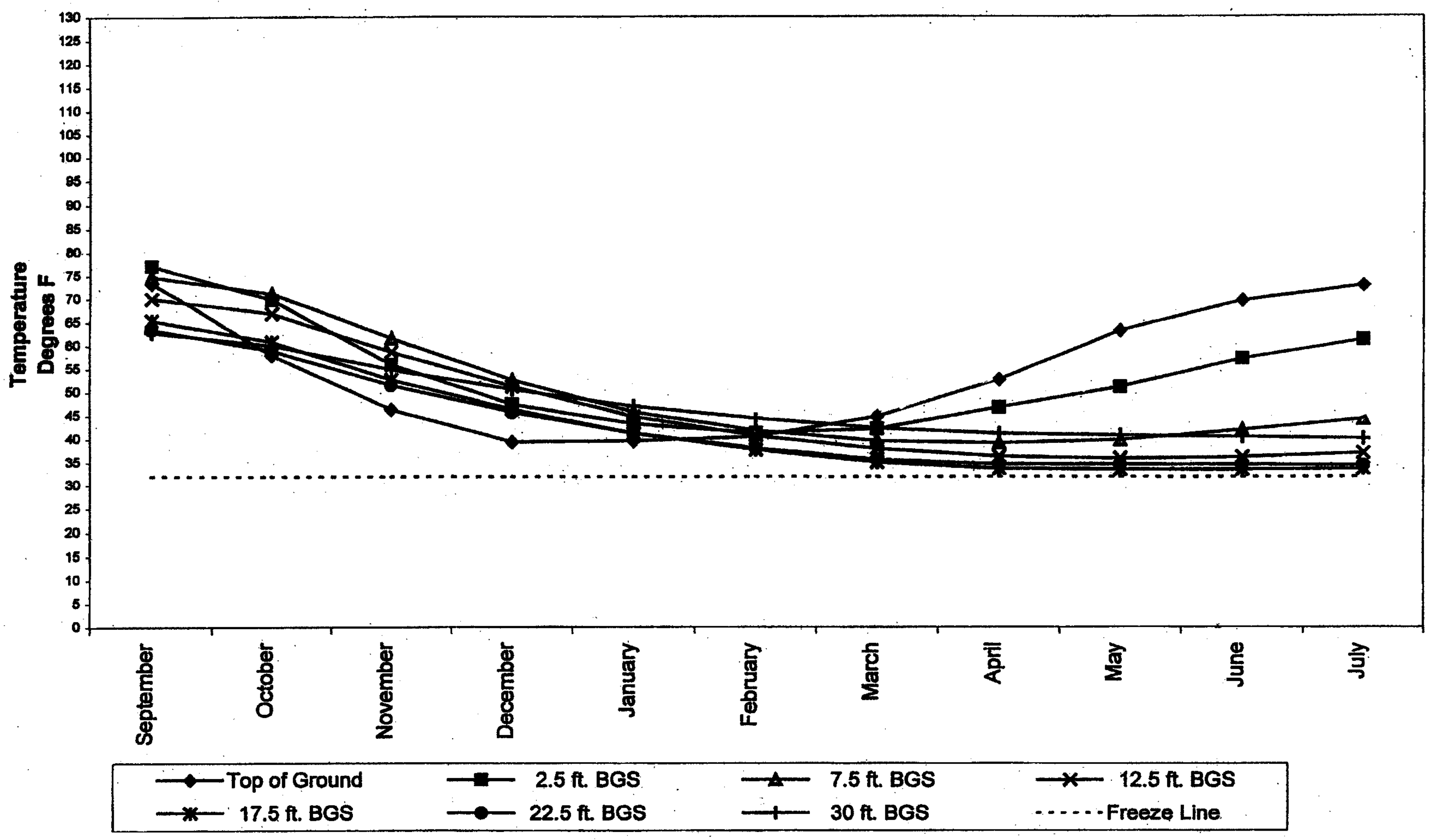


Figure 2-21
Subsurface Temperature Data Over Time for T-6

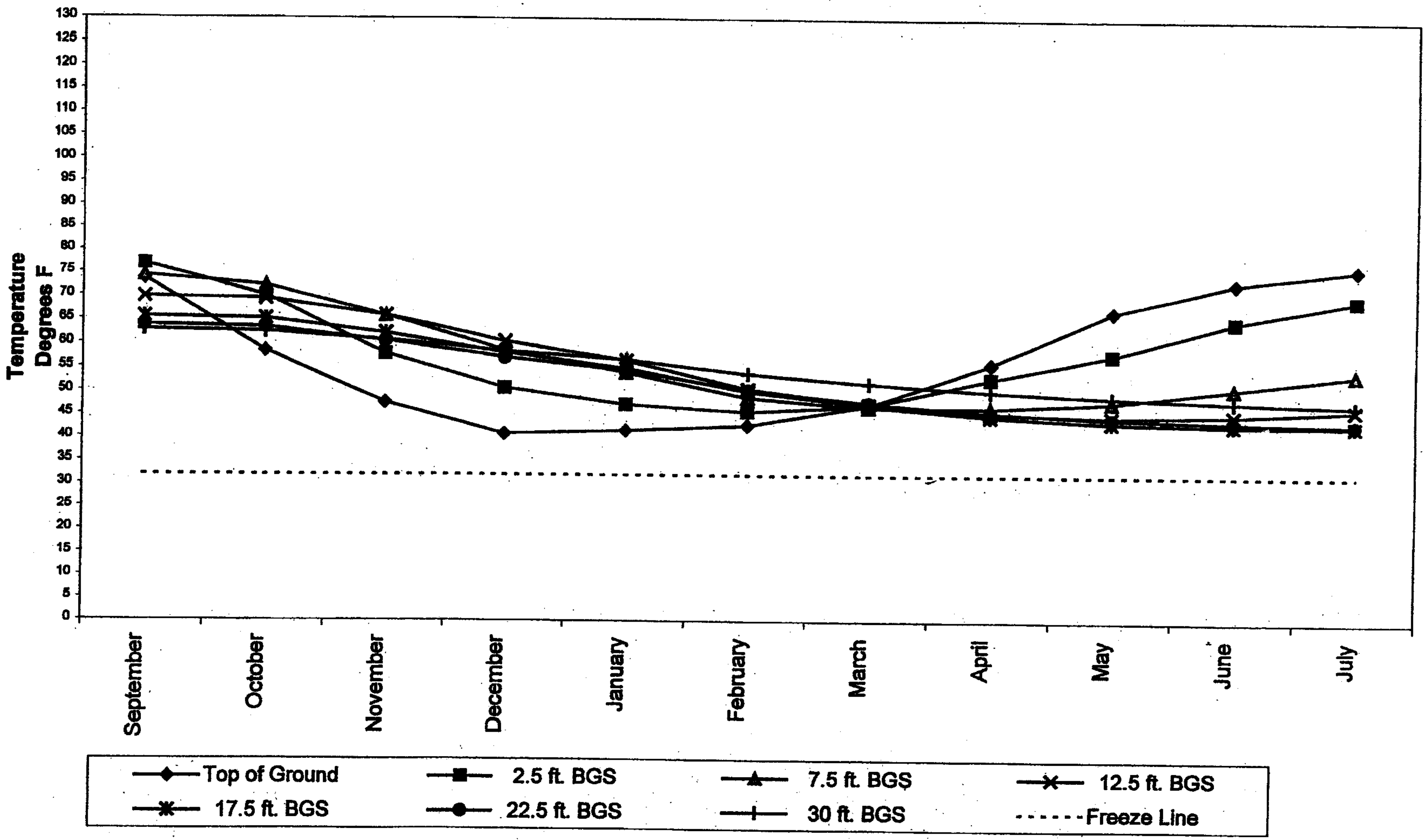


Figure 2-22
Subsurface Temperature Data Over Time for T-7

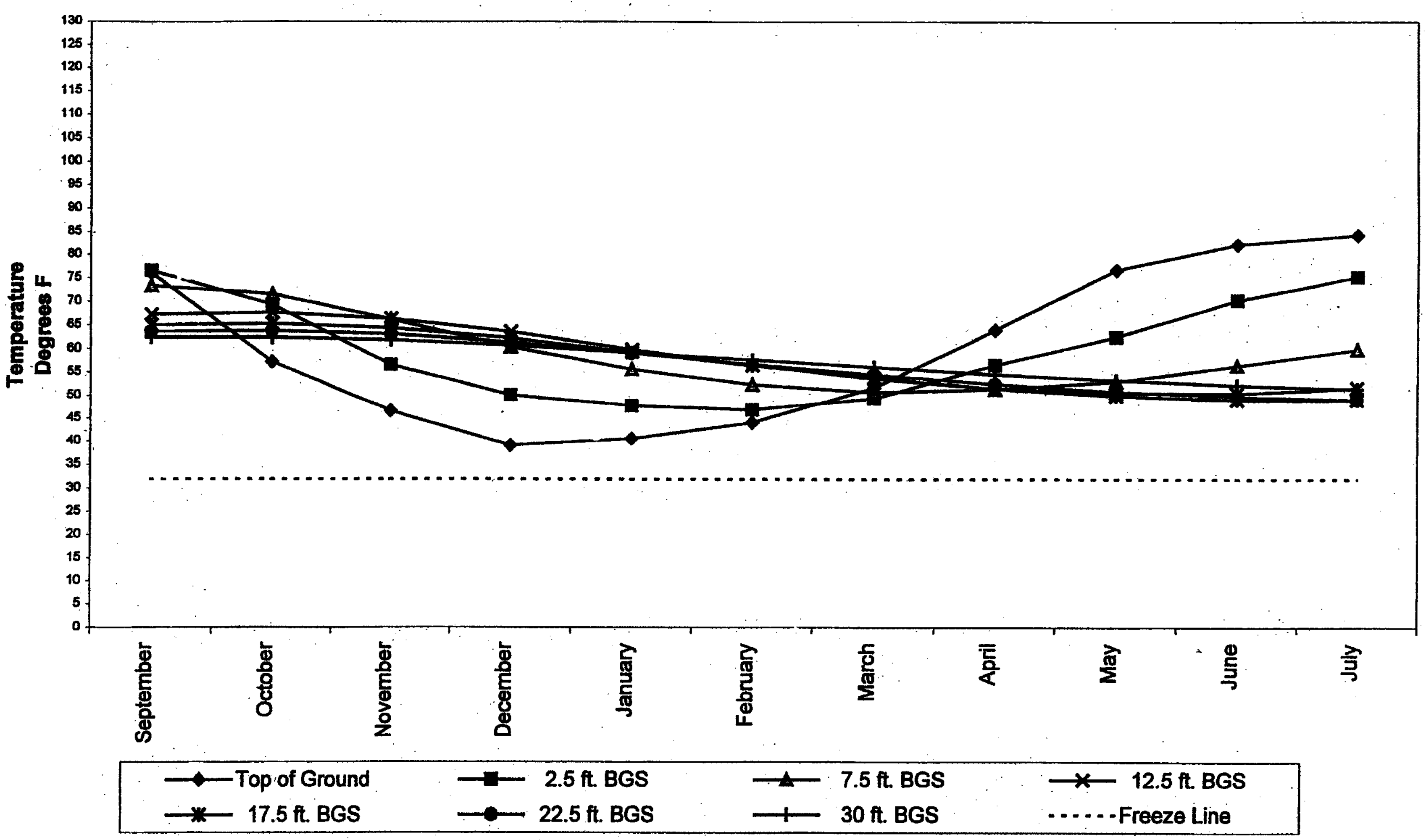
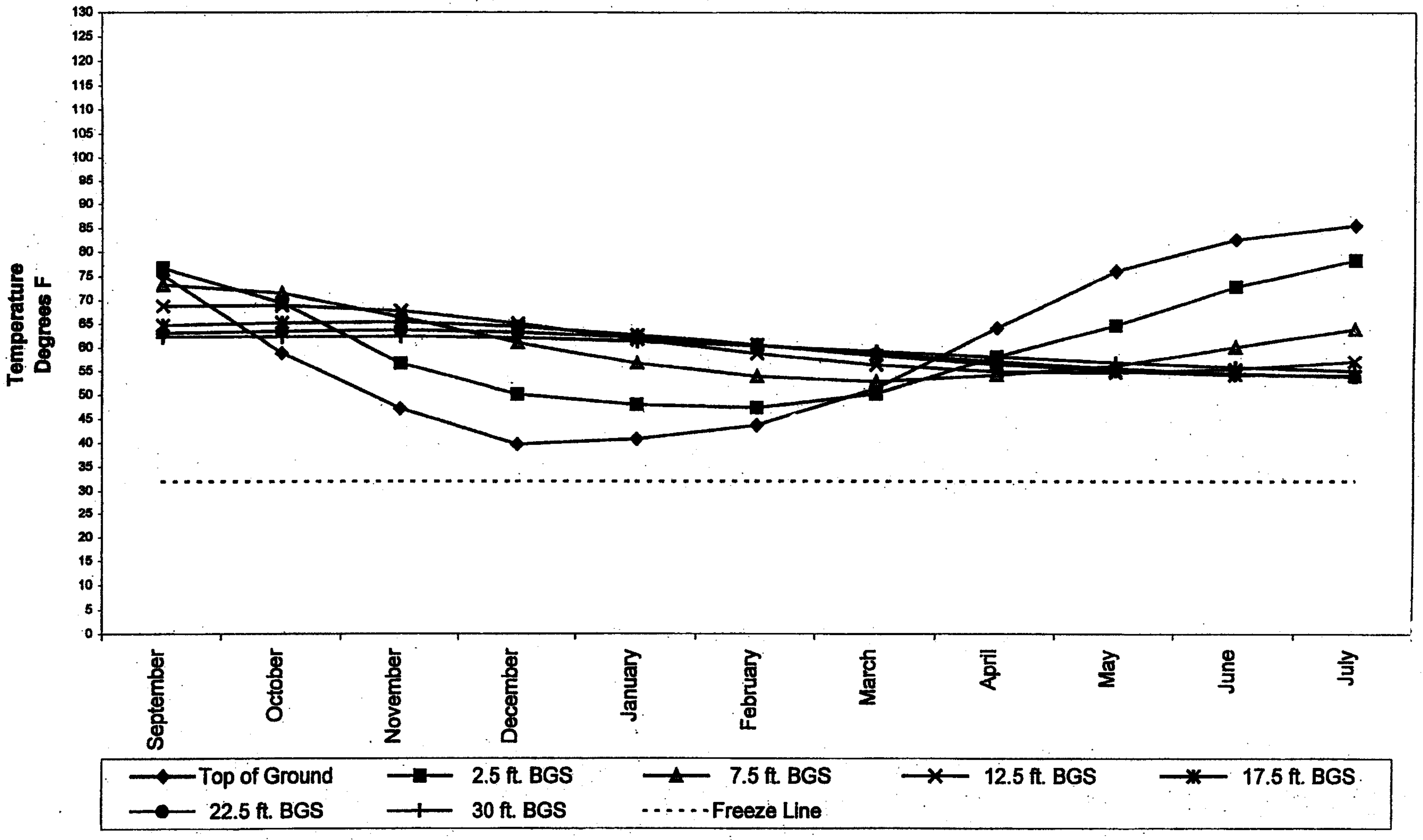


Figure 2-23
Subsurface Temperature Data Over Time for T-8



Once the design thickness was achieved, the maintenance freezing phase began and the refrigeration units operated on a 24-hour alternating run schedule to minimize power consumption. Maintenance freezing required significantly less energy then the initial freezedown. According to AFI, the barrier wall thickness remained fairly constant during this phase and will be maintained at the HRE pond site through fiscal year 2002 for DOE. The total volume of soil frozen was estimated to be about 134,000 cubic feet and the total volume of soil contained was estimated to be about 180,000 cubic feet (AFI 1998).

In late September 1998, AFI simulated a power outage at the HRE pond site. The refrigerant feed to the array of Thermoprobes was shut down for a period of 8 days while subsurface temperature data were continuously collected. AFI reported that ambient air temperatures during this period averaged between 32° C and 24° C. The barrier reportedly lost less than 2 percent of its design thickness during this period, with the maximum loss at the top of the barrier, just beneath the insulation. However, subsurface temperature data collected from T-3 showed that the centerline of the barrier from the bottom of the insulation to 30 feet bgs remained frozen throughout the 8-day testing period (AFI 1998).

2.1.6 Installation and Operating Costs

The cost to implement the freeze barrier technology at the HRE pond site was determined by assessing the following 12 cost categories.

1. Site preparation
2. Permitting and regulatory requirements
3. Capital equipment
4. Mobilization and startup
5. Labor
6. Supplies
7. Utilities
8. Effluent treatment and disposal
9. Residual waste shipping and handling
10. Analytical services
11. Equipment maintenance
12. Site demobilization

The actual costs associated with the implementation of the freeze barrier technology at the HRE pond site are presented and analyzed in Section 4.0. The demonstration costs are grouped into 12 cost categories, and a breakdown of these costs under the 12 cost categories is presented in Table 4-1 and Figure 4-1.

2.1.7 Data Quality

A data quality review and assessment was conducted to remove unusable values from the investigation data set, to evaluate the field and laboratory QC sample results, and to assess the overall data quality. All project data specified in the project QAPP that were collected to directly support demonstration objectives were reviewed, including those data relating to physical measurements.

The only critical measurement (measurement required to support a primary objective) was the fluorescent dye data concentration in groundwater and in the eluant from charcoal packet samples. A detailed review of the analytical data for these dyes was therefore conducted. Data from field QC samples and laboratory QC samples were reviewed to estimate the precision of the results and to demonstrate that measurements were not affected by cross-contamination. The QC data were evaluated against the QA objectives defined in the Freeze Barrier Technology Demonstration QAPP (EPA 1998). Accuracy was not an issue, since only relative values were of interest. For this reason, a QA objective and QC samples to evaluate accuracy were not required. The QC samples included laboratory blanks and sample duplicates. Initial and continuing calibrations were also reviewed to assure that proper procedures were implemented.

The following specific items were evaluated during the data review:

- Sample chain of custody, condition, and holding times
- Instrument performance checks
- Initial and continuing calibrations
- Blanks
- Sample/sample duplicate precision

The following subsections discuss the results of quality control activities that were implemented in relation to the fluorescent dye measurements and summarize any limitations of the analytical data based on the evaluation of QC sample results. It should be recognized that the fluorescent dye data was used to indicate whether penetration of a barrier had occurred; therefore, the most important issue was whether detections of dye could be differentiated from background fluorescence. The review of overall data quality indicates that the fluorescent dye data are useful for the purpose of evaluating the technology.

Sample Chain-of-Custody, Condition, and Holding Times

All samples collected at the demonstration site were hand-delivered from the field to the laboratory in good condition. Chain-of-custody protocols were followed for all samples delivered to the laboratory. Samples for analysis of dyes were analyzed or prepared within 2 weeks of sample collection, as specified in the QAPP.

Instrument Performance Check

Instrument performance checks were performed on an as-needed basis or whenever the spectrofluorophotometer was moved, serviced, or its components (for example, xenon lamps) were changed or serviced. Standard and blank results were used to assess instrument performance on a day-to-day basis. No anomalous results were documented during the daily analyses of the standards and blanks.

Initial and Continuing Calibrations

All calibration curves were linear with regression coefficients typically near 0.999. Calibration curves were constructed and plotted when standards were prepared and after all the samples were analyzed. For the C.I. Acid Red 92 (Phloxine B) dye, calibration data were produced for that specific batch of dye (in water samples). The calibration curve was plotted and included in each data package. No calibration was performed for charcoal eluant analyses, since these data are qualitative.

Blanks

The spectrofluorophotometer is capable of consistently detecting the dyes used in this investigation at concentrations of 0.0065 ppb. No tracers were reported in any of the laboratory blanks, indicating no laboratory contamination or interferences. Each laboratory blank was prepared in a clean, new test tube using either distilled water or Oak Ridge tap water. Oak Ridge tap water is representative as a blank, since it has background fluorescence but does not contain any dye. Eluant blanks were prepared from each new batch of eluant, and rinsed in one of the containers that would be used for preparation. If dye had been detected in a blank, the batch of eluant would have been discarded and a new batch prepared from new reagents; however, this was not necessary during analysis of the demonstration samples.

Sample/Sample Duplicate Precision

A comparison of sample and sample duplicate results indicates that most of the field duplicate results were within the QA objective of ± 25 percent relative percent difference (RPD). Out of 32 sample duplicates that were processed, only four had RPDs of greater than 25 percent. Overall, precision of the data appeared adequate.

The reason for the higher RPD percentages in the four duplicate samples that were outside of the QA objective is thought to be related to varying levels of flocculant and associated fluorescence of $Fe(OH)_2$ in the sample as compared to the duplicate. Variation in the amount of flocculant present between samples and their duplicates was observed on at least one occasion due to imperfect decanting of the supernatant.

3.0 TECHNOLOGY APPLICATIONS ANALYSIS

This section discusses the following topics regarding the applicability of the freeze barrier technology: applicable waste, factors affecting technology performance, site characteristics and support requirements, material handling requirements, technology limitations, potential regulatory requirements, and state and community acceptance. Information in this section is based on the results of the site demonstration at ORNL and additional information provided by AFI and other sources.

3.1 APPLICABLE WASTE

According to AFI, the frozen soil barrier can provide subsurface containment for most biological, chemical, and radioactive contaminants transportable in groundwater. At the HRE pond site, the SITE Program demonstration primarily examined the technology's ability to contain the radioactive contaminants Cs^{137} and Sr^{90}. A contaminant's effects on barrier wall integrity should be evaluated prior to implementing this technology at any contaminated site.

3.2 FACTORS AFFECTING TECHNOLOGY PERFORMANCE

Factors potentially affecting the performance of the freeze barrier technology include site hydrogeologic characteristics, engineered structures, and diffusion characteristics.

3.2.1 Hydrogeologic Characteristics

The technology's implementability is affected by the depth to and saturated thickness of the aquifer. The technology is most effective when it can be installed to completely contain groundwater over the entire saturated thickness of the aquifer. The base of the thermoprobes should be keyed into an underlying aquitard to prevent groundwater from flowing beneath the barrier wall. For sites with no underlying aquitard, the thermoprobes may be installed in a "V" or "U" configuration to promote complete isolation of the waste source. Near-surface refrigerant piping and proper ground insulation should be used to ensure complete isolation of the shallower portion of the aquifer.

Refrigeration technology has been used for freezing soils on large-scale construction engineering projects for over 100 years. Companies that employ this technology claim that barriers can be established to depths of 1,000 feet bgs. AFI recently prepared a quote on the installation of a frozen soil barrier to a depth of 450 feet bgs with a length of 3.5 kilometers for groundwater control at a mining site. However, another contractor was selected to install the frozen soil barrier. Deeper applications of this technology have not been conducted at contaminated sites. The effectiveness of facilitating deeper applications of this technology may require additional research.

3.2.2 Engineered Structures

Prior to barrier placement, geophysical measurements of the source area should be conducted to determine soil characteristics and to determine if subsurface structures exist. Based on observations during the SITE Program demonstration at the HRE pond site, subsurface structures may provide a conduit for movement of groundwater outside the barrier wall. The proximity of surface structures such as roads, foundations, and tanks also should be taken into account prior to placement of a frozen soil barrier due to the potential for frost heave effects.

3.2.3 Diffusion Characteristics

Prior to applying the freeze barrier technology, laboratory diffusion studies should be conducted on site-related contaminants to assess diffusion characteristics. Previous laboratory-scale diffusion studies have shown that a frozen soil barrier with a hydraulic permeability of less than $4x10E^{-10}$ centimeters per second can be formed effectively in saturated soils with a chromate concentration of 4,000 milligrams per kilogram (mg/kg) and a trichloroethylene concentration of 6,000 mg/kg. Tests using Cs also reportedly showed no detectable diffusion through a barrier with the same permeability; however, the immobility of Cs may have been partially attributable to sorption onto soil grains (DOE 1995). Laboratory diffusion studies using various contaminants of differing concentrations are required to determine the effects, if any, on barrier wall integrity.

3.3 SITE CHARACTERISTICS AND SUPPORT REQUIREMENTS

Site-specific factors can affect the application of the freeze barrier technology, and these factors should be considered before selecting the technology for use at a specific site. Site-specific factors addressed in this section are site area and preparation requirements; climate; utilities and supplies; maintenance; support systems; and personnel requirements. The support requirements for the ground freezing system may vary depending on the size of the containment area. This section presents support requirements based on information collected during the SITE demonstration at ORNL.

3.3.1 Site Area and Preparation Requirements

In addition to the hydrogeologic conditions that determine the technology's applicability and design, other site characteristics affect implementation of this technology. The amount of space required for a ground freezing system depends on the thickness of the barrier wall and size of the containment area. For the HRE pond demonstration, the array of thermoprobes encompassed an area of about 75 feet by 80 feet, with an average frozen soil barrier wall thickness of 12 feet. Thermoprobes may be installed in a "V" or "U" configuration to promote complete encapsulation and isolation of the waste source. At the HRE pond site, the thermoprobes were installed in a vertical position, with the bottom of each thermoprobe anchored in bedrock, to inhibit horizontal groundwater movement into and out of the waste source area.

The site must be accessible and have sufficient operating and storage space for heavy construction equipment. Access for a drill rig or pile driver to install the thermoprobes and temperature monitoring points for system operation is required. A crane may also be necessary to install the thermoprobes and to subsequently remove the thermoprobes from the containment area following remediation activities. Access for tractor trailers (for delivery of thermoprobes, refrigeration units and associated piping, construction supplies, and equipment) is preferable. Underground utilities crossing the path of the proposed system may require relocation if present, and overhead space should be clear of utility lines to allow installation equipment to operate. Construction around existing surface structures may also be required.

Where drilling is used as the installation technique, soil from drill cuttings at contaminated sites may require management as a potentially hazardous or radioactive waste. For this reason, roll-off boxes or 55-gallon drums to store the soil, and sufficient space near, but outside of the construction area for staging, should be available. During drilling activities at the HRE pond site, radiation levels in soil cuttings were continuously monitored and were classified as Category 1 (<1 milliradian [mRad]/hour), Category 2 (>1 mRad/hour), or Category 3 (>5 mRad/hour) to facilitate proper management of the waste (DOE 1998a). A portable tank or tanker truck should also be available for thermoprobe installation to temporarily store water generated during drilling activities. Where soil type and site conditions are appropriate, thermoprobes also may be installed by pile driving methods. This method eliminates handling drill cuttings and minimizes environmental disturbance. A building or shed also may be necessary to house the system control module and instrumentation wiring, as well as for use by workers during routine operation and maintenance (O&M) activities.

3.3.2 Climate Requirements

The thermoprobes used in the system design can operate in an "active" or "passive" mode and are used in temperate locations where reliance on low ambient temperatures (the passive mode application) is not feasible. For this reason, the system can be installed and operated in any climate. For applications in regions with high ambient temperatures, such as Oak Ridge, proper ground insulation is required to ensure that surficial soil (1 to 2 feet bgs) is adequately frozen.

3.3.3 Utility and Supply Requirements

The installation at Oak Ridge required water during construction for a safety shower, personnel decontamination, and equipment washing. Temporary arrangements were made during construction to supply a minimal quantity of water to the site. If water is unavailable, engineered controls must be made to minimize water requirements and temporary facilities arranged to deliver, store, and pump water during construction of the system.

Electricity is required to power the refrigeration units, instrumentation, and control system that regulates the temperature of the thermoprobes. Electrical power for the ground freezing system can be provided by portable generators or any standard electrical service. Based on information collected during the SITE demonstration and estimates provided by AFI, the electrical power required from system startup to establishment of a 12-foot-thick barrier wall was about 72,000 kilowatt-hours (kWh). Once frozen, the average power consumption required to maintain the barrier wall was reportedly about 288 kWh per day. The thermoprobes also can operate without electrical power whenever air temperature drops below the target soil temperature. Should a power loss or other system failure occur, an immediate breach in the barrier wall is unlikely because subsurface frozen soil thaws at a slow rate. As discussed in Section 2.1.5, thawing was evaluated during a simulated power outage at the HRE pond site and found to be minimal.

3.3.4 Maintenance Requirements

The system components should be inspected periodically for proper operation. Maintenance of the ground freezing system components is required only in the event of a mechanical failure associated with the refrigeration units and thermoprobes. Because the refrigeration units are standard unmodified items, they are easily serviced by a qualified heating, ventilation, and air conditioning (HVAC) technician. Maintenance of the refrigeration units includes, but is not limited to, leak repair, refrigerant recharge, and replacement of worn equipment. Maintenance and repair of the thermoprobes would require the attention of an AFI designer/fabricator due to the proprietary nature of the devices.

3.3.5 Support Systems

In situ temperature sensors, such as the temperature monitoring points used during the HRE pond SITE demonstration, may be required to monitor and track the development of the frozen soil barrier and ensure that refrigeration equipment is operating properly.

Groundwater tracing similar to that completed during this demonstration may be required to monitor barrier wall integrity. According to AFI, geophysical techniques such as soil resistivity that is capable of detecting barrier infrastructure properties such as voids also can be used to monitor performance of the barrier wall.

3.3.6 Personnel Requirements

Personnel requirements for the system are minimal. Personnel are required to periodically inspect the ground freezing system, including the thermoprobes and refrigeration units and associated piping, for general operating condition. A certified HVAC technician is required for routine maintenance of the refrigeration units. Personnel also should inspect the condition of the insulation and waterproofing membrane over the containment area and identify indications of potential problems, such as tears or uplifted edges.

Personnel working with the system at hazardous waste sites should have completed the training requirements under the Occupational Safety and Health Act (OSHA) outlined in Title 29 of the Code of Federal Regulations (CFR) §1910.120, which covers hazardous waste operations and emergency response. Personnel working with the system at radioactive waste sites, such as the HRE pond site, also should have completed radiation worker training in accordance with 10 CFR Part 20, which covers standards for protection against radiation. Personnel should also participate in a medical monitoring program as specified under OSHA and the Nuclear Regulatory Commission (NRC).

3.4 MATERIAL HANDLING REQUIREMENTS

Material handling requirements for the freeze barrier technology include those for the soil and water removed during drilling activities. Groundwater removed from boreholes during thermoprobe installation activities will probably contain site-related contaminants. Soils removed from below the water table in the vicinity of a contaminant plume may have become contaminated by contact with contaminated groundwater. For this reason, soil and water generated during construction activities may require handling, storage, and management as hazardous wastes. Precautions may include availability of lined, covered, roll-off boxes; drums; or other receptacles for the soil; storage tanks or drums for the water; and appropriate personal protective equipment (PPE) for handling contaminated materials. Contaminated soils should be stockpiled on site separately from soils determined to be clean, to minimize the amount of material requiring management as potentially hazardous waste.

3.5 TECHNOLOGY LIMITATIONS

Potential users of this technology must consider the possibility that formation of a soil barrier in arid conditions may require a suitable method of adding and retaining moisture in soils to achieve saturated conditions. AFI claims, however, that it is rarely necessary to add moisture to soils because the in situ moisture will migrate and concentrate in the frozen soil and create an impervious wall. The effectiveness of this technology for containment of contaminants in arid soils will require assessment.

The practicality of implementing this technology at some sites may be limited. As for most in situ containment systems, the need for intrusive construction activities requires a significant amount of open surface space, possibly precluding the use of this technology at certain sites. AFI claims, however, that the open surface area required to construct a frozen soil barrier is significantly less than any other barrier technology.

3.6 POTENTIAL REGULATORY REQUIREMENTS

This section discusses regulatory requirements pertinent to using the freeze barrier technology at Superfund, Resource Conservation and Recovery (RCRA) corrective action, and other cleanup sites. The regulations pertaining to applications of this technology depend on site-specific conditions; therefore, this section presents a general overview of the types of federal regulations that may apply under various conditions. State and local requirements also should be considered. Because these requirements vary, they are not presented in detail in this section. Table 3-1 summarizes the environmental laws and associated regulations discussed in this section.

3.6.1 Comprehensive Environmental Response, Compensation, and Liability Act

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended by SARA, authorizes the federal government to respond to releases of hazardous substances, pollutants, or contaminants that may present an imminent and substantial danger to public health or welfare. CERCLA pertains to the freeze barrier system by governing the selection and application of remedial technologies at Superfund sites. Remedial alternatives that significantly reduce the volume, toxicity, or mobility of hazardous substances and provide long-term protection are preferred. Selected

TABLE 3-1

SUMMARY OF ENVIRONMENTAL REGULATIONS

Act/Authority	Applicability	Application to the Freeze Barrier Technology	Citation
CERCLA	Superfund sites	This program authorizes and regulates the cleanup of releases of hazardous substances. It applies to all CERCLA site cleanups and requires that other environmental laws be considered as appropriate to protect human health and the environment.	40 CFR part 300
RCRA	Superfund and RCRA sites	RCRA regulates the transportation, treatment, storage, and disposal of hazardous wastes. RCRA also regulates corrective actions at treatment, storage, and disposal facilities.	40 CFR parts 260 to 270
CWA	Discharges to surface water bodies	NPDES requirements of the CWA apply to both Superfund and RCRA sites where treated water is discharged to surface water bodies. Pretreatment standards apply to discharges to POTWs. These regulations do not typically apply to containment technologies.	40 CFR parts 122 to 125, part 403
SDWA	Water discharges, water reinjection, and sole-source aquifer and wellhead protection	Maximum contaminant levels and contaminant level goals should be considered when setting water cleanup levels at RCRA corrective action and Superfund sites. Sole sources and protected wellhead water sources would be subject to their respective control programs. These regulations do not typically apply to the freeze barrier technology unless used in conjunction with a remediation program. Regulations governing underground injection may apply at sites requiring addition of soil moisture to achieve freezing.	40 CFR parts 141 to 149
CAA	Air emissions from stationary and mobile sources	The technology may be used to limit migration of contaminant plumes, and therefore may help reduce the potential for exposure to airborne VOCs emanating from contaminated groundwater. If VOC emissions occur or hazardous air pollutants are of concern, these standards may be ARARs for a site cleanup. However, this technology uses benign refrigerants, produces no air emissions, and does not degrade air quality. For these reasons, the CAA will not apply to this technology in most cases. State air program requirements also should be considered.	40 CFR parts 50, 60, 61, and 70
AEA and RCRA	Mixed wastes	AEA and RCRA requirements apply to the treatment, storage, and disposal of mixed waste containing both hazardous and radioactive components. OSWER and DOE directives provide guidance for addressing mixed waste.	AEA (10 CFR part 60) and RCRA (see above)
OSHA	All remedial actions	OSHA regulates on-site construction activities and the health and safety of workers at hazardous waste sites. Personnel working on installation and operation of the freeze barrier technology at Superfund or RCRA cleanup sites must meet OSHA requirements.	29 CFR parts 1900 to 1926
NRC	All remedial actions	These regulations include radiation protection standards for NRC-licensed activities.	10 CFR part 20

Note: Acronyms used in this table are defined in the "List of Acronyms and Abbreviations," (pages x through xi).

remedies must also be cost-effective, protective of human health and the environment, and must comply with environmental regulations to protect human health and the environment during and after remediation.

CERCLA requires identification and consideration of environmental requirements that are Applicable or Relevant and Appropriate Requirements (ARAR) for site remediation before implementation of a remedial technology at a Superfund site. Subject to specific conditions, EPA allows ARARs to be waived in accordance with Section 121 of CERCLA. The conditions under which an ARAR may be waived are (1) an activity that does not achieve compliance with an ARAR, but is part of a total remedial action that will achieve compliance (such as a removal action), (2) an equivalent standard of performance can be achieved without complying with an ARAR, (3) compliance with an ARAR will result in a greater risk to health and the environment than will noncompliance, (4) compliance with an ARAR is technically impracticable, (5) the situation involves a state ARAR that has not been applied consistently, and (6) for fund-lead remedial actions, compliance with the ARAR will result in expenditures that are not justifiable in terms of protecting public health or welfare, given the needs for funds at other sites. The justification for a waiver must be clearly demonstrated (EPA 1988a). Off-site remediations are not eligible for ARAR waivers, and all applicable substantive and administrative requirements must be met. CERCLA requires on-site discharges to meet all substantive state and federal ARARs, such as effluent standards. However, the freeze barrier wall is a containment technology and does not typically result in off-site discharges.

3.6.2 Resource Conservation and Recovery Act

RCRA, as amended by the Hazardous and Solid Waste Amendments of 1984, regulates management and disposal of municipal and industrial solid wastes. EPA and the states implement and enforce RCRA and state regulations. Some of the RCRA Subtitle C (hazardous waste) requirements under 40 CFR parts 264 and 265 may apply at CERCLA sites because remedial actions generally involve treatment, storage, or disposal of hazardous waste. However, RCRA requirements may be waived for CERCLA remediation sites, provided equivalent or more stringent ARARs are followed

Most RCRA regulations affecting conventional treatment technologies will not apply to the freeze barrier technology because once installed, a properly designed and maintained system does not generate any residual waste. However, the soil and groundwater removed from boreholes during drilling and installation activities may be contaminated and classified as hazardous waste. Wastes defined as hazardous under RCRA include characteristic and listed wastes. Criteria for identifying characteristic wastes are included in 40 CFR part 261 subpart C. Listed wastes from specific and nonspecific industrial sources, off-specification products, spill cleanups, and other industrial sources are itemized in 40 CFR part 261 subpart D. If soil and/or groundwater are classified as RCRA hazardous waste, they will require management, including storage, transport, and disposal, in accordance with Subtitle C of RCRA. Active industrial facilities generating hazardous waste are required to have designated hazardous waste storage areas, and operate under 90-day or 180-day storage permits, depending on generator status. A facility's storage area could be used as a temporary storage area for contaminated groundwater and/or soil generated during the installation of the freeze barrier technology. For nonactive facilities, or those not generating hazardous waste, a temporary storage area should be constructed on site following RCRA guidelines, and a temporary hazardous waste generator identification number should be obtained from the regional or state EPA office, as appropriate. Guidelines for hazardous waste storage are listed under 40 CFR parts 264 and 265.

Other applicable RCRA requirements may include (1) obtaining Uniform Hazardous Waste Manifests if the soil and/or groundwater are transported as a RCRA hazardous waste, and (2) placing restrictions on depositing the waste in land disposal units.

3.6.3 Clean Water Act

The Clean Water Act (CWA) governs discharge of pollutants to navigable surface water bodies or publicly owned treatment works (POTW) by providing for the establishment of federal, state, and local discharge standards. Because the freeze barrier technology does not normally result in discharge of contaminated groundwater to surface water bodies or POTWs, the CWA would not typically apply to the normal operation and use of this technology. According to AFI, however, if an open, water-cooled condensing system is used, the effect of the heated water on the local environment must be evaluated.

3.6.4 Safe Drinking Water Act

The Safe Drinking Water Act (SDWA), as amended in 1986, required EPA to establish regulations to protect human health from contaminants in drinking water. The legislation authorized national drinking water standards and a joint federal-state system for ensuring compliance with these standards. The SDWA also regulates underground injection of fluids and sole-source aquifer and well head protection programs. An underground injection control (UIC) permit was issued by TDEC for the injection of tracer dyes and potable water used during the technology demonstration; however, the technology would only require injection of fluids if the soil moisture content is too low to allow freezing to occur in soil pore water voids.

The National Primary Drinking Water Standards are found in 40 CFR parts 141 through 149. These drinking water standards are expressed as maximum contaminant levels (MCL) for some constituents, and maximum contaminant level goals (MCLG) for others. Under CERCLA (Section 121 (d)(2)(A)(ii)), remedial actions are required to meet the standards of the MCLGs when relevant. The freeze barrier technology is not a groundwater treatment technology, but it could improve the quality of groundwater by containing the source of contamination until appropriate remediation techniques can be applied. As a result, MCLGs would not apply to this technology unless used in conjunction with a groundwater treatment technology.

3.6.5 Clean Air Act

The Clean Air Act (CAA), as amended in 1990, regulates stationary and mobile sources of air emissions. CAA regulations are generally implemented through combined federal, state, and local programs. The CAA includes pollutant-specific standards for major stationary sources that would not be ARARs for the freeze barrier technology. However, state and local air programs have been delegated significant air quality regulatory responsibilities, and some have developed programs to regulate toxic air pollutants (EPA 1989). Therefore, state air programs should be consulted regarding installation and use of the freeze barrier technology. The only emissions associated with operation of the freeze barrier system, which are typical of most commercial refrigeration systems, include water condensate and heat. This technology also uses benign refrigerants and does not produce air emissions so the technology would not be subject to CAA regulations.

3.6.6 Mixed Waste Regulations

Use of the freeze barrier technology at sites with radioactive contamination, such as the HRE pond site, might involve containment of mixed waste. As defined by the Atomic Energy Act (AEA) and RCRA, mixed waste contains both radioactive and hazardous waste components. Such waste is subject to the requirements of both acts. However, when application of both AEA and RCRA regulations results in a situation that is inconsistent with the AEA (for example, an increased likelihood of radioactive exposure), AEA requirements supersede RCRA requirements (EPA 1988a). OSWER, in conjunction with the NRC, has issued several directives to assist in identification, treatment, and disposal of low-level radioactive mixed waste. Various OSWER directives include guidance on defining, identifying, and disposing of commercial, mixed, low-level radioactive, and hazardous waste (EPA 1988b). If the freeze barrier technology is used to contain low-level mixed waste, these directives should be considered, especially regarding contaminated soils removed during installation. If the technology is used to provide containment for high-level mixed waste or transuranic mixed waste during any remediation program, internal DOE orders should be considered when developing a protective remedy (DOE 1988). The SDWA and CWA also contain standards for maximum allowable radioactivity levels in water supplies.

3.6.7 Occupational Safety and Health Act

OSHA regulations in 29 CFR parts 1900 through 1926 are designed to protect worker health and safety. Both Superfund and RCRA corrective actions must meet OSHA requirements, particularly §1910.120, Hazardous Waste Operations and Emergency Response. Part 1926, Safety and Health Regulations for Construction, applies to any on-site construction activities. For example, drilling of boreholes for placement of thermoprobes and temperature monitoring points during the demonstration was required to comply with regulations in 29 CFR part 1926, subpart N. Any more stringent state or local requirements must also be met. In addition, health and safety plans for site remediation projects should address chemicals of concern and include monitoring practices to ensure that worker health and safety are maintained.

For most on-site workers, PPE will include gloves, hard hats, steel-toed boots, and coveralls. Depending on contaminant types and concentrations, additional PPE may be required. Noise levels should be monitored to ensure that workers are not exposed to noise levels above a time-weighted average of 85 decibels over an 8-hour day. Noise levels associated with the freeze barrier technology are limited to compressor noise from the refrigeration units.

3.7 STATE AND COMMUNITY ACCEPTANCE

State regulatory agencies will likely be involved in most applications of the freeze barrier technology at hazardous waste sites. Local community agencies and citizens' groups are often actively involved in decisions regarding remedial alternatives.

Because few applications of the freeze barrier technology have been completed, limited information is available to assess long-term state and community acceptance. However, state and community acceptance of this technology is generally expected to be high, for several reasons: (1) it provides a means to fully contain waste, thereby preventing the further spread of contaminants; (2) the barrier is environmentally safe, using benign working fluids; (3) the barrier wall does not have any lasting effects and is simply allowed to melt after thermoprobes are removed; and (4) the system generates no residual wastes requiring off-site management and does not transfer waste to other media.

TDEC oversees investigation and remedial activities at ORNL. State personnel were actively involved in the preparation of the QAPP and field work and data gathering activities during the technology demonstration. The state also issued a UIC permit for the groundwater tracing investigation. The role of states in selecting and applying remedial technologies will likely increase in the future as state environmental agencies assume many of the oversight and enforcement activities previously performed at the EPA Regional level. For these reasons, state regulatory requirements that are sometimes more stringent than federal requirements may take precedence for some applications. As risk-based closure and remediation become more commonplace, site-specific cleanup goals determined by state agencies will drive increasing numbers of remediation projects, including applications involving the freeze barrier technology.

4.0 ECONOMIC ANALYSIS

This economic analysis presents two cost estimates for applying the freeze barrier technology to prevent off-site migration of contaminants. The estimates are based on data compiled during the SITE demonstration and from additional information obtained from AFI, DOE, current construction cost estimating guidance, and SITE Program experience. Past studies by AFI have indicated that the costs for this technology are highly variable, and depend on the site hydrogeology, climate, regulatory requirements, and other site- and waste-specific factors. The following containment volumes and time frames presented for both cases represent typical applications for the freeze barrier technology anticipated by the vendor.

Two estimates have been performed in this analysis to determine costs for applying the freeze barrier technology. The first estimate (Case 1) presents a cost estimate that is based on costs incurred during the demonstration for operating the barrier wall at the HRE pond site at ORNL extrapolated over a 5-year period. The isolated area at the HRE pond site is about 75 feet by 80 feet (6,000 square feet), and the estimated isolated volume (to a depth of 30 feet bgs) is 180,000 cubic feet. The volume of soil frozen is estimated to be about 134,000 cubic feet, based on the perimeter length (310 feet), an assumed maximum frozen depth of 36 feet (estimated by AFI), and thickness of the barrier wall (12 feet).

The second estimate (Case 2) is for containment over a 10-year period for a site with conditions similar to the HRE pond site, but a larger containment area (see Section 4.2). The cost estimate for Case 2 is based on extrapolation of data from the HRE pond SITE demonstration costs over a 10-year period. For Case 2, the dimensions of the isolated area are assumed to be 150 feet by 200 feet, with an assumed aquitard depth of 30 feet bgs. The total isolated area is assumed to be 30,000 square feet, with a volume of 900,000 cubic feet. The volume of soil frozen is about 300,000 cubic feet, based on a perimeter of 700 feet, frozen depth of 36 feet bgs, and a thickness of 12 feet.

For sites with no aquitard, the barrier wall would be installed in a "V" or "U" configuration to promote complete isolation of a waste source. However, the SITE Program demonstration involved a vertical system, and cost data tor other configurations were not collected. For these reasons, both scenarios assume vertical systems.

This section summarizes factors that influence costs, presents assumptions used in this analysis, discusses estimated costs, and presents conclusions of the economic analysis. Tables 4-1 and 4-2 present the estimated costs generated from this analysis. Costs have been distributed among 12 categories applicable to typical cleanup activities at Superfund and RCRA sites, and the distribution of these costs is shown in Figures 4-1 and 4-2 (Evans 1990). Costs are presented in 1998 dollars, are rounded to the nearest 100 dollars, and are considered to be -30 percent to +50 percent order-of-magnitude estimates.

4.1 FACTORS AFFECTING COSTS

Costs for implementing the freeze barrier technology are significantly affected by site-specific factors, including site regulatory status, waste-related factors, containment duration, and site features and geology. The regulatory status of the site typically depends on the type of waste management activities that occurred on site, the relative risk to nearby populations and ecological receptors, the state in which the site is located, and other factors. The site's regulatory status affects costs by mandating ARARs and remediation goals that may affect the system design parameters and duration of the remediation project. Certain types of sites may have more stringent monitoring requirements than others, depending on regulatory status. Site features and geology determine the required installation depth and configuration of the freeze barrier system layout which will affect costs.

Waste-related factors affecting costs include the volume and distribution of contamination at the site, because these factors directly affect the size and positioning of the barrier that is required for containment. Formation of frozen soil barriers in areas where low freezing point contaminants are present may require a different refrigeration system then what was applied at the HRE pond site, which will affect costs. The type and concentration of contaminant will also affect disposal costs for investigation-derived wastes. Finally, the length of time that the barrier must remain in place will affect costs, due to ongoing electricity usage, general maintenance, and monitoring costs.

TABLE 4-1

ESTIMATED COSTS ASSOCIATED WITH THE FREEZE BARRIER TECHNOLOGY

Cost Category	Case 1		Case 2	
Barrier Volume	134,000 ft³		300,000 ft³	
Isolated Volume	180,000 ft³	$/ft³ᵃ	900,000 ft³	$/ft³ᵃ
Fixed Costs				
Site Preparation Costs				
Administrative	$10,000	$0.06	$10,000	$0.01
System design	150,000	0.83	75,000	0.08
Drilling/placement	127,500	0.71	270,400	0.30
Soil disposal	3,900	0.02	8,000	0.009
Surface seal	94,500	0.53	275,000	0.31
Total Site Preparation Costs	**$385,900**	**$2.15**	**$638,400**	**$0.71**
Total Permitting and Regulatory Costs	**$0**	**$0**	**$0**	**$0**
Mobilization and Startup Costs				
Mobilize and transport equipment	$7,700	$0.04	$17,700	$0.02
System installation and startup	96,000	0.53	221,000	0.25
Total Mobilization and Startup Costs	**$103,700**	**$0.58**	**$238,700**	**$0.27**
Capital Equipment Costs				
Thermoprobes	$75,000	$0.42	$172,500	$0.19
Refrigeration units	84,000	0.47	168,000	0.19
Piping, instrumentation, control system, temperature monitoring point materials, and miscellaneous materials	261,000	1.45	600,000	0.67
Total Capital Equipment Costs	**$420,000**	**$2.33**	**$940,500**	**$1.05**
Utility Costs				
Initial freeze down	$3,600	$0.02	$8,300	$0.009
Total Utility Costs	**$3,600**	**$0.02**	**$8,300**	**$0.009**
Total Effluent Treatment and Disposal Costs	**$0**	**$0**	**$0**	**$0**

TABLE 4-1 (Continued)

ESTIMATED COSTS ASSOCIATED WITH THE FREEZE BARRIER TECHNOLOGY

Cost Category	Case 1		Case 2	
Barrier Volume	140,000 ft³		300,000 ft³	
Isolated Volume	180,000 ft³	$/ft³[a]	900,000 ft³	$/ft³[a]
Total Waste Shipping & Handling Costs	$0	$0	$0	$0
Analytical Services Costs				
Background study	$2,300	$0.01	$1,800	$0.002
Total Analytical Services Costs[b]	**$2,300**	**$0.01**	**$1,800**	**$0.002**
Demobilization Costs				
System disassembly	$1,100	$0.006	$2,200	$0.002
Borehole abandonment	34,800	0.19	73,800	0.08
Total Demobilization Costs	**$35,900**	**$0.20**	**$76,000**	**$0.08**
Total Estimated Fixed Costs	**$951,400**	**$5.29**	**$1,903,700**	**$2.12**
Annual Costs				
Annual Labor Costs	**$9,100**	**$0.05**	**$8,600**	**$0.01**
Annual Supply Costs	**$1,300**	**$0.007**	**$1,000**	**$0.001**
Annual Utility Costs[c]	**$5,500**	**$0.03**	**$12,600**	**$0.01**
Annual Analytical Costs	**$12,600**	**$0.07**	**$9,000**	**$0.01**
Annual Equipment Maintenance Costs	**$14,300**	**$0.08**	**$32,000**	**$0.04**
Total Estimated Annual Costs	**$42,800**	**$0.24**	**$63,200**	**$0.07**
Total Estimated Fixed & Annual Costs	**$1,165,400**	**$6.50**	**$2,535,700**	**$2.80**
Cost per unit barrier volume ($/ft³)	**$8.30**		**$8.50**	

Notes:

[a] Costs per cubic foot of isolated waste.

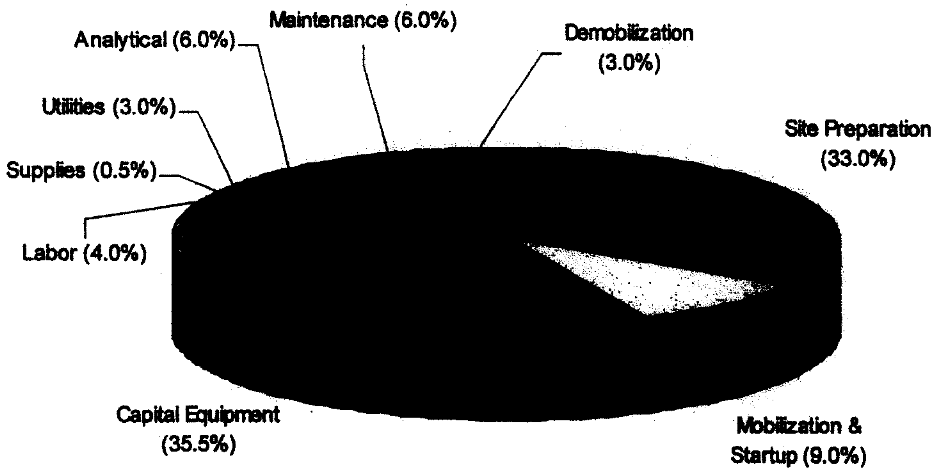
[b] Based on the assumption that a groundwater tracing investigation would be performed to verify barrier integrity for Case 2.

[c] Costs presented do not reflect costs associated with initial freeze down, which are listed in fixed costs.

TABLE 4-2

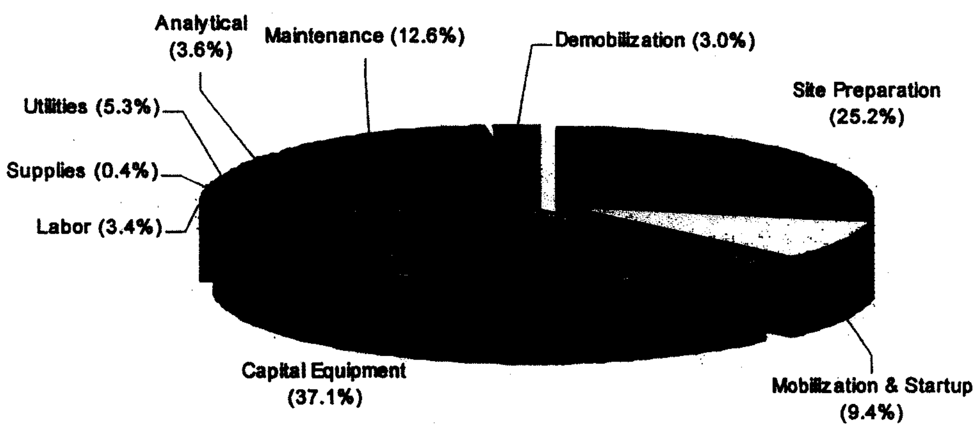
COST DISTRIBUTION FOR THE FREEZE BARRIER TECHNOLOGY

Cost Categories	Case 1 Costs	Case 1 % Costs	Case 2 Costs	Case 2 % Costs
Site Preparation	385,900	33.0	638,400	25.2
Permitting and Regulatory	0	0	0	0
Mobilization and Startup	103,700	9.0	238,700	9.4
Capital Equipment	420,000	35.5	940,500	37.1
Labor	45,500	4.0	86,000	3.4
Supplies	6,500	0.5	10,000	0.4
Utilities	31,100	3.0	134,300	5.3
Effluent Treatment & Disposal	0	0	0	0
Residual Shipping & Handling	0	0	0	0
Analytical Services	65,300	6.0	91,800	3.6
Equipment Maintenance	71,500	6.0	320,000	12.6
Site Demobilization	35,900	3.0	76,000	3.0
Total Costs	**$1,165,400**	**100**	**$2,535,700**	**100**



Note: effluent treatment and disposal, residual shipping and handling costs, and permitting and regulatory costs are not included because costs are $0 for this estimate.

Figure 4-2
Distribution of Total Costs for Case 2



Note: effluent treatment and disposal, residual shipping and handling, and permitting and regulatory costs are not included because costs are $0 for this estimate.

Site features affecting costs include site hydrogeology, location, and physical characteristics. Hydrogeologic conditions are significant factors in determining the applicability and design parameters of the barrier and should be thoroughly defined before applying this technology. The depth to groundwater and depth to the uppermost underlying aquitard, if present, determine the depth of the installation and the type of construction technology that will be employed. Sites with no underlying aquitard will require thermoprobes to be installed in closely spaced, directional boreholes in a "V" or "U" configuration. Each of these factors affect site preparation, capital, and operating costs. Site location and physical features will affect mobilization, demobilization, and site preparation costs. Mobilization and demobilization costs are affected by the relative distances that system materials must travel to the site. High visibility sites in densely populated areas may require higher security and the need to minimize obtrusive construction activities, noise, dust, and air emissions. Sites requiring extensive surficial preparation (such as constructing access roads, clearing large trees, working around or demolishing structures) or restoration activities will also incur higher costs. The availability of existing electrical power and water supplies may facilitate construction activities and continuing O&M activities for the ground freezing system. Within the U.S., significant regional variations may occur in costs for materials, equipment, and utilities.

4.2 ASSUMPTIONS OF THE ECONOMIC ANALYSIS

This section summarizes major assumptions regarding site-specific factors and equipment and operating parameters used for both cases. For Case 1, existing technology and site-specific data from the demonstration were used to present costs for extended use of the barrier wall over a 5-year period at the HRE pond site. Certain assumptions were made to account for variable site and waste parameters for Case 2. Other assumptions were made to simplify cost estimation for situations that would require complex engineering or financial functions. In general, most system operating issues and assumptions are based on information provided by AFI, DOE, and observations made during the SITE demonstration. Cost figures for both cases are established from information provided by AFI, DOE (MSE Technology Applications, Inc. [MSE] 1998), current environmental restoration cost guidance (R.S. Means Company, Inc. [Means] 1998), and SITE Program experience.

Assumptions regarding site- and waste-related factors for Case 1 include the following:

- The site is a former surface impoundment known as the HRE pond at DOE's ORNL facility in Oak Ridge, Tennessee. The HRE pond received radioactive liquid wastes, which consisted primarily of Cs and Sr. The site has been well-characterized in terms of hydrogeology and type and extent of contamination

- The estimated total volume of material within the HRE pond that would require containment is about 180,000 cubic feet

- The system would continue to be used as an interim containment measure to limit off-site migration of wastes to a nearby tributary

- The site has a series of monitoring wells, piezometers, and standpipes installed at depths ranging from 10 to 40 feet bgs that were used during previous site characterization work. The wells are located within, upgradient, and downgradient of the impoundment and would continue to be used as part of the groundwater tracing investigation to monitor barrier wall integrity. The site also has some nearby springs and a tributary that would continue to be used as recovery points during the investigation

- The site has existing electrical lines and an access road

- The site has no on-site structures that require demolition and did not require extensive clearing during construction activities. No utilities were on site that required relocation or that restricted operation of heavy equipment

- Electricity for the site is readily available at a cost of \$0.05 per kWh

- Contaminated water is located in a shallow aquifer that overlies a shale bedrock unit at a depth of about 30 feet bgs

- The aquifer is a moderately permeable clay mixed with shale fragments introduced from backfill material after the impoundment was closed. Groundwater is found at an average depth of 6 to 10 feet bgs.

Assumptions regarding system design and operating parameters for Case 1 include the following:

- The thermoprobes, using carbon dioxide as the two-phase working fluid, are installed vertically to a depth of about 30 feet bgs and anchored in the underlying shale bedrock unit

- A series of eight temperature monitoring points are placed at strategic locations in the northwest and southeast corners of the barrier wall to monitor the barrier wall

- Two 30-horsepower refrigeration units operating in cycles are required for system operation

- AFI will provide a representative as an on-site consultant during key phases of the construction

- Downtime for routine maintenance will be minimal and is therefore, not considered in this estimate. During the demonstration, AFI simulated a power outage which showed (based on temperature monitoring points data) that periodic downtime would not affect system performance because the barrier thaws slowly

- After construction, the ground freezing system operates without the constant attention of an operator. Routine labor requirements consist of monthly sampling and inspection of the thermoprobes, temperature monitoring points, refrigeration units and associated piping, and the surface seal

- This estimate assumes that the freeze barrier wall will be effective in containing groundwater contamination and therefore, effluent treatment and disposal costs will not be incurred

- The freeze barrier technology will not generate wastes other than soil from drilling activities

- Periodic maintenance of system components will be required for worn parts and refrigerant leaks associated with the refrigeration units and piping

- All system materials, including the thermoprobes, are fabricated at AFI's location in Anchorage, Alaska and transported to the site in Oak Ridge, Tennessee

- About 70 groundwater and surface water samples per month, or 840 per year, would be collected from the same recovery points and analyzed for the same dyes used during the demonstration for 5 years. Additional groundwater samples may also be required to monitor for the contaminants of concern in groundwater outside the containment area, but were not included in this estimate

- Labor costs for all 12 cost categories are presented as 1998 dollars and are not adjusted for inflation (Means 1998)

- Salvage values on equipment were considered negligible after 5 years of operation and were therefore not included in this estimate

Assumptions regarding site- and waste-related factors for Case 2 include the following:

- The location is a Superfund site in the southeastern U.S., and the site has been well-characterized in terms of hydrogeology and type and extent of contamination

- The system will be used as an interim containment measure to limit off-site migration of a contaminant plume. The estimated total volume of the contaminant plume requiring containment is about 900,000 cubic feet

- Site groundwater is assumed to be contaminated with radionuclides, including Cs and Sr

- The site has 10 monitoring wells at an average depth of 30 feet bgs that were installed during previous site characterization work. The wells are located within and downgradient of the containment area and will be used as dye injection/sampling points for a groundwater tracing investigation to monitor barrier wall integrity. No other potential sampling points such as springs or nearby streams exist within the site vicinity

- The site is located in a rural area, but is easily accessible to heavy equipment

- The site has no on-site structures requiring demolition and does not require extensive clearing. No utilities exist on site that require relocation or that restrict operation of heavy equipment

- Electricity for the site is readily available at a cost of $0.05 per kWh

- Contaminated water is located in a shallow aquifer that overlies a bedrock unit at a depth of 30 feet bgs

- The aquifer is a moderately permeable silty clay mixed with fill material in the site area. Locally, groundwater is found at an average depth of 10 feet bgs

Assumptions regarding system design and operating parameters for Case 2 include the following:

- The thermoprobes, using carbon dioxide as the two-phase working fluid, will be installed vertically to a depth of about 30 feet bgs and anchored in the underlying bedrock

- A series of eight temperature monitoring points will be placed within and outside the barrier wall so AFI can assess whether the system is operating as expected and to make adjustments to the system, if required

- Four 30-horsepower refrigeration units operating in cycles, similar to the units used for Case 1, will be required for system operation

- AFI will provide a representative as an on-site consultant for key phases of the construction

- Downtime for routine maintenance is assumed to be minimal and is not considered in this estimate. AFI has also indicated that downtime for maintenance would not affect system performance because ice thaws slowly

- After construction, the ground freezing system operates without the constant attention of an operator. Routine labor requirements consist of monthly sampling and inspection of the thermoprobes, temperature monitoring points, refrigeration units and associated piping, and the surface seal

- This estimate assumes that the freeze barrier wall will be effective in containing groundwater contamination and therefore, effluent treatment and disposal costs will not be incurred

- The freeze barrier technology is not expected to generate residual wastes. Soil from drilling activities will require management as a hazardous waste

- Periodic maintenance of system components will be required for worn parts and refrigerant leaks associated with the refrigeration units and piping

- All system materials, including the thermoprobes, will be fabricated at AFI's location in Anchorage, Alaska and transported to the site

- The number of samples to be collected for barrier performance monitoring is not expected to be as high as for Case 1, due to a decrease in the number of potential recovery points. For the background study, an estimated 120 samples will be collected from the 10 on-site monitoring wells. An estimated 600 samples per year will be collected during the groundwater tracing investigation over a 10-year period. Additional groundwater samples may be also required to monitor for the contaminants of concern in groundwater outside the containment area, but were not included in this estimate. Number of samples are based on information collected during the freeze barrier technology demonstration and may vary considerably from this estimate

- Labor costs for all 12 cost categories are presented as 1998 dollars (Means 1998)

- Salvage values on equipment were considered negligible after 10 years of operation and were therefore not included in this estimate

4.3 COST CATEGORIES

Table 4-1 presents cost breakdowns for each of the 12 cost categories for the freeze barrier containment technology. Data have been presented for the following cost categories: (1) site preparation, (2) permitting and regulatory, (3) mobilization and startup, (4) capital equipment, (5) labor, (6) supplies, (7) utilities, (8) effluent treatment and disposal, (9) residual waste shipping and handling, (10) analytical services, (11) equipment maintenance, and (12) site demobilization. Each of the 12 cost categories are discussed in the following sections.

4.3.1 Site Preparation

Site preparation costs include those for administration, engineering design, and preparation of the installation area, which includes costs associated with installing the thermoprobes and subsurface temperature monitoring points and sealing the surface of the containment area. Administrative costs include those for legal searches, contracting, and general project planning activities. Administrative costs for Case 1 were $10,000, or about 100 hours of technical staff labor at a rate of $50 per hour and

200 hours of administrative staff labor at a rate of $25 per hour (Means 1998). Based on costs from the demonstration, the administrative costs for Case 2 were assumed to also be about $10,000. However. administrative costs are highlv site-specific and may vary significantly from this estimate.

After a site assessment, AFI assists in designing an optimal system configuration for the site. The total system design cost for Case 1 was estimated to be $150,000. Design costs include engineering designs for thermoprobes and temperature monitoring points, including placement and construction, site layout, electrical power supply and piping configuration, and any other necessary engineering services. Itemized costs for each design component were not provided; therefore this estimate assumes that 2,000 hours at an average labor rate of $75 per hour were required for system design services (Means 1998). Based on AFI's experience with Case 1 and similar conditions assumed for Case 2, AFI's design costs are expected to be minimal because the same ground freezing system configuration for Case 1 would be applied to the Case 2 site therefore, design costs for Case 2 were assumed to be considerably less at a cost of about $75,000.

For Case 1, 58 30-foot-deep, 10-inch-diameter borings were drilled for placement of 50 thermoprobes and 8 temperature monitoring points using solid-stem auger and air rotary drilling methods. The total cost for drilling including mobilization, demobilization, miscellaneous materials, and installation of thermoprobes and temperature monitoring points was estimated to be $127,500, or $73.28 per foot drilled. Auger cuttings were categorized and managed off site by DOE personnel and therefore, costs for waste disposal were not incurred during the demonstration. For comparison of costs to Case 2, however, an estimated 26 cubic yards of soil was assumed to have been removed during installation of Thermoprobes and temperature monitoring points. For Case 1, the total estimated cost for waste disposal is about $3,900, which includes a loading and transport cost of $1,300, a hazardous waste tipping cost of $2,200, and a washout and manifesting cost of $400 (Means 1998). Costs for Thermoprobes and temperature monitoring points are discussed in Section 4.3.4, Capital Equipment.

Similar types of costs associated with preparing the site were assumed to be incurred for Case 2, although the site is much larger and overall site preparation costs would therefore increase accordingly. This estimate assumes that the barrier will require about 115 thermoprobes, and based on information collected from the freeze barrier technology demonstration would use a 6-foot spacing configuration and an estimated eight temperature monitoring points. A total of 123 10-inch-diameter borings would be drilled to a depth of 30 feet bgs using the same drilling methods used for Case 1. Based on drilling costs from the demonstration (Case 1), the total cost for drilling including mobilization, demobilization, miscellaneous materials, and installation of thermoprobes and temperature monitoring points was $270,400, or $73.28 per foot drilled. Auger cuttings generated from drilling activities may require management as a hazardous waste. This cost estimate assumes that the soil will be stored on site in 55-gallon drums pending characterization, and shipped off site and disposed of as a hazardous waste. The volume of soil estimated to be displaced and requiring disposal is about 54 cubic yards. The total estimated cost for waste disposal is about $8,000, which includes a loading and transport cost of $2,700, a hazardous waste tipping cost of $4,500, and a washout and manifesting cost of $800 (Means 1998). Actual costs for waste disposal are highly site-specific, and may vary substantially from this estimate, particularly if the soil requires incineration. Where site geologic conditions are appropriate, thermoprobes and temperature monitoring points may also be installed by pile-driving methods, eliminating the need for drilling and waste handling.

Following drilling activities for Case 1, an extruded polystyrene insulation is placed over the containment area to ensure that surficial soil was adequately frozen. A waterproofing membrane is then placed over the insulation to prevent rainfall infiltration. In high traffic areas, a surfacing layer will be added for skid and wear resistance. The total cost for surface seal materials, including labor for installation, was estimated at $94,500. Assuming the same type of surface seal is used at the Case 2 site and based on costs provided by AFI, the surface seal is estimated to cost about $275,000. According to AFI, larger areas can be efficiently sealed using pre-manufactured sheets of surface seal at half the cost of the spray applied system used at the HRE pond site.

The total estimated site preparation costs for Case 1 are $385,900, and for Case 2 are $638,400.

4.3.2 Permitting and Regulatory

In applications of the freeze barrier technology as part of a remediation program, permitting and regulatory costs will vary depending on whether remediation is performed at a Superfund or RCRA corrective action site. Superfund site remedial actions must be consistent with ARARs of environmental laws, ordinances, regulations, and statutes, including federal, state, and local standards and criteria. Remediation at RCRA corrective action sites requires additional monitoring and recordkeeping, which can increase the base regulatory costs.

For Case 1, a NEPA categorical exclusion was granted for the construction of the ground freezing system. A UIP was also issued by the TDEC for injection of dyes and potable water into groundwater conducted as part of the groundwater tracing investigations. No other regulatory permits were required for Case 1. However, information regarding regulatory costs was not available for Case 1 and therefore permitting and regulatory costs are not included in this estimate.

Because permitting and regulatory requirements are highly variable, the costs were not included for Case 2.

4.3.3 Mobilization and Startup

Mobilization costs consist of mobilizing the construction equipment and transporting materials to the site. Startup activities include installation of the piping network, refrigeration units, instrumentation, remote system controls. and electrical power supply hookup.

For Case 1, equipment and materials were transported from Anchorage, Alaska to Knoxville, Tennessee at an estimated cost of $5,000. Two semi-trailer trucks were necessary to haul the equipment to the site in Oak Ridge, Tennessee at an estimated ground transportation cost of $17.00 per mile or $2,000, for a total transportation cost of $7,000. Two workers at an estimated labor rate of $15 per hour worked about three 8-hour days to unload the equipment from the trucks, for a total cost of about $700. The total cost of mobilization and transportation for Case 1 was estimated to be $7,700.

The cost for connecting the piping system to the refrigeration units and thermoprobes, and installing and making electrical connections to the temperature monitoring points, control system, and instrumentation for Case 1, was reported by AFI to be about $96,000. This cost consisted of about 1,300 hours of labor at an estimated rate of $75 per hour for OSHA-trained field technicians to assemble and start up the system, which included a pressure test to determine if there were any leaks or blockages in the system.

The total mobilization and transportation costs for the Case 2 site were scaled up using a factor of 2.3 times the cost for the Case 1 site. This factor was determined based on the differences between the estimated volume of barrier required for each site. The increase in barrier volume for the Case 2 site will increase the amount of equipment (thermoprobes and refrigeration units) that will have to be transported to the site, which increases transportation costs. Using a factor of 2.3, the total estimated cost for mobilization and transportation of equipment to the Case 2 site are assumed to be $17,700.

The total assembly and startup costs for the Case 2 site, which was also scaled up from the Case 1 costs, are assumed to be about $221,000. This cost assumes an average labor rate of $75 per hour for field technicians to work an estimated 2,950 hours to assemble and start up the system. All field technicians are assumed to be trained in hazardous waste site health and safety procedures, so health and safety training costs are not included as a direct startup cost.

The total estimated mobilization and startup costs for Case 1 are $103,700; for Case 2, costs are assumed to be about $238,700.

4.3.4 Capital Equipment

Capital equipment for the ground freezing system consists of thermoprobes, temperature monitoring points, refrigeration units and associated copper piping, an instrumentation and control system, and miscellaneous materials. For this estimate, salvage values on equipment were considered negligible and were therefore not included in this estimate. Costs for the surface seal were previously discussed in Section 4.3.1, Site Preparation, and are not considered capital equipment costs for this estimate.

For the Case 1 site, the 30-horsepower barrier required 50 thermoprobes at a cost of $1,500 each, for a total cost of $75,000. Two 30-horsepower refrigeration units at a cost of $42,000 each, for a total cost of $84,000, were used for Case 1. Other capital equipment such as copper piping, the instrumentation and control system, eight temperature monitoring points, and miscellaneous materials were reported as a combined cost, for a total of $261,000. The total estimated costs for capital equipment for Case 1 are $420,000.

Based on the size of the containment area for Case 2, the barrier is estimated to require 115 thermoprobes at an assumed cost of $1,500 each, for a total cost of $172,500. Four 30-horsepower refrigeration units are estimated to be required for the initial freeze down and maintenance of the barrier for Case 2. At a cost of $42,000 per unit, a total cost of $168,000 would be incurred for the refrigeration units. To estimate the cost of piping, instrumentation and controls, temperature monitoring points, and miscellaneous materials, it was necessary to scale up the reported costs from Case 1 using a factor of 2.3. As stated in Section 4.3.3, this factor is based on the differences between the estimated volume of barrier required for each site. Using this scale-up factor, the remaining capital equipment required for Case 2 would cost an estimated $600,000. For Case 2, the total estimated capital equipment costs are $940,500.

4.3.5 Labor

Once the system is functioning, it can essentially operate unattended and requires only limited monitoring and sampling activities. System monitoring activities include (1) periodic inspection of the system to ensure that it is operating properly, and (2) inspection of the surface seal for tears or uplifted edges. For Case 1, these activities require about 4 hours per month by an AFI-trained person at an estimated labor rate of $50 per hour, resulting in a monthly cost of $200. Personnel are also required for sampling activities associated with a background study and groundwater tracing investigation using fluorescence dyes to monitor barrier wall integrity. Groundwater and surface water sampling activities at the Case 1 site would require an estimated 16 hours per month at a labor rate of about $35 per hour, for a total cost of $560 per month. The total monthly labor cost would be about $760 per month, or $9,100 per year. Over the 5-year life of the project, the total estimated labor costs would be $45,500 for Case 1.

Because the containment area for the Case 2 site is larger, an estimated 6 hours per month is assumed to be required for monitoring the system, at a labor rate of about $50 per hour, for a monthly cost of $300. Because there are less recovery points (ten monitoring wells) for Case 2 to conduct a background study and groundwater tracing investigation, sampling time is expected to be less then for Case 1 and is estimated to require 12 hours per month at a labor rate of about $35 per hour, for a total cost of $720 per month. This monthly cost correlates to an annual cost of $8,600, and an estimated total of $86,000 over the 10-year life of the project for Case 2.

Laboratory analytical costs are presented in Section 4.3.10, Analytical Services. Labor requirements associated with routine maintenance activities for thermoprobes, refrigeration units, and piping network for both cases are discussed in Section 4.3.11, Equipment Maintenance.

4.3.6 Supplies

The necessary supplies for sampling associated with a background study and groundwater tracing investigation include Level D disposable PPE and miscellaneous field supplies. Disposable PPE typically consists of latex inner gloves, nitrile outer gloves, and safety glasses. Disposable PPE is estimated to cost about $300 per year for Case 1. Field supplies for Case 1 consisted of fluorescent dyes, sample bottles, shipping containers, disposable bailers, and labels. Annual sampling supply costs were estimated to be about $1,000 per year, resulting in a total annual supply cost of $1,300 for Case 1. The total estimated costs for supplies over the 5-year life of the project is about $6,500.

Because there are fewer sampling points for a background study and groundwater tracing investigation for Case 2, the amount of sampling supplies is expected to be less then for Case 1. Annual sampling and PPE supply costs for Case 2 are estimated to be $1,000. The total estimated costs for supplies over the 10-year life of the project are about $10,000 for Case 2.

4.3.7 Utilities

Electricity is used to run the refrigeration units and to power the temperature monitoring points, instrumentation, and computer-controlled operating system. The electricity consumption rates for the system can be broken down into the initial freeze down cost when the barrier design thickness is reached, and an operating cost to maintain the barrier design thickness. Based on costs from the demonstration, freeze down for Case 1 was assumed to require about 72,000 kWh at a cost of $3,600.

Maintaining the freeze barrier for Case 1 requires about 300 kWh per day, or $15 per day at $0.05 per kWh rates, for an annual cost of $5,500. However, when outdoor temperatures are below freezing and heat load on the system is low, the entire system shuts down, thereby decreasing utility costs. The total estimated utility costs to maintain the barrier over the 5-year life of the project after the initial freeze down is about $27,500 for Case 1. Therefore, the total utility costs, including the initial freeze down and maintenance of the barrier over a 5-year period, are $31,100.

Electrical costs for Case 2 have been scaled up from Case 1, using a factor of 2.3, based on the larger frozen soil volume required for containment. Electricity costs may vary considerably depending on the geographic location of the site and local utility rates. As with Case 1, a utility rate of $0.05 per kWh was assumed for this estimate. The initial freeze down is estimated to cost about $8,300 (165,600 kWh), with annual utility requirements estimated to be about 251,900 kWh at a cost of $12,600. The total estimated utility costs to maintain the barrier over the 10-year life of the project after the initial freeze down are about $126,000 for Case 1. Therefore, the total utility costs, including the initial freeze down and barrier maintenance over a 10-year period, are $134,300 for Case 2.

Water is required for personnel and equipment decontamination during construction of the ground freezing system, but is not vital for system operation. Telephone service is required for remote monitoring of system performance and detection of system malfunction. Water and telephone costs are insignificant compared to electricity costs and are therefore not included in this estimate.

4.3.8 Effluent Treatment and Disposal

This estimate assumes that groundwater contamination will be effectively contained on site by the freeze barrier wall. For this reason, effluent treatment and disposal costs will not be incurred.

4.3.9 Residual Waste Shipping and Handling

The ground freezing system generates no residual wastes. However, soil from drilling activities during installation of the system may require handling as a hazardous waste and is discussed in Section 4.3.1, Site Preparation.

4.3.10 Analytical Services

Analytical services include costs for laboratory analyses, data reduction, and QA/QC. Sampling frequencies and number of samples are highly site-specific and are based on rainfall frequency, size of the containment area, and distance between the containment area and sampling points (nearby surface water bodies, springs, or monitoring wells).

During the background study at the Case 1 site, about 150 samples were collected over a 25-day period and analyzed for natural background fluorescence and dyes used during previous investigations, at a cost of about $15 per sample, for a total of $2,300. During the groundwater tracing investigation for Case 1, an average of 70 samples per month was collected over a 6-month period and analyzed at a cost of $15 per sample, for a total cost of about $6,300. Continued sampling at the same frequency as the demonstration period for Case 1 would require an estimated 840 samples per year, for a total analytical services cost of $12,600 annually. This estimate includes analytical services costs for standard QA/QC samples. This cost estimate includes only those samples associated with a groundwater tracing investigation for system performance monitoring. Additional groundwater samples may be also required to monitor for the contaminants of concern in groundwater outside the containment area, resulting in additional costs. The total estimated costs for analytical services over the 5-year life of the project are $63,000 for Case 1. Thus, the total analytical costs for the background study and monthly sampling are estimated to be $65,300.

Fewer groundwater samples are assumed for Case 2 because there are only 10 potential recovery points (monitoring wells) and no nearby springs or streams exist on site. For the purposes of this estimate, it is assumed that the cost for sample analysis is also $15 per sample. For the Case 2 background study, an estimated average of 120 groundwater samples will be collected from on-site monitoring wells over a 3- to 4-week period. The analytical services cost for the Case 2 background study is estimated to be about $1,800.

Because there are fewer potential recovery points for the Case 2 groundwater tracing investigation, an estimated average of 50 samples per month, or 600 samples per year, will be collected from on-site monitoring wells, for an analytical services cost of $9,000 annually. Case 2 assumes that standard

QA/QC samples will be analyzed at no additional cost. This cost estimate includes only those samples associated with a groundwater tracing investigation for system performance monitoring. Additional groundwater samples may be also required to monitor for the contaminants of concern in groundwater outside the containment area, resulting in additional costs. The total estimated costs for analytical services over the 10-year life of the project are $90,000 for Case 2. Therefore, the total analytical costs from the background study and monthly sampling are estimated to be $91,800.

4.3.11 Equipment Maintenance

Periodic maintenance of the ground freezing system components includes repairing refrigerant leaks, recharging refrigerant, and replacing worn equipment. Actual costs associated with maintenance activities for the demonstration were not provided; therefore, maintenance costs for Case 1 were estimated to be about 3 percent of capital equipment costs (excluding labor), for a total of $12,600 per year. Most maintenance activities associated with the refrigeration units and piping can be completed by an HVAC technician; however, maintenance of thermoprobes requires the attention of an AFI technician. Total routine maintenance labor is estimated to require about 4 hours per month, at an average labor rate of $35 per hour, for an annual cost of $1,700. The total annual maintenance cost for Case 1 is estimated to be $14,300, which corresponds to $71,500 over the 5-year life of the project.

For Case 2, the same annual estimate of 3 percent of capital costs is assumed to be required for routine maintenance activities, excluding labor, resulting in a cost of about $28,200. The labor required for routine maintenance of equipment for the Case 2 site was scaled up using a factor of 2.3 times the cost for the Case 1 site. The Case 2 site will have more equipment requiring maintenance which will increase the number of labor hours. Based on a factor of 2.3, about 9 hours of labor per month is estimated to be required to maintain the equipment, at a labor rate of $35 per hour or $3,800 annually. Based on these estimates, annual equipment maintenance for Case 2 would cost about $32,000, which corresponds to $320,000 over the 10-year life of the project.

4.3.12 Site Demobilization

After the system is shut down and allowed to thaw, the surface seal would be removed and disposed of as nonhazardous material or scrap. Following system shutdown, a two-person crew at an estimated labor rate of $35 per hour would work about two 8-hour days to disassemble the system for Case 1 at a cost of $1,100. The 50 thermoprobes and eight temperature monitoring points, installed at a depth of 30 feet bgs, would then be removed and the boreholes grouted to the ground surface at an estimated cost of $20 per foot, for a total cost of about $34,800. Thermoprobes and temperature monitoring points may be decontaminated and salvaged, if possible. However, as stated in Section 4.3.4, salvage values were not included in this estimate. Total site demobilization costs for Case 1 are assumed to be about $35,900.

For Case 2, a two-person crew also earning an estimated labor rate of $35 per hour would work about four 8-hour days to disassemble the system at a cost of $2,200. The same cost for Case 2, $20 per foot, is also assumed to be incurred for removal of 115 thermoprobes and eight temperature monitoring points also installed at a depth of 30 feet bgs, and grouting boreholes, for a total cost of about $73,800. Total site demobilization costs for Case 2 are assumed to be about $76,000.

4.4 ECONOMIC ANALYSIS SUMMARY

This analysis presents two cost estimates for installing the freeze barrier technology to prevent off-site migration of contaminants. Two cases are discussed: the first case (Case 1) involves a cost estimate that is based on costs collected during the demonstration for operating the barrier wall at the HRE pond site at ORNL over a 5-year period, and the second case (Case 2) involves applying the ground freezing system to a larger site having conditions similar to those encountered at the Case 1 site, over a 10-year period. Table 4-1 shows the estimated costs associated with the 12 cost categories presented in this analysis for both cases.

The total costs and percent distributions for the 12 cost categories in both cases are presented in Table 4-2. The predominant cost categories for Case 1 were capital equipment (35.5 percent) and site preparation (33.0 percent), accounting for over 60 percent of the total costs for both cases. For Case

1, other important cost categories included mobilization and startup (9.0 percent), equipment maintenance (6.0 percent), analytical services (6.0 percent), labor (4.0 percent), demobilization (3.0 percent), and utilities (3.0 percent). All other cost categories (permitting, supplies, effluent treatment, and residual shipping) accounted for less than 1 percent of the total costs. Figure 4-1 shows the distribution of total costs for Case 1.

For Case 1, extending the use of the barrier wall at the HRE pond site over a 5-year period resulted in total estimated fixed and total annual costs of about $1,165,400. This figure corresponds to a unit cost of $8.30 per cubic foot of frozen soil, or $6.50 per cubic foot of isolated volume. Fixed costs represent 82 percent and annual costs represent 18 percent of the total costs for the Case 1 estimate.

For the Case 2 estimate (see Figure 4-2), capital equipment (37.1 percent) and site preparation (25.2 percent) account for the majority of costs. Significant costs were accrued in the following categories: equipment maintenance (12.6 percent), mobilization and startup (9.4 percent), utilities (5.3 percent), analytical services (3.6 percent), labor (3.4 percent), and demobilization (3.0 percent). The costs for permitting, supplies, effluent treatment, and residual shipping accounted for less than 1 percent of the total costs for Case 2.

The total estimated cost for applying the freeze barrier technology to the Case 2 site over a 10-year period is approximately $2,535,700. Unit costs of $8.50 per cubic foot of frozen soil, or $2.80 per cubic foot of isolated volume, were calculated based on this estimate. About 75 percent of the total costs were for fixed costs, with the remaining 25 percent associated with annual costs. The annual costs for Case 2 are a larger fraction of the total costs than for Case 1, primarily due to the longer duration of the barrier application for this estimate.

5.0 TECHNOLOGY STATUS AND IMPLEMENTATION

To date, this SITE demonstration represents the first full-scale application of the AFI frozen soil barrier technology at a contaminated site. However, AFI has been developing, designing, fabricating, and installing ground freezing systems for about 30 years. AFI has used the technology to seal subsurface structures against flooding of groundwater; to stabilize soils for excavation; and for foundation and ground stabilization purposes. While the AFI ground freezing system has been primarily used in arctic and subarctic environments, such as Alaska, Canada, and Greenland, the system can also be used in more temperate locations as demonstrated at the HRE pond site.

Current plans for AFI's ground freezing at ORNL's HRE pond site include maintaining the frozen soil barrier through DOE's fiscal year 2002 to assess long-term performance of the barrier wall. DOE is also considering the use of the freeze barrier technology for containment of radiologically contaminated groundwater plumes at two other DOE facilities, including Savannah River and Hanford. The technology also is being considered for containment of a groundwater plume contaminated with polychlorinated biphenyls and dense nonaqueous-phase liquids at a site in Smithville, Canada.

6.0 REFERENCES

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APPENDIX

SUMMARY OF ANALYTICAL DATA FROM THE DEMONSTRATION OF THE FREEZE BARRIER TECHNOLOGY: JANUARY 1998 - JULY 1998

(15 Pages)

Analytical Results for
Eosine OJ and Phloxine B
(ppb)

Location	Description	Phase	Sample Type	Sample Date	Eosine OJ	Phloxine B
DLD	Dale's Little Dipper Spring	BKG	GS	1/26/98	1.30E-03	ND
I2	standpipe	BKG	GS	1/26/98	ND	ND
MW1 (1109)	monitoring well	BKG	GS	1/26/98	ND	ND
MW2 (1110)	monitoring well	BKG	GS	1/26/98	ND	ND
MW3 (1111)	monitoring well	BKG	GS	1/26/98	ND	ND
S2	small tributary	BKG	GS	1/26/98	ND	ND
S7	small tributary	BKG	GS	1/26/98	ND	ND
SBC	stream below culvert	BKG	GS	1/26/98	ND	ND
S1	small tributary	BKG	GS	1/26/98	ND	ND
STP10	standpipe	BKG	GS	1/26/98	ND	1.30E-03
STP2	standpipe	BKG	GS	1/26/98	2.38E-01	1.30E-03
STP9	standpipe	BKG	GS	1/26/98	2.09E-02	1.30E-03
STP5	standpipe	BKG	GS	1/26/98	ND	ND
W898	piezometer	BKG	GS	1/26/98	ND	ND
SBC	stream below culvert	BKG	GS	1/27/98	ND	ND
W898	piezometer	BKG	GS	1/27/98	ND	ND
MW2 (1110)	monitoring well	BKG	GS	1/28/98	ND	ND
MW4 (1112)	monitoring well	BKG	GS	1/28/98	1.30E-03	1.30E-03
SBC	stream below culvert	BKG	GS	1/28/98	ND	ND
W898	piezometer	BKG	GS	1/28/98	ND	ND
SBC	stream below culvert	BKG	GS	1/29/98	ND	ND
W898	piezometer	BKG	GS	1/29/98	ND	ND
DLD	Dale's Little Dipper Spring	BKG	GS	1/30/98	1.30E-03	ND
I2	standpipe	BKG	GS	1/30/98	ND	ND
MW1 (1109)	monitoring well	BKG	GS	1/30/98	ND	ND
MW3 (1111)	monitoring well	BKG	GS	1/30/98	ND	ND
S1	small tributary	BKG	GS	1/30/98	ND	ND
S2	small tributary	BKG	GS	1/30/98	ND	ND
S7	small tributary	BKG	GS	1/30/98	ND	ND
SBC	stream below culvert	BKG	GS	1/30/98	ND	ND
STP10	standpipe	BKG	GS	1/30/98	ND	1.30E-03
STP2	standpipe	BKG	GS	1/30/98	2.28E-02	1.30E-03
STP9	standpipe	BKG	GS	1/30/98	1.90E-02	1.30E-03
STP5	standpipe	BKG	GS	1/30/98	ND	ND
W898	piezometer	BKG	GS	1/30/98	ND	ND
MW2 (1110)	monitoring well	BKG	GS	1/31/98	ND	ND
MW4 (1112)	monitoring well	BKG	GS	1/31/98	1.30E-03	1.30E-03
SBC	stream below culvert	BKG	GS	1/31/98	ND	ND
W898	piezometer	BKG	GS	1/31/98	ND	ND

Analytical Results for
Eosine OJ and Phloxine B
(ppb)

Location	Description	Phase	Sample Type	Sample Date	Eosine OJ	Phloxine B
SBC	stream below culvert	BKG	GS	2/1/98	ND	ND
W898	piezometer	BKG	GS	2/1/98	ND	ND
DLD	Dale's Little Dipper Spring	BKG	GS	2/2/98	1.30E-03	ND
KL	Keller's Leak	BKG	GS	2/2/98	ND	ND
MW3 (1111)	monitoring well	BKG	GS	2/2/98	ND	ND
MW3 (1111)	monitoring well	BKG	C	2/2/98	ND	ND
S1	small tributary	BKG	GS	2/2/98	ND	ND
S1	small tributary	BKG	C	2/2/98	ND	ND
S2	small tributary	BKG	GS	2/2/98	ND	ND
S2	small tributary	BKG	C	2/2/98	ND	ND
S7	small tributary	BKG	GS	2/2/98	ND	ND
S7	small tributary	BKG	C	2/2/98	ND	ND
SBC	stream below culvert	BKG	GS	2/2/98	ND	ND
STP10	standpipe	BKG	GS	2/2/98	ND	1.30E-03
STP10	standpipe	BKG	C	2/2/98	ND	ND
STP2	standpipe	BKG	GS	2/2/98	2.47E-02	1.30E-03
STP9	standpipe	BKG	GS	2/2/98	1.33E-02	1.30E-03
STP5	standpipe	BKG	GS	2/2/98	ND	ND
STP5	standpipe	BKG	C	2/2/98	ND	ND
W898	piezometer	BKG	GS	2/2/98	ND	ND
MW2 (1110)	monitoring well	BKG	GS	2/3/98	ND	ND
MW4 (1112)	monitoring well	BKG	GS	2/3/98	1.30E-03	1.30E-03
SBC	stream below culvert	BKG	GS	2/3/98	ND	ND
W898	piezometer	BKG	GS	2/3/98	ND	ND
SBC	stream below culvert	BKG	GS	2/4/98	ND	ND
W898	piezometer	BKG	GS	2/4/98	ND	ND
SBC	stream below culvert	BKG	GS	2/5/98	ND	ND
W898	piezometer	BKG	GS	2/5/98	ND	ND
DLD	Dale's Little Dipper Spring	BKG	GS	2/6/98	1.30E-03	ND
MW2 (1110)	monitoring well	BKG	GS	2/6/98	ND	ND
MW3 (1111)	monitoring well	BKG	GS	2/6/98	ND	ND
MW4 (1112)	monitoring well	BKG	GS	2/6/98	1.30E-03	1.30E-03
S1	small tributary	BKG	GS	2/6/98	ND	ND
S2	small tributary	BKG	GS	2/6/98	ND	ND
S7	small tributary	BKG	GS	2/6/98	ND	ND
SBC	stream below culvert	BKG	GS	2/6/98	ND	ND
STP10	standpipe	BKG	GS	2/6/98	ND	1.30E-03
STP2	standpipe	BKG	GS	2/6/98	2.85E-02	1.30E-03
STP9	standpipe	BKG	GS	2/6/98	1.30E-03	1.30E-03

Analytical Results for
Eosine OJ and Phloxine B
(ppb)

Location	Description	Phase	Sample Type	Sample Date	Eosine OJ	Phloxine B
STSS	Trivelpiece Spring	BKG	GS	2/6/98	ND	ND
W898	piezometer	BKG	GS	2/6/98	ND	ND
		BKG	NSC	2/7/98		
		BKG	NSC	2/8/98		
DLD	Dale's Little Dipper Spring	BKG	GS	2/9/98	1.30E-03	ND
I2	standpipe	BKG	GS	2/9/98	ND	ND
MW1 (1109)	monitoring well	BKG	GS	2/9/98	ND	ND
MW2 (1110)	monitoring well	BKG	GS	2/9/98	ND	ND
MW2 (1110)	monitoring well	BKG	C	2/9/98	ND	ND
MW3 (1111)	monitoring well	BKG	GS	2/9/98	ND	ND
MW3 (1111)	monitoring well	BKG	C	2/9/98	ND	ND
MW4 (1112)	monitoring well	BKG	GS	2/9/98	1.30E-03	1.30E-03
S1	small tributary	BKG	GS	2/9/98	ND	ND
S1	small tributary	BKG	C	2/9/98	ND	ND
S2	small tributary	BKG	GS	2/9/98	ND	ND
S2	small tributary	BKG	C	2/9/98	ND	ND
S7	small tributary	BKG	GS	2/9/98	ND	ND
S7	small tributary	BKG	C	2/9/98	ND	ND
SBC	stream below culvert	BKG	C	2/9/98	ND	ND
STP10	standpipe	BKG	GS	2/9/98	ND	1.30E-03
STP2	standpipe	BKG	GS	2/9/98	3.79E-02	1.30E-03
STP9	standpipe	BKG	GS	2/9/98	1.90E-02	1.30E-03
STSS	Trivelpiece Spring	BKG	GS	2/9/98	ND	ND
STSS	Trivelpiece Spring	BKG	C	2/9/98	ND	ND
W898	piezometer	BKG	C	2/9/98	ND	ND
		BKG	NSC	2/10/98		
		BKG	NSC	2/11/98		
MW2 (1110)	monitoring well	BKG	GS	2/12/98	ND	ND
MW4 (1112)	monitoring well	BKG	GS	2/12/98	5.14E-02	ND
AFIP	piezometer	BKG	GS	2/13/98	ND	1.30E-03
DLD	Dale's Little Dipper Spring	BKG	GS	2/13/98	1.30E-03	ND
I2	standpipe	BKG	GS	2/13/98	ND	ND
MW1 (1109)	monitoring well	BKG	GS	2/13/98	ND	ND
MW2 (1110)	monitoring well	BKG	C	2/13/98	ND	ND
MW3 (1111)	monitoring well	BKG	GS	2/13/98	ND	ND
MW4 (1112)	monitoring well	BKG	C	2/13/98	1.30E-03	1.30E-03
S1	small tributary	BKG	GS	2/13/98	ND	ND
S2	small tributary	BKG	GS	2/13/98	ND	ND
S7	small tributary	BKG	GS	2/13/98	ND	ND

Analytical Results for
Eosine OJ and Phloxine B
(ppb)

Location	Description	Phase	Sample Type	Sample Date	Eosine OJ	Phloxine B
SBC	stream below culvert	BKG	C	2/13/98	ND	ND
STP10	standpipe	BKG	GS	2/13/98	ND	ND
STP2	standpipe	BKG	GS	2/13/98	ND	1.30E-03
STP9	standpipe	BKG	GS	2/13/98	6.07E-02	1.30E-03
STSS	Trivelpiece Spring	BKG	GS	2/13/98	1.90E-02	1.30E-03
W898	piezometer	BKG	GS	2/13/98	ND	ND
		BKG	C	2/13/98	ND	ND
		BKG	NSC	2/14/98		
MW2 (1110)	monitoring well	BKG	GS	2/15/98	ND	ND
MW4 (1112)	monitoring well	BKG	GS	2/15/98	1.30E-03	1.30E-03
		BKG	NSC	2/16/98		
DLD	Dale's Little Dipper Spring	BKG	GS	2/17/98	1.30E-03	ND
MW2 (1110)	monitoring well	BKG	C	2/17/98	ND	ND
MW3 (1111)	monitoring well	BKG	GS	2/17/98	ND	ND
MW4 (1112)	monitoring well	BKG	C	2/17/98	ND	ND
S1	small tributary	BKG	GS	2/17/98	ND	ND
S2	small tributary	BKG	GS	2/17/98	ND	ND
S7	small tributary	BKG	GS	2/17/98	ND	ND
SBC	stream below culvert	BKG	GS	2/17/98	ND	ND
SBC	stream below culvert	BKG	C	2/17/98	ND	ND
STP10	standpipe	BKG	GS	2/17/98	ND	1.30E-03
STP2	standpipe	BKG	GS	2/17/98	1.14E-02	1.30E-03
STP9	standpipe	BKG	GS	2/17/98	7.17E-02	1.30E-03
STSS	Trivelpiece Spring	BKG	GS	2/17/98	ND	ND
W898	piezometer	BKG	GS	2/17/98	ND	ND
W898	piezometer	BKG	C	2/17/98	ND	ND
		BKG	NSC	2/18/98		
MW4 (1112)	monitoring well	TR	GS	2/19/98	1.30E-03	1.30E-03
SBC	stream below culvert	TR	GS	2/19/98	ND	ND
W898	piezometer	TR	GS	2/19/98	ND	ND
AFIP	piezometer	TR	GS	2/20/98	ND	1.30E-03
DLD	Dale's Little Dipper Spring	TR	GS	2/20/98	1.09E+03	ND
MW2 (1110)	monitoring well	TR	GS	2/20/98	ND	ND
MW3 (1111)	monitoring well	TR	GS	2/20/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	2/20/98	1.30E-03	1.30E-03
S1	small tributary	TR	GS	2/20/98	ND	ND
S2	small tributary	TR	GS	2/20/98	ND	ND
S7	small tributary	TR	GS	2/20/98	ND	ND
SBC	stream below culvert	TR	GS	2/20/98	ND	ND
STP10	standpipe	TR	GS	2/20/98	ND	1.30E-03

Analytical Results for
Eosine OJ and Phloxine B
(ppb)

Location	Description	Phase	Sample Type	Sample Date	Eosine OJ	Phloxine B
STP2	standpipe	TR	GS	2/20/98	2.75E-02	1.30E-03
STP9	standpipe	TR	GS	2/20/98	1.52E-02	ND
STSS	Trivelpiece Spring	TR	GS	2/20/98	ND	ND
W898	piezometer	TR	GS	2/20/98	ND	ND
MW2 (1110)	monitoring well	TR	GS	2/21/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	2/21/98	1.30E-03	1.30E-03
SBC	stream below culvert	TR	GS	2/21/98	ND	ND
W898	piezometer	TR	GS	2/21/98	ND	ND
W898	piezometer	TR	C	2/21/98	ND	ND
MW4 (1112)	monitoring well	TR	C	2/22/98	1.30E-03	1.30E-03
SBC	stream below culvert	TR	GS	2/22/98	ND	ND
W898	piezometer	TR	GS	2/22/98	ND	ND
AFIP	piezometer	TR	GS	2/23/98	ND	1.30E-03
DLD	Dale's Little Dipper Spring	TR	GS	2/23/98	6.27E+02	ND
KL	Keller's Leak	TR	GS	2/23/98	ND	ND
MW2 (1110)	monitoring well	TR	GS	2/23/98	ND	ND
MW3 (1111)	monitoring well	TR	GS	2/23/98	ND	ND
MW3 (1111)	monitoring well	TR	C	2/23/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	2/23/98	1.30E-03	1.30E-03
S1	small tributary	TR	GS	2/23/98	ND	ND
S1	small tributary	TR	C	2/23/98	ND	ND
S2	small tributary	TR	GS	2/23/98	ND	ND
S2	small tributary	TR	C	2/23/98	ND	ND
S7	small tributary	TR	GS	2/23/98	ND	ND
S7	small tributary	TR	C	2/23/98	ND	ND
SBC	stream below culvert	TR	GS	2/23/98	ND	ND
STP10	standpipe	TR	GS	2/23/98	ND	1.30E-03
STP10	standpipe	TR	C	2/23/98	ND	ND
STP2	standpipe	TR	GS	2/23/98	7.55E-02	1.30E-03
STP9	standpipe	TR	C	2/23/98	7.60E-03	1.30E-03
STSS	Trivelpiece Spring	TR	GS	2/23/98	ND	ND
STSS	Trivelpiece Spring	TR	C	2/23/98	ND	ND
W898	piezometer	TR	GS	2/23/98	ND	ND
MW2 (1110)	monitoring well	TR	GS	2/24/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	2/24/98	1.30E-03	1.30E-03
SBC	stream below culvert	TR	GS	2/24/98	ND	ND
W898	piezometer	TR	GS	2/24/98	ND	ND
W898	piezometer	TR	C	2/24/98	ND	ND
AFIP	piezometer	TR	GS	2/25/98	ND	1.30E-03

Analytical Results for
Eosine OJ and Phloxine B
(ppb)

Location	Description	Phase	Sample Type	Sample Date	Eosine OJ	Phloxine B
MW2 (1110)	monitoring well	TR	GS	2/25/98	ND	ND
MW3 (1111)	monitoring well	TR	GS	2/25/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	2/25/98	1.30E-03	1.30E-03
S1	small tributary	TR	GS	2/25/98	ND	ND
S2	small tributary	TR	GS	2/25/98	ND	ND
S7	small tributary	TR	GS	2/25/98	ND	ND
SBC	stream below culvert	TR	GS	2/25/98	ND	ND
STP10	standpipe	TR	GS	2/25/98	ND	1.30E-03
STP2	standpipe	TR	GS	2/25/98	5.20E-03	1.30E-03
STP9	standpipe	TR	GS	2/25/98	7.60E-03	1.30E-03
STSS	Trivelpiece Spring	TR	GS	2/25/98	ND	ND
W898	piezometer	TR	GS	2/25/98	ND	ND
MW2 (1110)	monitoring well	TR	GS	2/26/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	2/26/98	1.30E-03	1.30E-03
SBC	stream below culvert	TR	GS	2/26/98	ND	ND
W898	piezometer	TR	GS	2/26/98	ND	ND
AFIP	piezometer	TR	GS	2/27/98	ND	1.30E-03
KL	Keller's Leak	TR	GS	2/27/98	ND	ND
MW2 (1110)	monitoring well	TR	GS	2/27/98	ND	ND
MW3 (1111)	monitoring well	TR	GS	2/27/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	2/27/98	1.30E-03	1.30E-03
S1	small tributary	TR	GS	2/27/98	ND	ND
S2	small tributary	TR	GS	2/27/98	ND	ND
S7	small tributary	TR	GS	2/27/98	ND	ND
SBC	stream below culvert	TR	GS	2/27/98	ND	ND
SBC	stream below culvert	TR	C	2/27/98	ND	ND
SCS	Steel Cylinder Spring	TR	GS	2/27/98	ND	ND
STP10	standpipe	TR	GS	2/27/98	ND	1.30E-03
STP9	standpipe	TR	GS	2/27/98	1.30E-03	1.30E-03
STSS	Trivelpiece Spring	TR	GS	2/27/98	ND	ND
W898	piezometer	TR	GS	2/27/98	ND	ND
MW2 (1110)	monitoring well	TR	GS	2/28/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	2/28/98	1.30E-03	1.30E-03
SCS	Steel Cylinder Spring	TR	GS	2/28/98	ND	ND
W898	piezometer	TR	GS	2/28/98	ND	ND
MW2 (1110)	monitoring well	TR	GS	3/1/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	3/1/98	1.30E-03	1.30E-03
SCS	Steel Cylinder Spring	TR	GS	3/1/98	ND	ND
W898	piezometer	TR	GS	3/1/98	ND	ND

Analytical Results for
Eosine OJ and Phloxine B
(ppb)

Location	Description	Phase	Sample Type	Sample Date	Eosine OJ	Phloxine B
MW2 (1110)	monitoring well	TR	GS	3/2/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	3/2/98	1.30E-03	1.30E-03
SCS	Steel Cylinder Spring	TR	GS	3/2/98	ND	ND
W898	piezometer	TR	GS	3/2/98	ND	ND
MW2 (1110)	monitoring well	TR	GS	3/3/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	33/3/98	1.30E-03	1.30E-03
SCS	Steel Cylinder Spring	TR	GS	3/3/98	ND	ND
W898	piezometer	TR	GS	3/3/98	ND	ND
MW2 (1110)	monitoring well	TR	GS	3/4/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	3/4/98	1.30E-03	1.30E-03
SCS	Steel Cylinder Spring	TR	GS	3/4/98	ND	ND
W898	piezometer	TR	GS	3/4/98	ND	ND
MW2 (1110)	monitoring well	TR	GS	3/5/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	3/5/98	1.30E-03	1.30E-03
SCS	Steel Cylinder Spring	TR	GS	3/5/98	ND	ND
W898	piezometer	TR	GS	3/5/98	ND	ND
AFIP	piezometer	TR	GS	3/6/98	ND	1.30E-03
MW2 (1110)	monitoring well	TR	GS	3/6/98	ND	ND
MW3 (1111)	monitoring well	TR	GS	3/6/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	3/6/98	1.30E-03	1.30E-03
S1	small tributary	TR	GS	3/6/98	ND	ND
S2	small tributary	TR	GS	3/6/98	ND	ND
S7	small tributary	TR	GS	3/6/98	ND	ND
SCS	Steel Cylinder Spring	TR	GS	3/6/98	ND	ND
STP10	standpipe	TR	GS	3/6/98	ND	3.20E-01
STP2	standpipe	TR	GS	3/6/98	3.04E-02	1.30E-03
STP9	standpipe	TR	GS	3/6/98	1.51E-02	1.30E-03
STSS	Trivelpiece Spring	TR	GS	3/6/98	ND	ND
W898	piezometer	TR	GS	3/6/98	ND	ND
MW2 (1110)	monitoring well	TR	GS	3/7/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	3/7/98	ND	ND
SCS	Steel Cylinder Spring	TR	GS	3/7/98	ND	ND
W898	piezometer	TR	GS	3/7/98	ND	ND
MW2 (1110)	monitoring well	TR	GS	3/8/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	3/8/98	ND	ND
SCS	Steel Cylinder Spring	TR	GS	3/8/98	ND	ND
W898	piezometer	TR	GS	3/8/98	ND	ND
DLD	Dale's Little Dipper Spring	TR	GS	3/9/98	3.66E+02	ND
MW2 (1110)	monitoring well	TR	GS	3/9/98	ND	ND

Analytical Results for
Eosine OJ and Phloxine B
(ppb)

Location	Description	Phase	Sample Type	Sample Date	Eosine OJ	Phloxine B
MW4 (1112)	monitoring well	TR	GS	3/9/98	ND	ND
W898	piezometer	TR	GS	3/9/98	ND	ND
SBC	stream below culvert	TR	GS	3/9/98	ND	ND
SCS	Steel Cylinder Spring	TR	GS	3/9/98	ND	ND
W898	piezometer	TR	GS	3/9/98	ND	ND
W898	piezometer	TR	GS	3/10/98	ND	ND
SBC	stream below culvert	TR	GS	3/10/98	ND	ND
MW2 (1110)	monitoring well	TR	GS	3/11/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	3/11/98	ND	ND
W898	piezometer	TR	GS	3/11/98	ND	ND
SBC	stream below culvert	TR	GS	3/11/98	ND	ND
STP2	standpipe	TR	GS	3/11/98	4.74E-02	1.30E-03
AFIP	piezometer	TR	GS	3/12/98	ND	1.30E-03
MW3 (1111)	monitoring well	TR	GS	3/12/98	ND	ND
W898	piezometer	TR	GS	3/12/98	ND	ND
S1	small tributary	TR	GS	3/12/98	ND	ND
S2	small tributary	TR	GS	3/12/98	ND	ND
S7	small tributary	TR	GS	3/12/98	ND	ND
SBC	stream below culvert	TR	GS	3/12/98	ND	ND
STP10	standpipe	TR	GS	3/12/98	ND	3.07E-02
STP2	standpipe	TR	GS	3/12/98	1.82E-01	1.30E-03
STP9	standpipe	TR	GS	3/12/98	2.64E-02	1.30E-03
STSS	Trivelpiece Spring	TR	GS	3/12/98	ND	ND
MW2 (1110)	monitoring well	TR	GS	3/13/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	3/13/98	1.30E-03	1.30E-03
W898	piezometer	TR	GS	3/13/98	ND	ND
SBC	stream below culvert	TR	GS	3/13/98	ND	ND
W898	piezometer	TR	GS	3/14/98	ND	ND
SBC	stream below culvert	TR	GS	3/14/98	ND	ND
MW2 (1110)	monitoring well	TR	GS	3/15/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	3/15/98	1.30E-03	1.30E-03
W898	piezometer	TR	GS	3/15/98	ND	ND
SBC	stream below culvert	TR	GS	3/15/98	ND	ND
W898	piezometer	TR	GS	3/16/98	ND	ND
SBC	stream below culvert	TR	GS	3/16/98	ND	ND
MW2 (1110)	monitoring well	TR	GS	3/17/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	3/17/98	1.30E-03	1.30E-03
W898	piezometer	TR	GS	3/17/98	ND	ND
SBC	stream below culvert	TR	GS	3/17/98	ND	ND

Analytical Results for
Eosine OJ and Phloxine B
(ppb)

Location	Description	Phase	Sample Type	Sample Date	Eosine OJ	Phloxine B
AFIP	piezometer	TR	GS	3/18/98	ND	ND
DLD	Dale's Little Dipper Spring	TR	GS	3/18/98	1.83E+01	ND
W898	piezometer	TR	GS	3/18/98	ND	ND
OF283	Overflow 283	TR	GS	3/18/98	ND	ND
SBC	stream below culvert	TR	GS	3/18/98	ND	ND
SCS	Steel Cylinder Spring	TR	GS	3/18/98	ND	ND
STP10	standpipe	TR	GS	3/18/98	ND	ND
STP2	standpipe	TR	GS	3/18/98	6.79E-02	ND
STP9	standpipe	TR	GS	3/18/98	1.30E-03	1.30E-03
MW2 (1110)	monitoring well	TR	GS	3/19/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	3/19/98	1.30E-03	1.30E-03
W898	piezometer	TR	GS	3/19/98	ND	ND
SBC	stream below culvert	TR	GS	3/19/98	ND	ND
DLD	Dale's Little Dipper Spring	TR	GS	3/20/98	9.10E+01	ND
W898	piezometer	TR	GS	3/20/98	ND	ND
SBC	stream below culvert	TR	GS	3/20/98	ND	ND
STP1	standpipe	TR	GS	3/20/98	1.30E-03	1.30E-03
STP10	standpipe	TR	GS	3/20/98	ND	1.30E-03
STP2	standpipe	TR	GS	3/20/98	ND	1.30E-03
STP9	standpipe	TR	GS	3/20/98	4.15E-02	1.30E-03
MW2 (1110)	monitoring well	TR	GS	3/21/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	3/21/98	1.30E-03	1.30E-03
W898	piezometer	TR	GS	3/21/98	ND	ND
SBC	stream below culvert	TR	GS	3/21/98	ND	ND
W898	piezometer	TR	GS	3/22/98	ND	ND
SBC	stream below culvert	TR	GS	3/22/98	ND	ND
AFIP	piezometer	TR	GS	3/23/98	ND	1.30E-03
DLD	Dale's Little Dipper Spring	TR	GS	3/23/98	4.19E+02	ND
MW2 (1110)	monitoring well	TR	GS	3/23/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	3/23/98	ND	ND
W898	piezometer	TR	GS	3/23/98	ND	ND
S7	small tributary	TR	GS	3/23/98	ND	ND
SBC	stream below culvert	TR	GS	3/23/98	ND	ND
STP1	standpipe	TR	GS	3/23/98	1.30E-03	1.30E-03
STP10	standpipe	TR	GS	3/23/98	ND	1.59E-02
STP2	standpipe	TR	GS	3/23/98	2.28E-02	1.30E-03
STP9	standpipe	TR	GS	3/23/98	2.09E-02	1.30E-03
W898	piezometer	TR	GS	3/24/98	ND	ND
SBC	stream below culvert	TR	GS	3/24/98	ND	ND

Analytical Results for
Eosine OJ and Phloxine B
(ppb)

Location	Description	Phase	Sample Type	Sample Date	Eosine OJ	Phloxine B
DLD	Dale's Little Dipper Spring	TR	GS	3/25/98	3.56E+02	ND
MW2 (1110)	monitoring well	TR	GS	3/25/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	3/25/98	1.30E-03	1.30E-03
W898	piezometer	TR	GS	3/25/98	ND	ND
SBC	stream below culvert	TR	GS	3/25/98	ND	ND
STP10	standpipe	TR	GS	3/25/98	ND	ND
STP9	standpipe	TR	GS	3/25/98	1.30E-03	1.30E-03
W898	piezometer	TR	GS	3/26/98	ND	ND
SBC	stream below culvert	TR	GS	3/26/98	ND	ND
AFIP	piezometer	TR	GS	3/27/98	ND	1.30E-03
DLD	Dale's Little Dipper Spring	TR	GS	3/27/98	4.56E+02	ND
MW3 (1111)	monitoring well	TR	GS	3/27/98	ND	ND
OF283	Overflow 283	TR	GS	3/27/98	ND	ND
S1	small tributary	TR	GS	3/27/98	ND	ND
S1	small tributary	TR	C	3/27/98	ND	ND
S2	small tributary	TR	GS	3/27/98	ND	ND
S2	small tributary	TR	C	3/27/98	ND	ND
S7	small tributary	TR	GS	3/27/98	ND	ND
S7	small tributary	TR	C	3/27/98	ND	ND
SBC	stream below culvert	TR	GS	3/27/98	ND	ND
SBC	stream below culvert	TR	C	3/27/98	ND	ND
STP10	standpipe	TR	GS	3/27/98	ND	1.30E-03
STP2	standpipe	TR	GS	3/27/98	3.61E-02	ND
STP9	standpipe	TR	GS	3/27/98	1.30E-03	1.30E-03
STSS	Trivelpiece Spring	TR	GS	3/27/98	ND	ND
		TR	NSC	3/28/98		
		TR	NSC	3/29/98		
		TR	NSC	3/30/98		
SBC	stream below culvert	TR	GS	3/31/98	ND	ND
		TR	NSC	4/1/98		
AFIP	piezometer	TR	GS	4/2/98	ND	1.30E-03
DLD	Dale's Little Dipper Spring	TR	GS	4/2/98	4.50E+00	ND
KL	Keller's Leak	TR	GS	4/2/98	ND	ND
STP10	standpipe	TR	GS	4/2/98	ND	1.30E-03
STP2	standpipe	TR	GS	4/2/98	9.44E-02	ND
STP9	standpipe	TR	GS	4/2/98	1.30E-03	ND
SBC	stream below culvert	TR	GS	4/3/98	ND	ND
		TR	NSC	4/4/98		
		TR	NSC	4/5/98		

Analytical Results for
Eosine OJ and Phloxine B
(ppb)

Location	Description	Phase	Sample Type	Sample Date	Eosine OJ	Phloxine B
		TR	NSC	4/6/98		
SBC	stream below culvert	TR	GS	4/7/98	ND	ND
		TR	NSC	4/8/98		
		TR	NSC	4/9/98		
SBC	stream below culvert	TR	GS	4/10/98	ND	ND
		TR	NSC	4/11/98		
		TR	NSC	4/12/98		
		TR	NSC	4/13/98		
SBC	stream below culvert	TR	GS	4/14/98	ND	ND
AFIP	piezometer	TR	GS	4/15/98	ND	1.30E-03
OF283	Overflow 283	TR	GS	4/15/98	ND	ND
STP10	standpipe	TR	GS	4/15/98	ND	1.30E-03
TCP	terra cotta pipe	TR	GS	4/15/98	ND	ND
		TR	NSC	4/16/98		
SBC	stream below culvert	TR	GS	4/17/98	ND	ND
		TR	NSC	4/18/98		
		TR	NSC	4/19/98		
		TR	NSC	4/20/98		
SBC	stream below culvert	TR	GS	4/21/98	ND	ND
		TR	NSC	4/22/98		
		TR	NSC	4/23/98		
SBC	stream below culvert	TR	GS	4/24/98	ND	ND
		TR	NSC	4/25/98		
		TR	NSC	4/26/98		
MW2 (1110)	monitoring well	TR	GS	4/27/98	ND	ND
AFIP	piezometer	TR	GS	4/28/98	ND	7.99E-01
SBC	stream below culvert	TR	GS	4/28/98	ND	ND
STP1	standpipe	TR	GS	4/28/98	1.30E-03	1.30E-03
STP10	standpipe	TR	GS	4/28/98	ND	2.35E-01
STP2	standpipe	TR	GS	4/28/98	ND	1.30E-03
MW4 (1112)	monitoring well	TR	GS	4/29/98	1.30E-03	7.10E-03
		TR	NSC	4/30/98		
MW2 (1110)	monitoring well	TR	GS	5/1/98	ND	ND
SBC	stream below culvert	TR	GS	5/1/98	ND	ND
W898	piezometer	TR	GS	5/1/98	ND	ND
		TR	NSC	5/2/98		
SBC	stream below culvert	TR	GS	5/3/98	ND	ND
MW2 (1110)	monitoring well	TR	GS	5/4/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	5/4/98	1.30E-03	1.30E-03

Analytical Results for
Eosine OJ and Phloxine B
(ppb)

Location	Description	Phase	Sample Type	Sample Date	Eosine OJ	Phloxine B
SBC	stream below culvert	TR	GS	5/5/98	ND	ND
W898	piezometer	TR	GS	5/5/98	ND	ND
		TR	NSC	5/6/98		
MW4 (1112)	monitoring well	TR	GS	5/7/98	1.30E-03	1.30E-03
AFIP	piezometer	TR	GS	5/8/98	ND	2.44E-01
DLD	Dale's Little Dipper Spring	TR	GS	5/8/98	1.30E+00	ND
FS	Frank's Spring	TR	GS	5/8/98	ND	ND
KL	Keller's Leak	TR	GS	5/8/98	ND	ND
MH	manhole south of pond	TR	GS	5/8/98	ND	ND
MW2 (1110)	monitoring well	TR	GS	5/8/98	ND	ND
MW3 (1111)	monitoring well	TR	GS	5/8/98	ND	ND
OF283	Overflow 283	TR	GS	5/8/98	ND	ND
S1	small tributary	TR	GS	5/8/98	ND	ND
S2	small tributary	TR	GS	5/8/98	ND	ND
STP1	standpipe	TR	GS	5/8/98	1.30E-03	1.30E-03
STP10	standpipe	TR	GS	5/8/98	ND	1.30E-03
STP2	standpipe	TR	GS	5/8/98	1.52E-02	2.03E-02
STP5	standpipe	TR	GS	5/8/98	ND	ND
STP6	standpipe	TR	GS	5/8/98	ND	ND
STP7	standpipe	TR	GS	5/8/98	ND	ND
STP9	standpipe	TR	GS	5/8/98	1.30E-03	1.30E-03
TCP	terra cotta pipe	TR	GS	5/8/98	ND	ND
W898	piezometer	TR	GS	5/8/98	ND	ND
		TR	NSC	5/9/98		
		TR	NSC	5/10/98		
MW2 (1110)	monitoring well	TR	GS	5/11/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	5/11/98	1.30E-03	1.30E-03
SBC	stream below culvert	TR	GS	5/12/98	ND	ND
W898	piezometer	TR	GS	5/12/98	ND	ND
		TR	NSC	5/13/98		
MW4 (1112)	monitoring well	TR	GS	5/14/98	1.30E-03	1.30E-03
MW2 (1110)	monitoring well	TR	GS	5/15/98	ND	ND
SBC	stream below culvert	TR	GS	5/15/98	ND	ND
W898	piezometer	TR	GS	5/15/98	ND	ND
		TR	NSC	5/16/98		
		TR	NSC	5/17/98		
MW2 (1110)	monitoring well	TR	GS	5/18/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	5/18/98	1.30E-03	1.30E-03
W898	piezometer	TR	GS	5/19/98	ND	ND

Analytical Results for
Eosine OJ and Phloxine B
(ppb)

Location	Description	Phase	Sample Type	Sample Date	Eosine OJ	Phloxine B
		TR	NSC	5/20/98		
MW4 (1112)	monitoring well	TR	GS	5/21/98	1.30E-03	1.30E-03
MW2 (1110)	monitoring well	TR	GS	5/22/98	ND	ND
W898	piezometer	TR	GS	5/22/98	ND	ND
		TR	NSC	5/23/98		
		TR	NSC	5/24/98		
MW4 (1112)	monitoring well	TR	GS	5/25/98	1.30E-03	1.30E-03
W898	piezometer	TR	GS	5/26/98	ND	ND
		TR	NSC	5/27/98		
MW4 (1112)	monitoring well	TR	GS	5/28/98	1.30E-03	1.30E-03
AFIP	piezometer	TR	GS	5/29/98	ND	3.30E-02
MW2 (1110)	monitoring well	TR	GS	5/29/98	ND	ND
MW3 (1111)	monitoring well	TR	GS	5/29/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	5/29/98	1.30E-03	1.30E-03
W898	piezometer	TR	GS	5/29/98	ND	ND
STP1	standpipe	TR	GS	5/29/98	3.07E-02	2.03E-02
STP10	standpipe	TR	GS	5/29/98	ND	2.60E-02
STP2	standpipe	TR	GS	5/29/98	3.61E-02	2.24E-02
STP5	standpipe	TR	GS	5/29/98	ND	ND
STP6	standpipe	TR	GS	5/29/98	ND	ND
STP8	standpipe	TR	GS	5/29/98	ND	ND
STP9	standpipe	TR	GS	5/29/98	1.30E-03	1.30E-03
		TR	NSC	5/30/98		
		TR	NSC	5/31/98		
MW2 (1110)	monitoring well	TR	GS	6/1/98	ND	ND
W898	piezometer	TR	GS	6/1/98	ND	ND
SBC	stream below culvert	TR	GS	6/1/98	ND	ND
		TR	NSC	6/2/98		
		TR	NSC	6/3/98		
		TR	NSC	6/4/98		
STP6	standpipe	TR	GS	6/5/98	ND	ND
MW2 (1110)	monitoring well	TR	GS	6/5/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	6/5/98	1.30E-03	1.30E-03
W898	piezometer	TR	GS	6/5/98	ND	ND
SBC	stream below culvert	TR	GS	6/5/98	ND	ND
		TR	NSC	6/6/98		
		TR	NSC	6/7/98		
MW2 (1110)	monitoring well	TR	GS	6/8/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	6/8/98	1.30E-03	1.30E-03

Analytical Results for
Eosine OJ and Phloxine B
(ppb)

Location	Description	Phase	Sample Type	Sample Date	Eosine OJ	Phloxine B
W898	piezometer	TR	GS	6/8/98	ND	ND
SBC	stream below culvert	TR	GS	6/8/98	ND	ND
		TR	NSC	6/9/98		
MW3 (1111)	monitoring well	TR	GS	6/10/98	ND	ND
STP10	standpipe	TR	GS	6/10/98	ND	1.30E-03
STP5	standpipe	TR	GS	6/10/98	ND	ND
STP6	standpipe	TR	GS	6/10/98	ND	ND
STP9	standpipe	TR	GS	6/10/98	1.90E-02	1.30E-03
MW4 (1112)	monitoring well	TR	GS	6/11/98	1.30E-03	1.30E-03
MW2 (1110)	monitoring well	TR	GS	6/12/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	6/12/98	1.30E-03	1.30E-03
W898	piezometer	TR	GS	6/12/98	ND	ND
SBC	stream below culvert	TR	GS	6/12/98	ND	ND
		TR	NSC	6/13/98		
		TR	NSC	6/14/98		
MW2 (1110)	monitoring well	TR	GS	6/15/98	ND	ND
W898	piezometer	TR	GS	6/15/98	ND	ND
SBC	stream below culvert	TR	GS	6/15/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	6/16/98	1.30E-03	1.30E-03
		TR	NSC	6/17/98		
		TR	NSC	6/18/98		
MW2 (1110)	monitoring well	TR	GS	6/19/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	6/19/98	1.30E-03	1.30E-03
W898	piezometer	TR	GS	6/19/98	ND	ND
SBC	stream below culvert	TR	GS	6/19/98	ND	ND
		TR	NSC	6/20/98		
		TR	NSC	6/21/98		
MW2 (1110)	monitoring well	TR	GS	6/22/98	ND	ND
W898	piezometer	TR	GS	6/22/98	ND	ND
SBC	stream below culvert	TR	GS	6/22/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	6/23/98	1.30E-03	1.30E-03
FS	Frank's Spring	TR	GS	6/24/98	ND	ND
MH	manhole south of pond	TR	GS	6/24/98	ND	ND
MW3 (1111)	monitoring well	TR	GS	6/24/98	ND	ND
STP5	standpipe	TR	GS	6/24/98	ND	ND
STP6	standpipe	TR	GS	6/24/98	ND	ND
STP8	standpipe	TR	GS	6/24/98	ND	ND
STP9	standpipe	TR	GS	6/24/98	1.30E-03	9.40E-03
STSS	Trivelpiece Spring	TR	GS	6/24/98	ND	ND

Analytical Results for
Eosine OJ and Phloxine B
(ppb)

Location	Description	Phase	Sample Type	Sample Date	Eosine OJ	Phloxine B
		TR	NSC	6/25/98		
MW4 (1112)	monitoring well	TR	GS	6/26/98	1.30E-03	1.30E-03
W898	piezometer	TR	GS	6/26/98	ND	ND
SBC	stream below culvert	TR	GS	6/26/98	ND	ND
		TR	NSC	6/27/98		
		TR	NSC	6/28/98		
MW2 (1110)	monitoring well	TR	GS	6/29/98	ND	ND
W898	piezometer	TR	GS	6/29/98	ND	ND
SBC	stream below culvert	TR	GS	6/29/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	6/30/98	1.30E-03	1.30E-03
		TR	NSC	7/1/98		
MW2 (1110)	monitoring well	TR	GS	7/2/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	7/3/98	2.70E-03	1.30E-03
W898	piezometer	TR	GS	7/3/98	ND	ND
SBC	stream below culvert	TR	GS	7/3/98	ND	ND
		TR	NSC	7/4/98		
		TR	NSC	7/5/98		
W898	piezometer	TR	GS	7/6/98	ND	ND
SBC	stream below culvert	TR	GS	7/6/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	7/7/98	1.30E-03	1.30E-03
		TR	NSC	7/8/98		
		TR	NSC	7/9/98		
MW4 (1112)	monitoring well	TR	GS	7/10/98	1.30E-03	1.30E-03
		TR	NSC	7/11/98		
		TR	NSC	7/12/98		
MW2 (1110)	monitoring well	TR	GS	7/13/98	ND	ND
MW4 (1112)	monitoring well	TR	GS	7/14/98	1.30E-03	1.30E-03

Notes:
BKG = background
TR = tracer
GS = grab sample
C = charcoal
ND = none detected
ppb = parts per billion
NSC = no samples collected

ATTACHMENT A

VENDOR'S CLAIMS FOR THE TECHNOLOGY

(Note: All information in this appendix was provided by the vendor, Arctic Foundations, Inc. [AFI]. Inclusion of any information is at the discretion of AFI, and does not necessarily constitute U.S. Environmental Protection Agency concurrence or endorsement.)

VENDOR'S CLAIMS

A.1 Background

Since 1862, ground freezing has been used to augment soil properties at civil works and mining sites to facilitate construction. Freezing gives load-bearing strength to soils and has frequently been used for large scale engineering projects. AFI has produced over 600 foundation and ground stabilization systems since the early 1970s. Systems have been installed at sites including hangars, towers, antennae, schools, houses, apartments, hospitals, power stations, maintenance facilities, pipelines, oil production facilities, water treatment facilities, sewage treatment and containment facilities, roadways, air fields, shopping centers, libraries, and storage tanks.

In 1962, the Atomic Energy Commission disposed of over 6,800 kilograms of radioactively contaminated material in a burial mound at the Project Chariot site in northwestern Alaska. The naturally occurring frozen soil at the site (permafrost) was deemed to be the perfect containment medium for the radionuclides. Indeed, upon remediation of the site in 1995, it was found that virtually no transport of radionuclides into the permafrost had occurred. There are several sites where the impermeability of permafrost is used to prohibit migration of contaminants such as sewage, landfill leachate, and mining tailings in Alaska, Canada, and Russia. The technology of freezing soil has just recently been considered as a hazardous waste containment technology.

A.2 Freeze Barrier Technology

Generally, soil refrigeration for ground freezing is performed using a series of concentric pipes (thermoprobes) installed in a line to approximate the geometry of the proposed frozen barrier. Pumping cold brine down the inside pipe and letting it flow back through the annular space between the inner and outer pipes freezes the soil. The frozen soil grows on the outside of the concentric pipes until it connects to the frozen cylinder formed on the adjacent pipe in the array. The typical refrigerating medium used to chill the brine is ammonia. The brine is commonly a mixture of calcium chloride and water. Should a leak occur in the brine system, the possibility exists that the antifreeze brine will solution-thaw the frozen soil and cause a breach in the barrier. Likewise, groundwater contamination can occur and brine contaminated soil may have to be excavated and cleaned, depending upon the environment where the work is taking place.

The thermosyphons or passive heat removal devices, efficiently move heat against gravity without the need for an external energy source. They are the most widely used passive refrigeration systems for creation, maintenance, and augmentation of permafrost. In cold region applications where the mean annual air temperature is below freezing, they are completely self-sufficient refrigeration devices. In the pure passive form, thermosyphons function with no moving parts. Thermosyphons operate because of a two-phase working fluid. The working fluid is contained in a closed vessel, which is usually partially buried. Whenever the above ground portion of the vessel is subjected to air that is cooler than the buried portion, heat is released to the air by condensation of the vapor within the vessel. The condensate flows via gravity to the portion of the vessel below the ground where it evaporates and the vapors return to the top. The cycling repeats until the air temperature rises above the soil temperature. These devices are thermodynamically similar to heat pumps; that is, they absorb heat by vaporizing a liquid, carry heat in the vapor phase, and release heat by condensing the vapor.

Hybrid thermosyphons incorporate an integral heat exchanger to allow the units to be driven with a standard mechanical refrigeration system. A typical system utilizing hybrid thermosyphons includes an active (powered) refrigeration condenser, an interconnecting supply and return piping system, and system controls. The hybrid thermosyphons will function actively without direct dependence on the ambient air temperature. If ambient temperatures are sufficiently low enough, the hybrid units will function passively, thereby reducing energy costs.

A.3 Deployment of Freeze Barriers

Frozen barriers are well suited to control a variety of contaminants including, but not limited to, radionuclides, DNAPLs, hydrocarbons, sewage, landfill leachate, and other hazardous chemicals. They can be deployed at a wide variety of sites at any depth from the ground surface to several thousand feet deep. The barrier can be continuous from the surface to a great depth or it can be restricted to a predetermined zone below the surface. Freezing can be confined to specific subsurface target zones for more efficient energy usage. Subsurface heat loads due to flowing groundwater, utilities, and other sources can be quantified and accounted for in the design of the barrier. It can be used to form a vertical, horizontal, or angled impervious barrier or as an encapsulating soil mass. The configuration of the barrier is primarily constrained by the installation techniques that are available. The temperature of the barrier can be adjusted to ensure the necessary liquid to solid phase change even though certain contaminants may effect a depression of the phase change temperature to a point well below 0°C. Frozen barriers can be developed in soils that are saturated or relatively dry. It is rarely necessary to add moisture because the in-situ moisture will migrate and concentrate in the frozen soil and create an impervious wall. The movement of waterborne contaminants only serves to accelerate this process.

The frozen barrier technology can also be used for immobilization of aqueous contaminants such as tritium. As there is no large scale method of removing tritium from groundwater, one simple method for treatment is to contain or immobilize tritiated water until the tritium has decayed to acceptable levels. Typically, 2 to 3 half-lives, or about 30 years of containment is the time period considered for most tritium treatment provided the source is eliminated. Similarly, ^{90}Sr with a half-life of approximately 29 years could be immobilized for 90 years or so to significantly reduce the contamination hazard. Immobilization periods must correspond to contamination levels and acceptable standards or the immobilization may be used as a stopgap measure to preclude the spread of contamination until technology can be found for remediation. The majority of system components for a frozen soil barrier using hybrid thermosyphons have no wear parts other than the skid-mounted condensing units so it is a relatively simple procedure to replace worn out components. In fact, the hybrid thermosyphons are not particular on how they are driven, so newer refrigeration technologies may provide increased efficiencies when the original equipment mechanical systems wear out.

A.4 Advantages and Innovative Features

Although there are numerous developed and embryonic technologies, such as steel, concrete, slurry walls, or grout curtains, that purport to contain or immobilize hazardous wastes, few can match the use of a frozen barrier created and maintained with thermosyphons. This technology is proven to be effective independent of climatic zone. The self-healing feature of the frozen barrier makes it attractive in locations where ground movement may occur. The soil strengthening feature is advantageous where weak soils are present or where the plane of the barrier may be on the slip surface of a potential slope failure. One of the most appealing features of the frozen barrier is the reversibility feature, that is, when the barrier is no longer needed, it is simply allowed to thaw with no lasting effect on the subgrade. Reversibility allows new science to be used in the future without being hamstrung by technology that may be outdated. The frozen soil barrier also offers the following advantages over conventional containment systems:

- Ice does not degrade or weaken over time
- The system does not create unwanted reactions and by-products in the subsurface
- It provides a means to fully contain wastes, including a bottom, without excavation
- Maintenance costs are extremely low, allowing continued use for extended periods
- The barrier uses benign refrigerants and does not have any lasting effects

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Environmental Protection
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