United States
Environmental Protection
Agency

SITE Technology Capsule

Arctic Foundations, Inc. Freeze Barrier System

Introduction

In 1980, the U.S. Congress passed the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), also known as Superfund, which is committed to protecting human health and the environment from uncontrolled hazardous waste sites. CERCLA was amended by the Superfund Amendments and Reauthorization Act (SARA) in 1986. SARA mandates cleaning up hazardous waste sites by implementing permanent solutions and using alternative treatment technologies or resource recovery technologies to the maximum extent possible.

State and federal agencies and private organizations are exploring a growing number of innovative technologies for treating hazardous wastes. These new technologies are needed to remediate the more than 1,200 sites on the National Priorities List. The sites involve a broad spectrum of physical, chemical, and environmental conditions requiring diverse remedial approaches.

The U.S. Environmental Protection Agency (EPA) has focused on policy, technical, and informational issues related to exploring and applying new technologies to Superfund site remediation. One EPA initiative to accelerate the development, demonstration, and use of innovative site remediation technologies is the Superfund Innovative Technology Evaluation (SITE) Program.

EPA SITE Technology Capsules summarize the latest information available on selected innovative technologies. The Technology Capsules assist EPA remedial project managers, EPA on-scene coordinators, contractors, and other remedial managers in evaluating site-specific information to determine a technology's applicability for site remediation.

This Technology Capsule provides information on the Arctic Foundations, Inc. (AFI), freeze barrier system. AFI developed the freeze barrier system to prevent migration of contaminants in groundwater by completely isolating contaminant source areas until appropriate remediation techniques can be applied. Contaminants are contained in situ with frozen native soils serving as the containment medium.

The freeze barrier system was demonstrated from September 1997 to July 1998 at the U. S. Department of Energy (DOE) Oak Ridge National Laboratory (ORNL) facility in Oak Ridge, Tennessee. The freeze barrier system was installed to form a 75-foot by 80-foot box-like structure around a former waste collection pond. The pond formerly served as a collection and retention basin for low-level radioactive wastes.

This Technology Capsule describes the AFI freeze barrier system and summarizes results from the SITE demonstration. The capsule includes the following information:

- Abstract
- Site Background and System Construction
- Technology Applicability
- Site Requirements
- Performance Data
- Technology Status
- Sources of Further Information

SITE
SUPERFUND INNOVATIVE
TECHNOLOGY EVALUATION

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Abstract

AFI, of Anchorage, Alaska has developed a freeze barrier system designed to prevent the migration of contaminants in groundwater by completely isolating a contaminant source area. The system can be used for long-term containment of a source or temporary containment until appropriate remediation techniques can be applied. With this system, contaminants are contained in situ with frozen native soils serving as the containment medium. The EPA SITE Program evaluated the system at the DOE ORNL facility in Oak Ridge, Tennessee from September 1997 to July 1998.

For the demonstration, an array of freeze pipes called "thermoprobes" was installed around a former waste collection pond. The thermoprobes were installed vertically to a depth of 32 feet below ground surface (bgs) and anchored in bedrock. The thermoprobes were connected to a refrigeration system by a copper 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 the frozen region around each thermoprobe began to expand and build outward, coalescing with frozen regions developed around other thermoprobes, until an impermeable frozen soil barrier formed.

A great deal of the data for the demonstration were collected by parties other than EPA, including AFI, DOE, and the Tennessee Department of Environmental Conservation (TDEC). Demonstration personnel collected independent data to evaluate the technology's performance with respect to primary and secondary objectives. Groundwater and surface water samples were collected from locations upgradient and downgradient of the barrier wall, and also from locations within the barrier wall. The water samples were analyzed for two tracer dyes, one of which was injected into an upgradient monitoring well and the other injected into a standpipe located within the barrier wall, to determine the effectiveness of the freeze barrier system in isolating the contaminant source area. Other data were collected to determine the effects of the barrier wall on hydrogeologic conditions and to monitor development of the frozen soil barrier, as well as documenting installation and operating parameters for the system.

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, the 1996 groundwater tracing investigation indicated that groundwater flowed in a radial pattern from the former pond area, which was not the case during the demonstration groundwater tracing investigation.

Sixteen days following tracer injection, tracer that was injected into the standpipe located within the barrier was detected outside the barrier in a standpipe located northwest of the former pond, and was subsequently detected in downgradient wells and standpipes located north and west of the former pond. The tracer was first detected at the standpipe adjacent to the northwest corner of the former pond. Apparently, the tracer was later carried to the other downgradient locations through the old drainage ditches on the north and west sides of the former pond. These drainage ditches were designed to contain any overflow from the former pond and likely provided a preferential pathway for tracer transport.

Historical information indicates that a subsurface pipe in the northwest corner of the former pond may have been left in place when the pond was closed. This indication is further supported by a geophysical survey conducted prior to the demonstration that detected an anomaly in the northwest corner of the former pond, suggesting that a pipe may exist. The alignment of the anomaly is very close to the standpipe located northwest of the former pond where dye was first detected. Although it cannot be determined with certainty, it appears that the dye was transported from the former pond through a breach in the northwest corner that was most likely associated with a subsurface pipe in the wall of the former pond. Available information also indicates that the former pond is underlain by fractured bedrock. Therefore, it is also possible that the breach was associated with fractured bedrock underlying the former pond.

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 system. The first case presents a cost estimate for extending the use of the freeze barrier system at DOE's HRE pond site over a 5-year period. The second case is based on applying the freeze barrier system to a Superfund site over a 10-year period. The cost estimate for Case 2 assumes that site conditions were somewhat similar to those encountered at the HRE pond site, with the exception of the types of wastes in groundwater and size of the containment area. Case 2 assumes that groundwater is contaminated with radionuclides with a volume of 900,000 cubic feet requiring containment. Based on these assumptions, the total cost per unit volume of frozen soil was about $8.50 per cubic foot for Case 1 and $9.30 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 $6.60 per cubic foot for Case 1 and $3.10 per cubic foot for Case 2. Costs for applications of

the freeze barrier system may vary significantly from these estimates, depending on site-specific factors.

The AFI freeze barrier system demonstration, described in detail in an Innovative Technology Evaluation Report, was based on the nine decision-making criteria used in the Superfund feasibility study process. Results of the demonstration are summarized in Table 1.

Site Background and System Construction

The SITE Program demonstration of the freeze barrier system was conducted over a 5-month period from February 1997 to July 1998. The system was demonstrated at DOE's ORNL Waste Area Grouping 9 in Oak Ridge, Tennessee. A former unlined surface impoundment known as the HRE pond was the specific location for the system demonstration. When it was operational, 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 was about 15 feet bgs.

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 . 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; an influent line carrying these wastes reportedly entered the northwest corner of the HRE pond. 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. 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.

In 1986, DOE conducted a soil and groundwater characterization study in and around the former pond to determine the concentrations of radiological contaminants. As part of these activities, six soil borings were advanced and a series of monitoring wells, piezometers, and standpipes were installed. 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. 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 5 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.

Predemonstration Activities

Predemonstration activities, including 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 ORNL's HRE pond site between June 6, 1996 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 tracers 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 tracer transport patterns to those observed during the demonstration groundwater tracing investigation after the barrier wall was in place.

The dyes rhodamine WT and eosine OJ were selected for use during the groundwater tracing investigation. On June 7, 1996, 9.01 X 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 X 10^2 grams of eosine OJ dye was injected into standpipe I2 located near the center of the asphalt cap covering the former pond. 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.

During the groundwater tracing investigation, charcoal packets and water samples were collected from groundwater and surface water recovery points including monitoring wells, standpipes, piezometers, springs, and a nearby tributary (see Figure 1). Rhodamine WT was detected at 16 recovery points and eosine OJ was detected at 12 recovery points. Recovery points DLD, SBC, S3, S4, S5, S6, and S7 showed detectable concentrations of

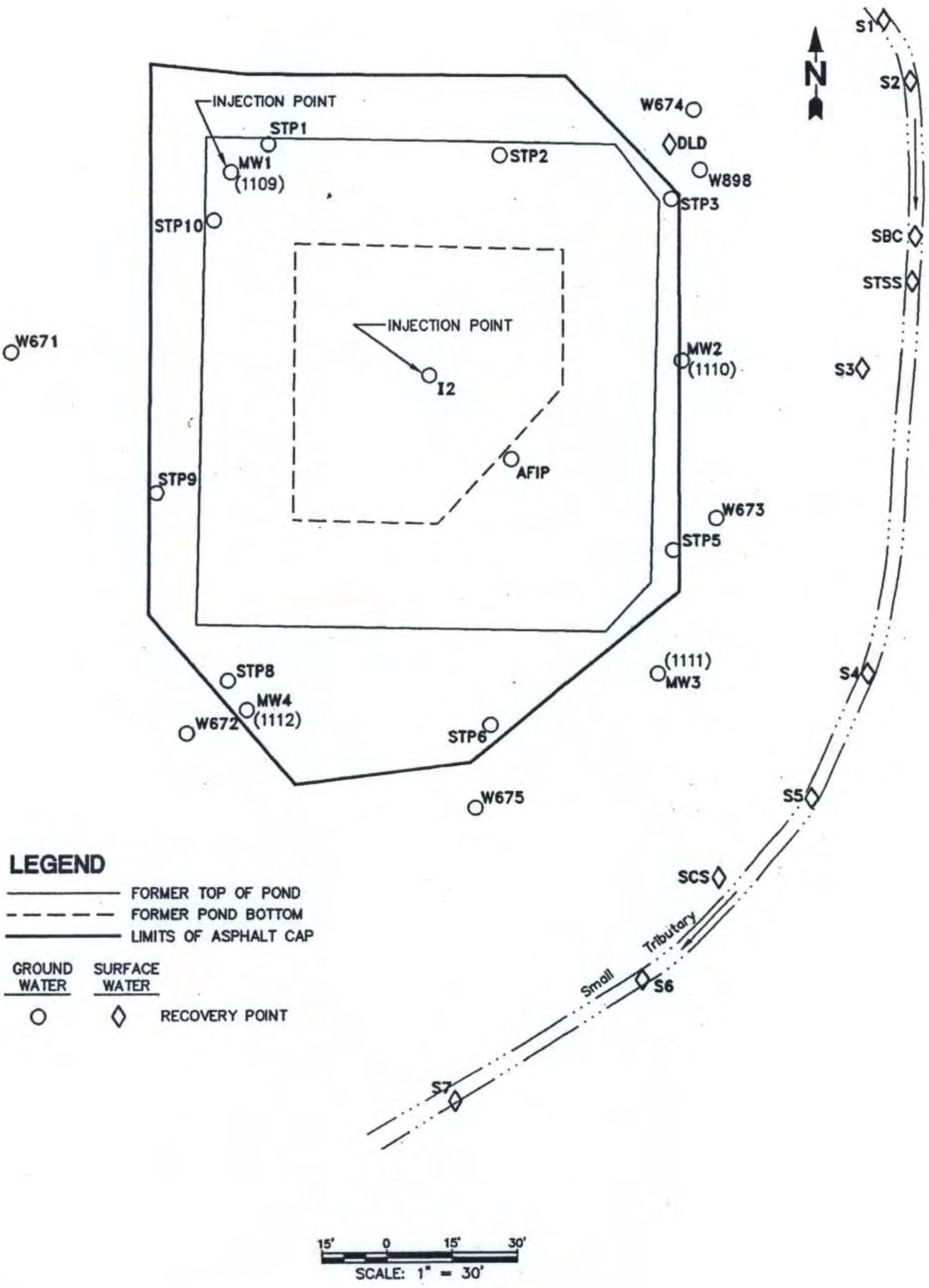

Figure 1. Dye injection and recovery points.

Table 1. Feasibility Study Evaluation Criteria for the Freeze Barrier System

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 applied. • Human health risk can be reduced by sealing off a hazardous waste area, thereby preventing the further spread of contaminants. • 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 areas without excavation, decreasing the potential for waste mobilization. • The barrier uses benign materials and does not create any reactions or by-products in the subsurface area in which it is applied.
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 equipment and delivery vehicles. • The actual space requirements depend on the size of the containment area and thickness of the barrier wall. • 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. • 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 full-scale 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 $2,124,600. Annual operating and maintenance costs, including those for utilities, supplies, analytical services, labor, and equipment maintenance are estimated to be about $67,000.
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.

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 arrived between 39 and 50 days following dye injection.

Groundwater transport of eosine OJ tracer occurred between 15 and 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 between 50 and 56 days following dye injection (EPA 1996). The eosine OJ results suggest 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 investigation also showed that groundwater transport out of the former pond occurs in a radial pattern and 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 groundwater is transported in a radial pattern out of the former pond. 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 investigation.

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. According to DOE the survey identified three anomalies, one of which extended through the northwest portion of the former pond that was consistent with a subsurface pipe. The two other anomalies were interpreted as possible buried scrap metal in the northwest and southeast corners of the former pond. 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.

A total of 58 boreholes were drilled, using hollow-stem auger and air rotary drilling methods, to a depth of about 32 feet bgs into the underlying bedrock. Fifty thermoprobes, spaced about 6 feet apart, were installed into the boreholes with the base of each thermoprobe anchored in bedrock (Figure 2). The annular space around each thermoprobe was then filled with quartz sand. AFI also installed a piezometer to a depth of about 7 feet bgs within the confines of the barrier wall, just southeast of standpipe I2.

Eight temperature monitoring points were installed in the remaining eight boreholes, using the same general procedures used to install the thermoprobes (Figure 2). The temperature monitoring points were placed at strategic locations to monitor development of the frozen barrier wall. Temperature monitoring points were set inside protective casings to protect the instruments and allow replacement without having to redrill.

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.

Following placement of thermoprobes and temperature monitoring points, cracks and voids in the asphalt cap over the site surface were filled with an asphalt patching material. An extruded polystyrene insulation material was then placed over the asphalt surface and cut to fit securely around the thermoprobes, piezometer, and temperature monitoring points. A waterproofing membrane was placed over the insulation to prevent infiltration of rain or surface water (Figure 2). Concrete pavers were placed along the perimeter of the membrane 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 alternating thermoprobes in the array surrounding the former pond was plumbed to the same refrigeration unit. Before the system was charged with refrigerant, the system underwent pressure testing to ensure that there were no leaks or blockages. The freeze barrier system was activated in mid-September 1997.

Technology Applicability

AFI claims that its freeze barrier system can provide subsurface containment for a variety of sites and wastes, including the following: underground storage tanks; nuclear waste sites; plume control; burial trenches, pits, and ponds; in situ waste treatment areas; chemically

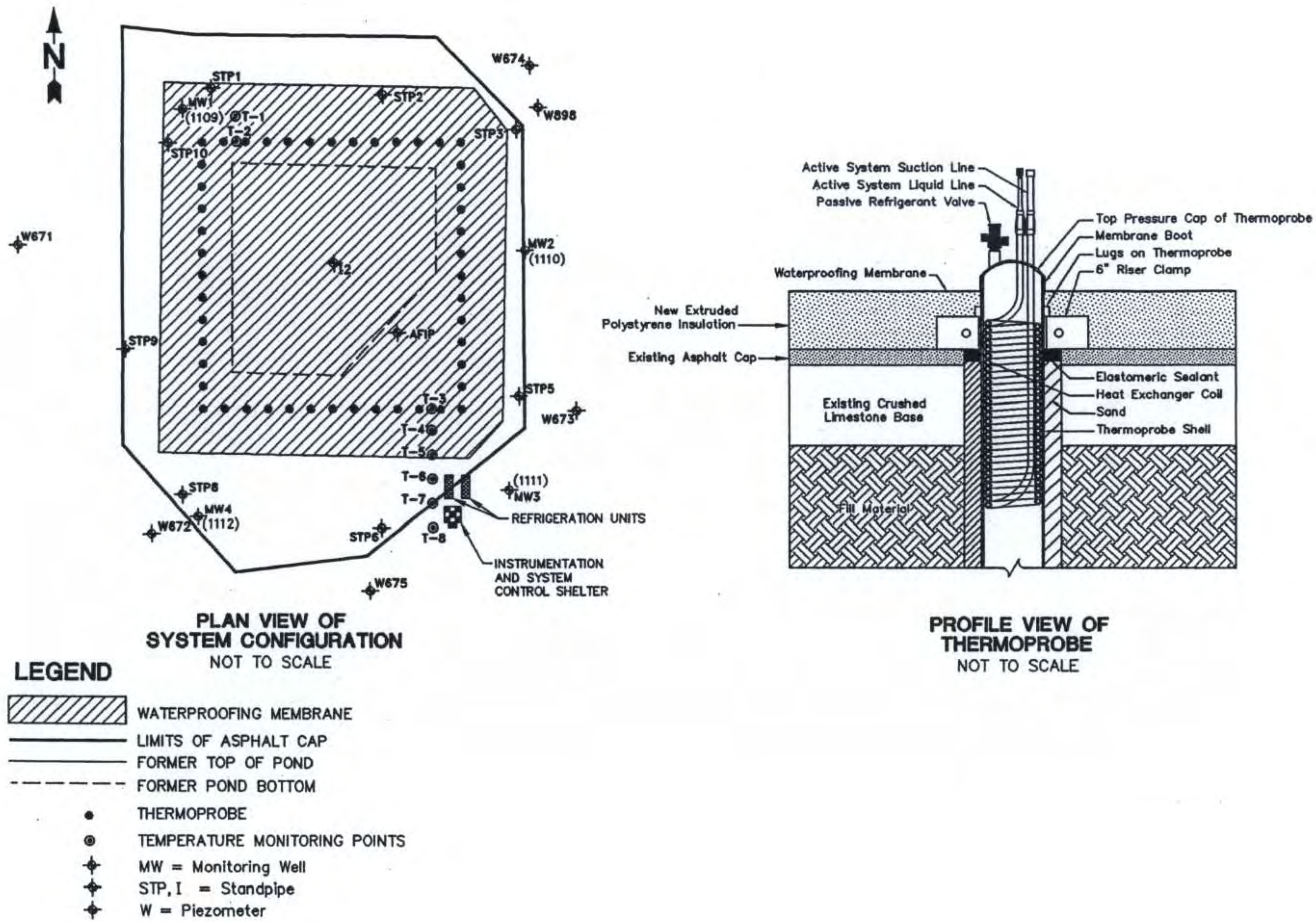

Figure 2. Plan view of system configuration and profile view of thermoprobe.

contaminated sites; and spent fuel storage ponds. AFI claims that the system is adaptable to any geometry; drilling technology presents the only constraint.

Potential users of this system 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. An effective means of homogeneously adding moisture to soils will be required. The effectiveness of this system for containment of contaminants in arid soils will require assessment. The practicality of implementing this system 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 system at certain sites.

Material handling requirements for the freeze barrier system 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 for handling contaminated materials. Contaminated soils should be stockpiled on site separately from clean soils to minimize the amount of material requiring management as potentially hazardous waste.

Site Requirements

In addition to the hydrogeologic conditions that determine the technology's applicability and design, other site characteristics affect implementation of this system. 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 SITE 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 are typically installed in a "V" or "U" configuration to ensure complete encapsulation and isolation of the waste source. At the HRE pond, the thermoprobes were installed in a vertical position, with the bottom of each thermoprobe anchored in bedrock.

The site must be accessible and have sufficient operating and storage space for heavy construction equipment. Access for a drill rig to install the thermoprobes and temperature monitoring points for system operation is required. A crane also may 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 cranes and drill rigs to operate. Construction around existing surface structures also may be required.

Soil from drill cuttings at contaminated sites may require management as a potentially hazardous 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, 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) waste to facilitate proper disposition of the waste. A portable tank or tanker truck also should be available for thermoprobe installation to temporarily store water removed from the boreholes, if necessary. Where soil type and site conditions are appropriate, thermoprobes may be installed by pile driving methods. This method eliminates handling drill cuttings with limited environmental disturbance. A building or shed may be necessary to protect the system control module and instrumentation wiring, as well as for use by workers during routine operation and maintenance activities.

Performance Data

EPA established primary and secondary objectives for the SITE demonstration of the freeze barrier system. The objectives were based on EPA's understanding of the freeze barrier system, SITE Program demonstration goals, and input from AFI. Primary objectives were considered critical for the system demonstration, while secondary objectives involved collecting additional data considered useful, but not critical to the system demonstration. The objectives also were selected to provide potential users of the freeze barrier system with technical information to determine if the system 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 system.

Primary Objective

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

P1 - Determine the effectiveness of the freeze barrier system 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 freeze barrier system'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 (phloxine B) 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 (eosine OJ) 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 system, and was based on observations made during the demonstration, demonstration data, and data provided by AFI.

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; and evaluation of the primary and secondary objectives.

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 tracer recovery points located downgradient and across gradient from the two tracer injection points (standpipe I2 and monitoring well MW1 [1109]). The samples were collected and analyzed in accordance with the Freeze Barrier Technology Demonstration QAPP.

The demonstration background study was conducted over a 21-day period 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 residuals 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. A total of 15 charcoal packets and 359 grab samples of water were collected from the recovery points shown in Figure 1. The samples were analyzed for the two dyes phloxine B and eosine OJ, using a spectrofluorophotometer.

Results of the Demonstration Background Study

The demonstration background study was conducted in January 1998 following establishment of the barrier wall. Analytical results indicated the presence of residual concentrations of the dyes eosine OJ and rhodamine WT that were used during the 1996 groundwater tracing investigation conducted by EPA. 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 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, located northwest (upgradient) of the HRE 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 piping connected to the HRE building entered the former pond from the northwest and may have been left in place after the pond closed. 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. However, it is unknown whether this pathway was open or closed after placement of the barrier wall.

Evaluation of Objective P1

Determine the effectiveness of the freeze barrier system 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.

Phloxine B was detected outside the former pond at recovery points STP10, AFIP, STP1, STP2, STP9, and MW4 (1112). Figure 3 shows the inferred migration pathway from the phloxine B injection point at standpipe I2 to the recovery points where phloxine B was detected. Phloxine B was first recovered about 16 days after tracer 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. The second detection of phloxine B occurred 10 weeks after tracer injection at recovery point AFIP.

The probability that piping may exist in the northwest portion of the former pond cannot be discounted in relation to the recovery of phloxine B at recovery point STP10. The pathway from standpipe I2 to the area near standpipe STP10 is close to the alignment of a geophysical anomaly that was detected prior to the demonstration, which was inferred to be a pipe. Although this is not the exact location for the piping, there are no as-built diagrams available to confirm their final location. 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.

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 anomalously high in comparison to that in standpipe STP10. 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, which created a 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.

Phloxine B also was detected at concentrations above background at recovery points STP1, STP2, MW4 (1112), and STP9 between 69 and 126 days following tracer 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 ditch locations and flow directions, based on information provided by DOE, are shown in Figure 3. 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 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.

Other data gathered during the demonstration period, with the exception of the groundwater tracing investigation using phloxine B, provide evidence that the ground freezing system was effective in impeding horizontal groundwater flow in the containment area. Based on available information, the critical dye (phloxine B) injected into standpipe I2 was transported beyond the limits of the frozen soil barrier either through a breach in the barrier wall most likely associated with a subsurface pipe or beneath the barrier wall through fractured bedrock. According to DOE, however, the slow drainage of the former pond following establishment of the barrier wall likely would have resulted in slower transport of phloxine B dye through fractured bedrock to standpipe STP10 than what was observed during

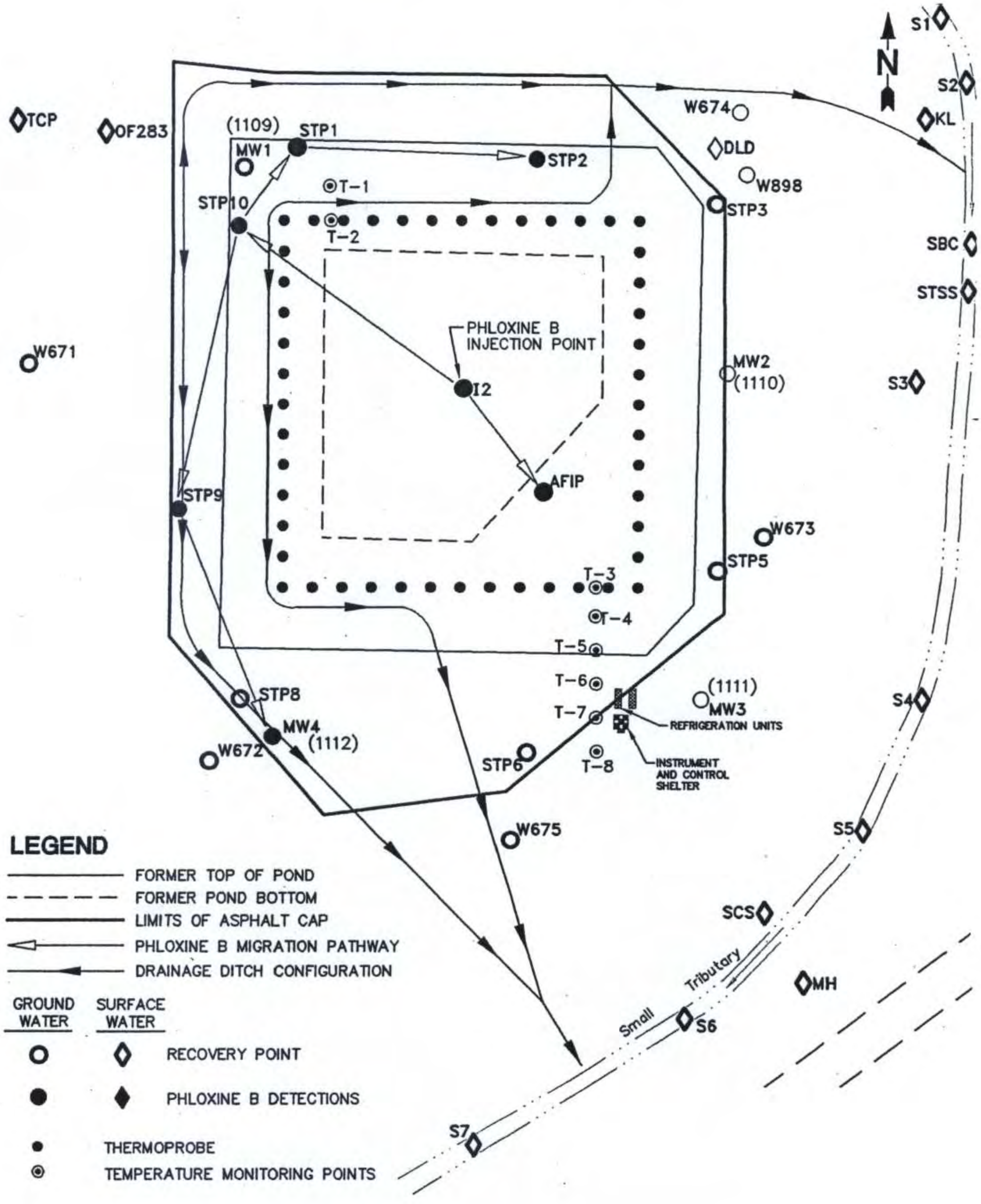

Figure 3. System configuration and inferred dye migration pathways.

the demonstration. Supporting information is summarized below:

Water level data and predemonstration groundwater tracing data collected from locations within and outside the former pond before emplacement of the barrier wall showed that groundwater within and outside the pond was hydraulically connected prior to construction of the barrier. However, water level data collected from standpipe I2 within the containment area following establishment of the barrier wall showed that the water table dropped and did not respond to storm events, compared to water levels collected outside the containment area that did show responses to storm events. These data indicated that the barrier wall was effective in impeding groundwater recharge into the containment area.

Subsurface temperature data collected from temperature monitoring points T-1 and T-2, located in the northwest corner of the barrier, showed that soil temperature from the ground surface to about 30 feet bgs remained well below 32° F. Based on experience, however, AFI claims that the barrier wall was frozen to a depth of about 36 feet bgs.

Results of the demonstration groundwater tracing investigation compared to the 1996 groundwater tracing investigation showed that the barrier wall disrupted groundwater conditions within and outside the former pond area. Phloxine B results from the demonstration groundwater tracing investigation showed that transport out of the former pond was limited to the northwest corner, compared to the results of the 1996 investigation and DOE's gas tracer studies that showed tracer transport in a more radial pattern from standpipe I2. The demonstration groundwater tracing investigation did not show tracer transport directly to the on-site tributary as observed during the 1996 groundwater tracing investigation, indicating that the barrier was disrupting groundwater flow patterns in and around the former pond area.

TDEC personnel collected surface water samples from the weir box located about 40 feet southeast of the former pond, 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. According to TDEC, 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.

Evaluation of Objectives S-1 and S2

Verify whether flow pathways outside the former pond were still open after placement of the freeze barrier wall and evaluate the hydrogeologic isolation of the former pond before and after placement of the freeze barrier wall.

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. The following sections describe the groundwater conditions encountered before and after establishment of the barrier wall in the former pond area.

Pre-Barrier Groundwater Conditions

Water level data collected from monitoring locations I2, STP10, and MW2 (1110) compared to precipitation data, 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 the same types of water level oscillations during storm events, providing evidence that groundwater within and outside the former pond is hydraulically connected. 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 highly permeable layer. This relationship is apparent in the hydrograph for standpipe I2, where the elevation 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, assuming the asphalt cap is 1 foot thick.

The 1996 groundwater tracing investigation 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 former pond to areas outside the former 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.

Post-Barrier Groundwater Conditions

The water level within the HRE pond was significantly impacted by the barrier wall. The water table elevation exhibited a slow downward slope and did not respond to storm events compared to locations outside the containment area after freezing was initiated. 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. The slow decline also may have been a result of slow seepage through fractured bedrock in the base of the former pond. Figure 4 shows the hydrograph for standpipe I2. Analytical results also show some distinct peaks just prior to the demonstration groundwater tracing investigation that require some explanation. According to DOE, 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.

Results of the eosine OJ demonstration groundwater tracing investigation suggest that the barrier wall also had an effect on horizontal groundwater flow in the HRE pond area. Tracer transport behavior during the demonstration groundwater tracing investigation differed from the 1996 groundwater tracing investigation. The 1996 groundwater tracing investigation showed tracer transport from 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. The eosine OJ dye, injected into monitoring well MW1 (1109) during the demonstration groundwater tracing investigation, only showed tracer transport to recovery points STP1, STP2, STP9, MW4 (1112), and DLD. However, eosine OJ was only detected at a concentration above background in downgradient recovery point DLD (1.09e+03 ppb), 2 days following dye injection. This change in transport behavior is likely due to diversion of dye-laden groundwater around the barrier wall because concentrations in all samples, with the exception of recovery point DLD, were below demonstration background levels, indicating that peak concentrations may not have been attained within the demonstration period. This behavioral change is apparent in the eosine OJ data for recovery point MW4 (1112), where the highest concentration detected during the demonstration groundwater tracing investigation did not occur until 2 weeks prior to the end of the demonstration. However, this fact cannot be determined with any certainty because samples were not collected after the demonstration period ended.

Results from the 1996 investigation also show that tracer was transported to the downstream locations (SBC and S3 through S7) more rapidly than it was transported to the locations closer to the pond (STP2, W898, W674, and DLD). Tracer injected into monitoring well MW1 (1109) bypassed the upgradient recovery points and discharged directly into the tributary, indicating that a preferential pathway may exist on the north side of the former pond. Tracer transport to the tributary was not observed during the demonstration groundwater tracing investigation, indicating that horizontal groundwater flow may have been impeded as a result of the barrier wall.

According to DOE, water table elevations downgradient of the former pond also were 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.

Evaluation of Objective S-3

Monitor development of the freeze barrier wall.

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. Six temperature monitoring points 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.

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 -32° F. 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 about the first week of November 1997. 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. According to AFI, the design thickness was selected based on AFI's past experience using the thermoprobe placement configuration similar to what was applied to the HRE pond site. 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 32° F, from mid-January through mid-July 1998.

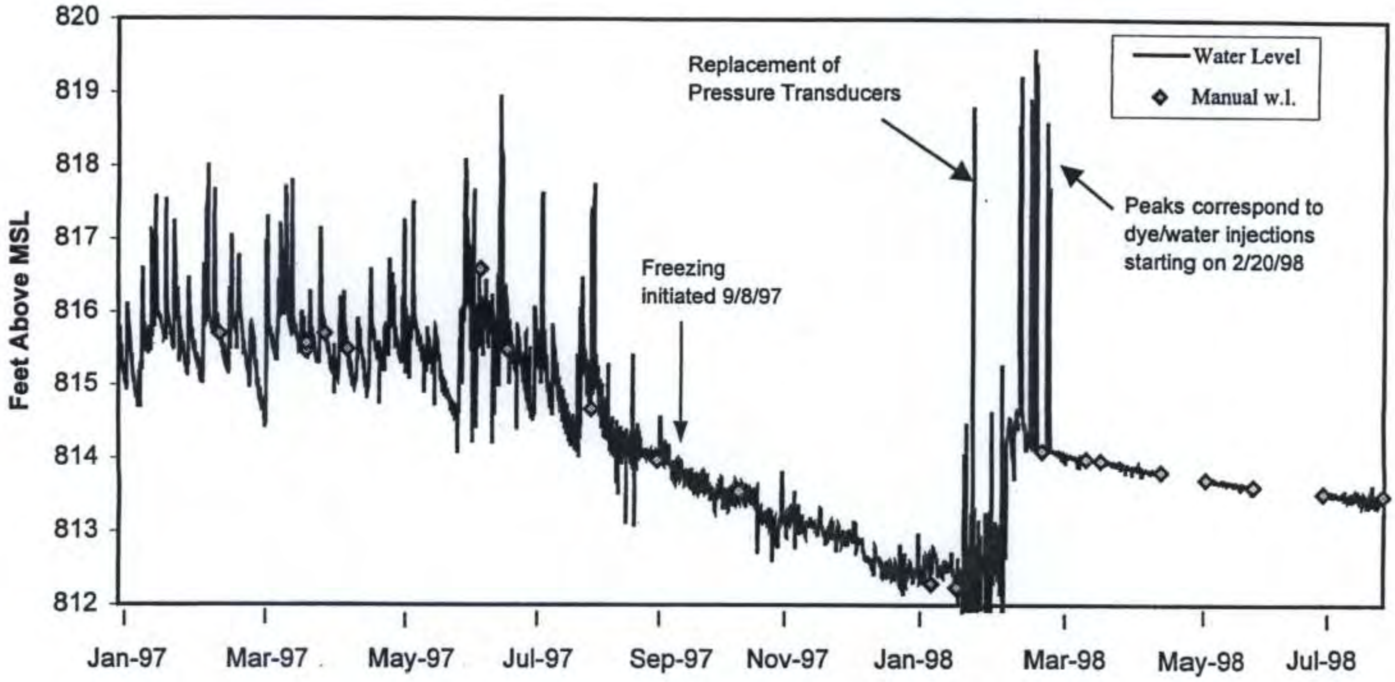

Figure 4. Hydrograph for Standpipe I2.

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 lower energy levels then the initial freezedown. According to AFI, the barrier wall thickness remained fairly constant during this phase and is expected to be maintained at the HRE pond site until October 1, 1999. The total volume of soil frozen is about 134,000 cubic feet and the total volume of soil contained is about 180,000 cubic feet.

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 35° 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 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.

Evaluation of Objective S-4

Document installation and operating parameters of the freeze barrier wall to determine costs.

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 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 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 were somewhat similar to those encountered at the HRE pond site, with the exception of the types of wastes in groundwater and size of the containment area. Case 2 assumes that groundwater is contaminated with radionuclides with a volume of 900,000 cubic feet requiring containment. Based on these assumptions, the total costs per unit volume of frozen soil was about $8.50 per cubic foot for Case 1 and $9.30 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 $6.60 per cubic foot for Case 1 and $3.10 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.

Technology Status

To date, this SITE demonstration represents the first full-scale application of the AFI frozen soil barrier system at a contaminated site. However, AFI has been developing, designing, fabricating, and installing ground freezing systems for about 30 years. AFI has used the system 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 for at least 1 additional year beginning October 1, 1998 to assess long-term performance of the barrier wall. DOE also is considering the use of the freeze barrier system for containment of radiologically contaminated groundwater plumes at two other DOE facilities, including Savannah River and Hanford. The system 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.

Sources of Further Information

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