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Frozen Soil Barrier Technology

INNOVATIVE TECHNOLOGY SUMMARY REPORT

demonstrated at

**SEG Facilities
Oak Ridge, TN
in cooperation with
U.S. Department of Energy
Oak Ridge Operations**

prepared for

U.S. Department of Energy
Office of Environmental Management
Office of Technology Development

April 1995



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U.S. Department of Energy



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SECTION 1

SUMMARY

Technology Description

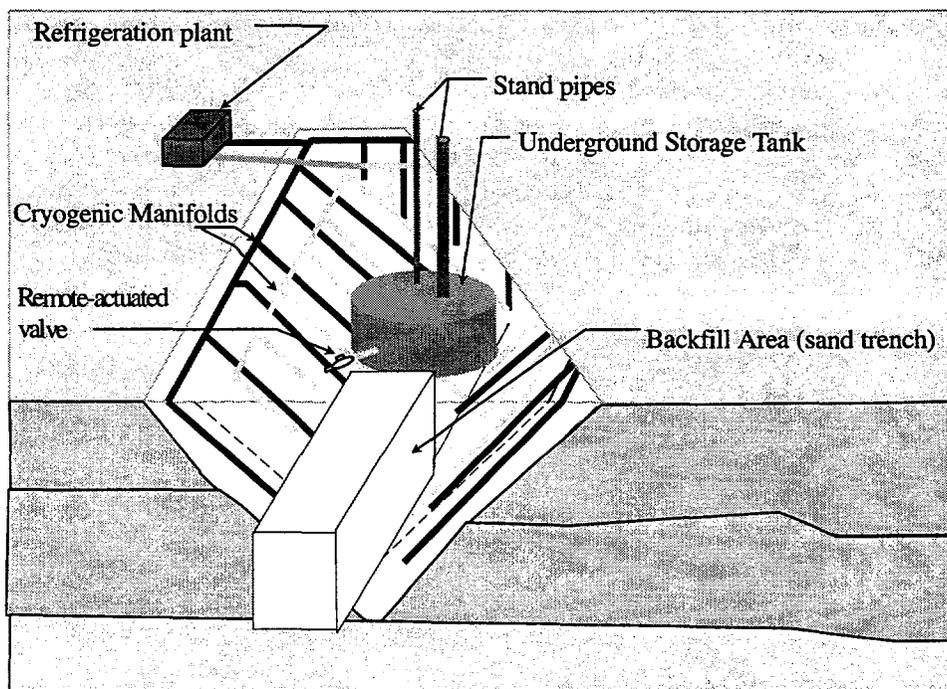
The technology of using refrigeration to freeze soils has been employed in large-scale engineering projects for a number of years. This technology bonds soils to give load-bearing strength during construction; to seal tunnels, mine shafts, and other subsurface structures against flooding from groundwater; and to stabilize soils during excavation. Examples of modern applications include several large subway, highway, and water supply tunnels.

Ground freezing to form subsurface frozen soil barriers is an innovative technology designed to contain hazardous and radioactive contaminants in soils and groundwater. Frozen soil barriers that provide complete containment ("V" configuration) are formed by drilling and installing refrigerant piping (on 8-ft centers) horizontally at approximately 45° angles for sides and vertically for ends and then recirculating an environmentally safe refrigerant solution through the piping to freeze the soil porewater. Freeze plants are used to keep the containment structure at subfreezing temperatures. Advantages for this technology include the following:

- It can provide complete containment.
- It uses benign material (water/ice) as a containment medium.
- Frozen barriers can be removed (by thawing).
- Frozen barriers can be repaired in situ (by injecting water into the leakage area).

Technology Status

A full-scale "V-shaped" containment structure (56 ft long x 56 ft wide x 28 ft deep) was demonstrated from May 12 to October 10, 1994, at a nonhazardous site on SEG property at the Gallaher Road Facility in Oak Ridge, Tennessee. The project was sponsored under the U.S. Department of Energy In-Situ Remediation Integrated Demonstration Program by the Office of Technology Development (EM-50). Surrogate solutions (200 ppm Rhodamine-WT) were used to test the integrity characteristics of the barrier.



Key Results

- Time-constrained laboratory studies showed that effective frozen soil barriers (hydraulic permeabilities $< 4 \times 10^{-10}$ cm/sec) can be formed in saturated soils for chromate (4000 mg/kg) and trichloroethylene (TCE) (6000 mg/kg). Tests with cesium-137 showed no detectable diffusion through the barrier although sorption on the soil grains may have been responsible for the immobility.
- Soil movement can be predicted accurately for fine-grained soils based on past civil engineering practices.
- Computer modeling of heat transfer characteristics and soil temperature for fine-grained soils was validated.
- Costs associated with engineering, construction, operation, and maintenance of frozen soil barriers in fine-grained soils using full-scale equipment were established (for a nonhazardous site).
- Electropotential studies utilizing frozen soil's low electrical conductivity properties showed low ionic transport across the frozen soil barrier, indicating that the barrier is an effective deterrent to ionic transport.
- Excavation of the nonfrozen soil within the contained area and ground penetrating radar studies showed (1) the inner area to be in the predicted formation ("V" shape) and (2) the frozen wall thicknesses to be approximately 15 ft in the sand trench area and 5 to 9 ft in the clay-dominated areas.
- Diffusion studies (with Rhodamine-WT as the tracer) conducted by Los Alamos National Laboratory (LANL) confirmed barrier integrity.
- An in-place temperature-monitoring system provided soil temperature information confirming barrier formation.
- The Frozen Soil Barrier process is based upon U.S. Patent No. 4,860,544, issued to RKK Ltd. for CRYOCELL ground freezing technology.

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SECTION 2

TECHNOLOGY DESCRIPTION

1.0 Purpose

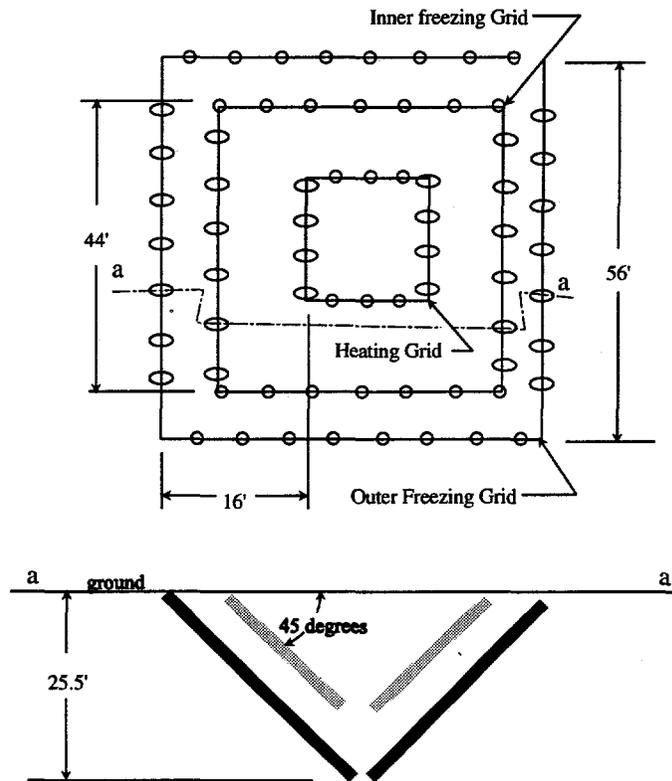
The purpose of this project was to provide the U.S. Department of Energy with an innovative technique for controlling waste migration in soils by demonstrating the use of frozen soil barriers. This project had the following goals and objectives:

- Demonstrate in situ isolation of a simulated waste from the environment.
- Provide complete containment of the simulated waste.
- Construct a subsurface barrier without adding injectants or any barrier materials.
- Demonstrate long-term control of in situ waste.
- Conduct barrier monitoring and integrity testing.

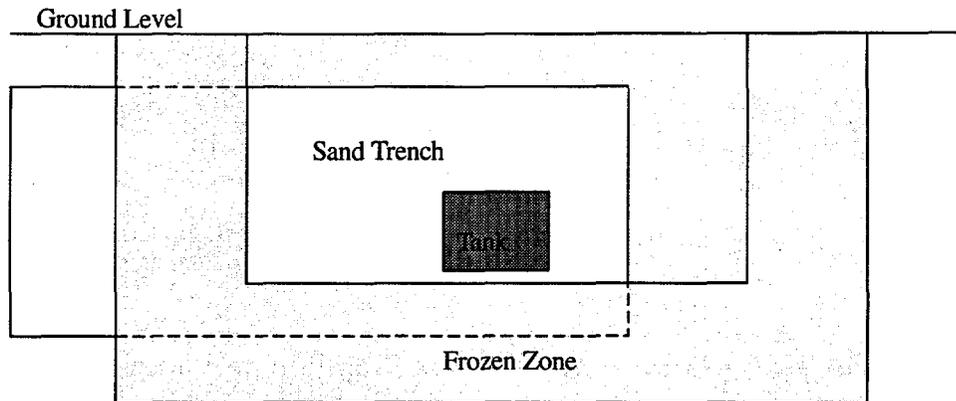
2.0 Description of the Demonstration Facility

The dimensions of the frozen soil barrier region were 56 ft by 56 ft (outside) and 33 ft by 33 ft (inside) once the ice barrier was fully formed.

- Freeze pipes were installed in double-rowed configuration for overlap.
- Pipes were installed at a 45° angle to establish a bottom to the containment structure.
- Pipes were set on 8-ft centers with the two rows set at 4-ft centerlines, and the ice wall was allowed to grow together forming the barrier.
- An array of heating pipes was installed inside the freeze grid to allow some oil heave control.
- The piping material was 4-in. schedule 10 carbon steel for both freeze and heat grids.
- Monitoring was accomplished through additional pipes inserted around the site. Resistance temperature detectors (RTDs) were placed inside these pipes at 5-ft intervals.



A sand trench was built to cross the area that would be consumed by the frozen barrier to insure that the tracer material would have an adequate flow path. The native soil was determined to be clayey with low permeability. The trench was 8 ft below the surface and 6 ft thick with native soil packed over to backfill to grade.



A carbon steel tank measuring 52.5 in. high by 65 in. diameter was buried in the center of the sand trench. This tank was used as the distribution point for releasing the tracer during the barrier integrity testing phase of the project. The site was covered with a plastic liner to prevent rain infiltration, insulate against surface warming, and allow the freeze front to reach the surface.

Ground freezing apparatus used for the demonstration project consisted of surface equipment (refrigeration unit, heat source, and piping) and subsurface equipment (freeze pipes, heat pipes, and monitoring wells).

Major surface components and/or characteristics of the freeze barrier demonstration are as follows:

- Refrigeration Capacity Two 40-Ton Units
- Refrigerant R-22
- Compressor Rotary Screw
- Condenser Evaporative
- Evaporators Shell and Tube
- Evaporator Temperature Approximately 35°C
- Coolant (calcium chloride brine) 1.28 specific gravity

Component	Horsepower
Compressor Motor	250
Condenser Fan Motor	20
Condenser Water Pump Motor	2
Lube Oil Pump	3
Brine Pump	40
Ancillary Pumps and Controls	5
Total	320

The following chart shows power requirements for the two 40-ton refrigeration units used on site:



SECTION 3

PERFORMANCE

Testing the frozen barrier consisted of looking at the physical aspects of soil freezing, the containment characteristics of the barrier, and the physical characteristics of the barrier once it was formed.

This evaluation was accomplished with four kinds of testing:

- computer model validation;
- soil movement testing, including heat grid tests;
- barrier diffusion and leaking tank tests; and
- barrier integrity testing.

Results obtained are discussed in the next section.

Computer Model Validation

Purpose

To compare predicted energy consumption and frozen barrier temperatures during formation and operation of the frozen barrier, to confirm the accuracy of ground freezing calculations, and to improve the parameters used in such calculations.

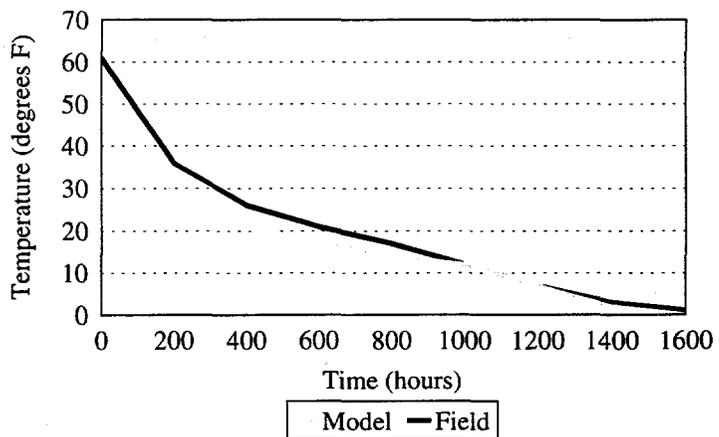
Test Equipment

Computer model, monitoring system (for both soil and brine temperature), flowmeters, and electrical meter.

Test Results

- The field data and calculated temperature data are in close agreement.
- Actual power consumption (420,000 kW-hours) showed good agreement with predicted values (380,000 kW-hours).
- To the extent that convective heat transfer coefficients can be quantified and the thermal properties of the soil can be characterized, this analysis provides an effective analytical tool for predicting how long it takes to develop the freeze barrier to the design thickness and the shape of the freeze wall. Finite element analysis can be a useful tool for developing freeze wall designs and selecting refrigeration equipment.

Temperature vs. Time - Comparison of Field Data and Modelling Results



Field data from monitoring well TPI-4A



Soil Movement Test

Purpose

This test measured soil movement and stresses on a tank buried in the center of the barrier test facility. Soil movement was expected because of the wet and fine-grained nature of the soil at the site, which is classified as "frost-susceptible" by the U.S. Army Corps of Engineers' Cold Regions Research and Engineering Laboratory (CRREL) according to their grain size criterion for silty and clayey soils. This test also determined the effect on soil movement when the heating grid was used.

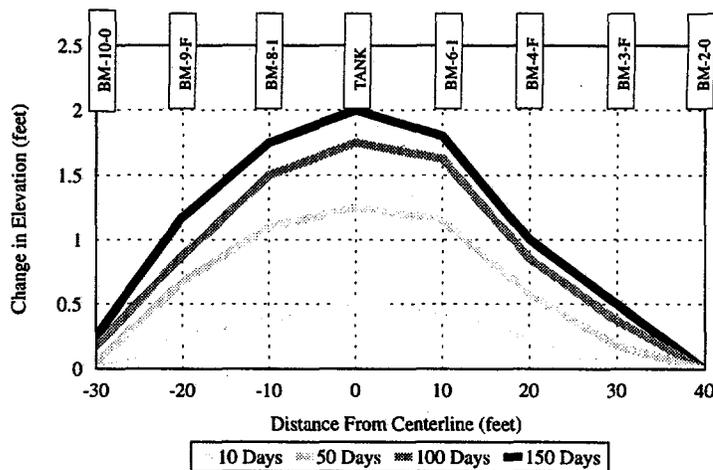
Test Equipment

Ten benchmarks, transit, strain gages, flowmeters, and temperature sensors were installed within the demonstration site. Benchmarks were constructed by drilling 3-ft-deep holes by hand with a post hole digger. Holes were backfilled with concrete, and 36-in. sections of iron rebar were inserted into the concrete. Approximately 10 to 12 in. of rebar was exposed at the marker surface. In addition, two benchmarks for the tank (the 2-in. and 4-in. risers) were measured.

Test Results

- The heat grid was effective in slowing the rate of increase in tank movement.
- The maximum stress calculated as part of the analysis was 4,000 psi. The allowable stress for carbon steel is 12,000 psi.
- Soil movement of 1.65 ft observed during first 70 days was in good agreement with predicted values (between 1.20 and 2.24 ft).
- Maximum lift of any monuments was 2.25 ft.
- The heat grid was effective in controlling inward growth of the barrier (ice).

Soil Movement Data BM-1-0 through BM-10-0



Barrier Diffusion and Leaking Tank Test

Purpose and Plan

The barrier diffusion and leaking tank testing were to provide quantitative measures of the effectiveness of the frozen soil barrier in preventing the passage of hazardous and radioactive wastes in the form of water-borne chemicals. Design of the tracer experiments had three phases: (1) hydraulic conductivity testing of the permeable sand trench crossing a segment of the then-unformed cryogenic barrier wall using fluorescein, (2) demonstration of containment by the cryogenic barrier wall following closure by releasing Rhodamine-WT from the tank inside the containment structure, and (3) comparison of tracer movement in the frozen native soil with that in unfrozen native soil at the demonstration site.

Test Equipment

Diffusion monitoring wells, tracers (200 ppm solutions of fluorescein, Rhodamine-WT), and fluorescence spectrometer.



Test Results

- Substantial hydraulic conductivity was shown through the sand trench by the appearance of fluorescein in recovery well WO-A (outside the planned barrier) in less than 4 hours (Figure 5).
- Rhodamine was found only inside the barrier region, showing barrier integrity (see Figure 6).
- Phase 3 tests showed that Rhodamine migrated approximately 2 feet in unfrozen soils, while essentially no Rhodamine tracer was found below open-ended well casings within the freeze barrier.

Barrier Integrity Testing

Purpose and Plan

Barrier integrity testing consisted of (1) measuring the electropotential of the soil to indicate reduced ionic transport properties (reduced electrical conductivity of frozen soil) through the frozen soil region and (2) performing ground penetrating radar studies of the barrier wall after the barrier-contained interior (unfrozen section) was excavated.

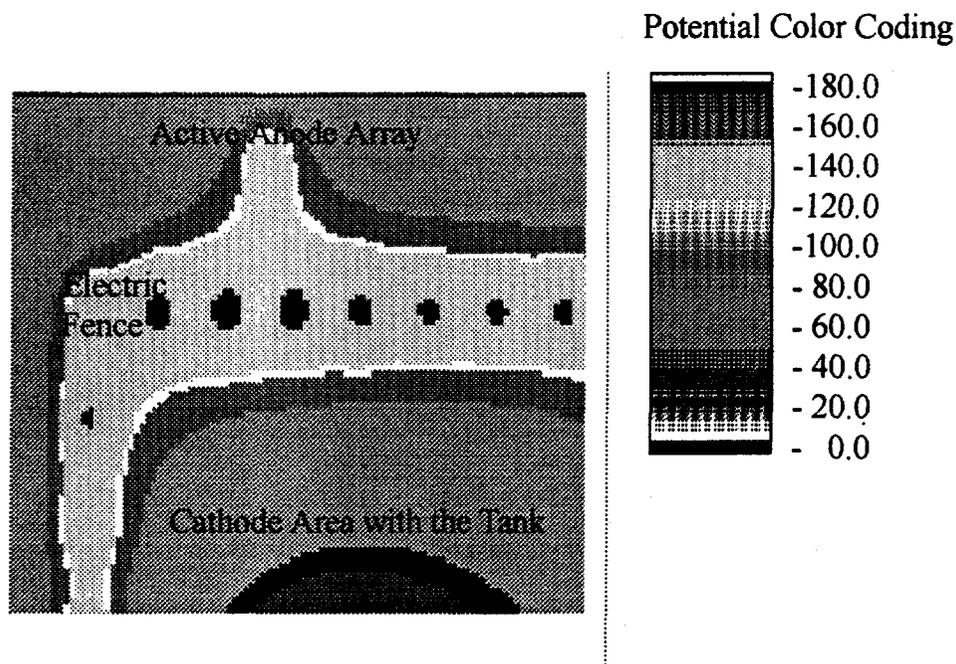
Test Equipment

Passive and active electrodes (for electropotential measurements), computer data collection and analysis system, and ground penetrating radar instrumentation.

Test Results

- Electropotential measurements showed low ionic transport across the frozen soil barrier walls.
- Excavation of the contained area within the frozen barrier confirmed the desired "V" configuration, and subsequent ground penetrating radar measurements showed the barrier wall to be approximately 12–15 ft thick within the sand trench area and approximately 5–9 ft thick within clay-dominated areas.

Uniform Electric Flux Field in the Southeast Corner of the "ICE BARRIER"



SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVE TECHNOLOGIES

Technology Applicability

- Radioactive, heavy metal, and organic contaminants can be contained by this technology.
- Laboratory studies have shown that frozen soil barriers with low hydraulic permeabilities ($< 4 \times 10^{-10}$ cm/sec) can be formed in saturated soil conditions.
- Formation of frozen soil barriers in saturated, fine-grained soils has been demonstrated in the field.
- The formation of frozen soil barriers in arid conditions will require a suitable method of homogeneously adding moisture to the soils to achieve saturated conditions before the technology can be assessed for that application.
- Soil movement should be a factor to consider for applications in fine-grained soils around structures (buildings, submerged tanks and piping, etc.).
- Barriers should be such that they will not degrade upon contact with contaminant solutions.
- Formation of frozen soil barriers in areas where plumes of low-freezing-point contaminants (TCE, etc.) exist may require more expensive cryogenics (e.g., liquid nitrogen).

Competing Technologies

- Frozen soil barrier technology is competitive with other subsurface flow-control technologies such as liners, slurry walls, sheet piling, and grouting.
- Comparison with other technologies is difficult because of the unique aspects of ground freezing technology, including complete containment and removability. In addition, ground freezing incurs additional energy, operation, and maintenance costs over time that other containment technologies do not. However, it appears that this technology can be effectively applied in fine-grained, saturated soils for "complete" containment applications of relatively moderate durations where future remedial action of the contaminant source and subsequent barrier removal are desired.

Technology Maturity

- The technology of using refrigeration for the freezing of soils has been employed in large scale engineering projects for a number of years. It bonds soils to give load-bearing strength during construction; to seal tunnels, mine shafts, and other subsurface structures against flooding from groundwater; and to stabilize soils during excavation. Examples of modern applications include several large subway, highway, and water supply tunnels.
- Frozen soil barriers have not been demonstrated at an actual contaminated site.



SECTION 5

COST

The total capital cost for the SEG Demonstration was \$481,427. It can be assumed that if demonstration costs such as those for the extra sensors and test support were deducted and if costs were reduced by purchasing (vs renting) equipment and by decreasing barrier thickness (which would mean less drilling, energy consumption, etc.), the real cost would be about \$332,754. Engineering, health and safety, and permitting costs are not reflected in that figure. The maintenance cost for this frozen barrier was estimated to be \$3322/month.

The contact area of the envelope created by the frozen barrier was 2223 ft². The volume of frozen soil composing the frozen barrier was 35,694 ft³, and the volume of soil contained by the frozen barrier was 8175 ft³.

The cost shown below are for volume of ice formed. The results of the cost analysis are:

	Cost Attributes	First-Year Total	15-Year Average Maintenance Cost	15-Year Maintenance Cost Per Month
SEG Demon (\$481,427)	Frozen Barrier Volume	14/ft ³	1.2/ft ³	0.09/ft ³
Actual Site (\$332,754)	Frozen Barrier Volume	10/ft ³	1.12/ft ³	0.09/ft ³

	5.5 Months	Year 1 Total	Years 2-5	Years 6-10	Years 11-15
SEG Demon	13/ft ³	14/ft ³	4/ft ³	6/ft ³	6/ft ³
Actual Site	9/ft ³	10/ft ³	4/ft ³	6/ft ³	6/ft ³

In contrast with these calculations, if one of literally several hundred types of grout were used in place of a frozen barrier, costs could range from \$1/ft³ to \$37/ft³. These types of grout use a multiplicity of ingredients/recipes including Portland cement, bentonite, waxes, chemical components, and proprietary "magic dust." However, grout does not have the advantages of moderate-duration "complete" containment and removal capabilities as frozen soil barriers do.



SECTION 6

REGULATORY/POLICY ISSUES

Regulatory Considerations

- No permit was required for this demonstration because the demonstration was performed on a nonhazardous site and a benign barrier material (water) was used. Regulatory participation was encouraged. If moisture additions were required (e.g., for arid site applications) in soils of high hydraulic conductivity (sandy soils), concerns about contaminant migration downward would have to be addressed. In addition, refrigerants of low toxicity (in cases of refrigerant pipe leakage) must be used and complete in situ barrier integrity must be confirmed by subsurface barrier verification techniques before regulatory acceptance can be gained.

Safety, Risks, Benefits, and Community Reaction

Worker Safety

- Health and safety issues for installation (drilling, etc.) and operation are essentially equivalent to those for conventional environmental monitoring applications (monitoring well drilling, etc.).

Community Safety

- Frozen soil barrier systems do not produce contaminant releases because benign materials (water, nontoxic refrigerants, etc.) are used.
- No unusual or significant safety concerns are raised by the transport of equipment, samples, waste, or other materials associated with frozen soil barrier systems.

Environmental Impacts

- Drilling for refrigerant piping installation is required.
- Surface piping manifolds are required to supply refrigerant to the system.
- Compressor (refrigerant plant) noise is minimal.



SECTION 7

LESSONS LEARNED

Design Issues

- In situ temperature sensors installed within the refrigerant piping provided valuable information on barrier formation and refrigeration equipment operation.
- Typical refrigeration equipment (piping, refrigeration plants, etc.) can be used to form in situ frozen soil barriers. Single-row piping may be adequate to form barriers of sufficient thicknesses to contain contaminants. In addition, a single refrigeration plant (40 ton) can be employed to maintain barrier integrity (soil freezing conditions) after initial heat removal is acquired.
- Computer modeling for soil heat transfer characteristics can be used to predict barrier formation.
- Methods need to be designed for "injecting" moisture and lower-freezing-point refrigerants into barrier areas where leaks are detected (or where refrigerants have leaked because of pipe breakage).
- Soil movement can be predicted using experiences of past civil engineering practices and should be a consideration when designing a system for applications involving structures.
- Careful installation of the refrigerant piping is necessary to ensure "complete" barrier formation.
- For applications in humid and high ambient temperature regions, proper ground insulation and near-surface refrigerant piping may be required to ensure that surface to 1–2-ft depths are adequately frozen (if desired).
- In situ sensors (electrical conductivity, etc.) should be preinstalled in the soil to monitor barrier formation.
- Geophysical measurements of the barrier area should be performed before freezing to establish soil characteristics and heterogeneities.

Technology Limitations/Needs for Future Development

- Remote sites will require electrical power and utility installation.
- Technology applications for arid/sandy environments are undetermined until suitable methods are developed for homogeneously adding and retaining moisture in the soils.
- Technology applications in fine-grained soils around structures (submerged tanks, etc.) may be limited because of soil movement.
- Longer-duration applications at actual contaminated sites need to be studied to assess diffusion characteristics, costs, etc.
- In situ subsurface barrier verification technologies (enhanced ground penetrating radar, seismic, acoustics, electropotential, tracers, etc.) need to be developed that are capable of detecting barrier traverses as well as barrier infrastructure properties (voids, etc.).
- Additional laboratory diffusion studies may be required for various contaminants of differing concentrations. Contaminant solutions' effects on barrier degradation should be studied.



APPENDIX A

DEMONSTRATION SITE CHARACTERISTICS

Site History/Background

The site used for the demonstration project is located at the SEG Gallaher Road Facility in Oak Ridge, Tennessee.

The demonstration site is approximately 200 ft west of the access road entrance to the plateau area above Gallaher Road. The plateau area is a large, flat, unpaved area approximately the size of a football field. The plateau was constructed by "cutting and filling" with soil removed from a hillside (about 30 ft high) located along the southeastern side of the site about 25 years ago. The plateau was graded to its current contour and has not been used for any other known purpose.

Description of Soil Testing and Results

Soil testing was performed at the site on September 8 and September 9, 1993. The test report includes soil moisture contents, sieve analyses (hydrometer), and unit weight determination. A total of six test borings were drilled with augers to depths ranging from 25 to 46.3 ft.

Moisture content samples were taken in 5-ft intervals during penetration testing. The moist unit weight of the sample was obtained with a Shelby tube. The unit weight of the undrained soil at boring B-5 was 108.8 lb/ft³.

Subsurface soils encountered at the site at the time of our exploration generally consisted of 13 to 22 ft of fill soils that overlie residual soils. The fill soils were composed of stiff to hard red-brown silty clay, with varying amounts of chert fragments. The residual soils were composed of stiff to soft red-brown to brown silty clay and clayey silt, with varying amounts of chert fragments.

The soils were very fine as determined by hydrometer testing. The consistency of residual soil generally graded from stiff to soft with depth. The residual soils at the site are typical of the soils encountered overlying the dolomite of the Knox Group of the lower Ordovician System in the Oak Ridge area.

Moisture contents obtained from the soil samples show the following:

Boring Number	Number of Samples	High (%)	Low (%)	Average (%)
1	3	37.2	32.3	33.9
2	9	43.0	12.1	26.5
4	6	37.8	20.8	27.9
5	8	40.0	16.8	31.2

Fill currently at the site is not the result of placement of the soil from a remote location. As already discussed, the plateau was constructed about 25 years ago by a previous owner and was formed in a cut and fill fashion with soils from the adjacent hillside. All of the material observed during the soil analysis was homogenous and indigenous to the immediate area for each borehole. It is not known whether the fill was compacted when placed, but the soil is very stiff as shown by the penetration testing. The plateau is unpaved and flat (no slope), does not require grading, and supports a ground cover consisting of a few weeds (no grass or trees).



APPENDIX B

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