

THE FROZEN SOIL BARRIER DEMONSTRATION PROJECT

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ABSTRACT

The Frozen Soil Barrier Demonstration Project was implemented to verify the technical feasibility and real costs of deploying a frozen soil barrier at a radiologically contaminated site. This project was a full-scale demonstration of a frozen soil barrier being used to contain radioactive contaminants emanating from a decommissioned settling pond associated with an experimental fusion reactor at the Oak Ridge National Laboratory. The work began in September of 1996 and progressed through to December of 1998. The frozen barrier has been operational since November 1, 1997. This project showed that frozen soil barriers offer a proven technology to retain below grade hazardous substances at relatively low costs with minimal effect on the environment.

INTRODUCTION

Oak Ridge National Laboratory (ORNL) is one of three facilities established on the 23,500 hectare Oak Ridge Reservation (ORR) in eastern Tennessee in 1943 as part of the World War II Manhattan Project. . The Laboratory's initial mission was to produce and chemically separate the first gram quantities of plutonium as part of the national effort to produce the atomic bomb. As its role in the development of nuclear weapons decreased over time, other research tasks were undertaken at ORNL, including the design, construction, and testing of various reactor types. One of these prototype reactors was the liquid fuelled Homogeneous Reactor Experiment (HRE) constructed in Melton Valley.

An earthen impoundment, dubbed the HRE Pond, was constructed to receive and treat low level liquid wastes derived from the HRE evaporator and shield water between 1957 and 1961. The impoundment was constructed using in situ material and borrowed clay sized soils. The pond bottom was cut into the natural terrain to bedrock. Because of the sloping terrain, the uphill pond walls were comprised of in situ natural soils cut to a slope and lined with clay. The lower walls were embankments built with material from the interior excavation and also lined and topped with borrowed clay. In 1970, the HRE Pond was decommissioned by backfilling with

clay and shale materials and then covering the surface with asphalt paving. No attempt was made to plug or remove the inlet and outlet pipelines.

Contaminates at the HRE Pond consist primarily of ^{137}Cs and ^{90}Sr with trace amounts of ^{238}Pu , ^{239}Pu , ^{241}Am , and ^{244}Cm . Potentially, ^{234}U , ^{235}U , and ^{238}U are present. Heavy metals and polychlorinated biphenyls (PCBs) were also detected in the pond sediments during characterization. In 1984, the impoundment was estimated to contain approximately 75 Curies (Ci) of ^{90}Sr and 16 Ci of ^{137}Cs in the buried sediments. An ongoing monitoring program at ORNL determined that the contaminants were being hydraulically transported out of the old pond and potentially being carried to surface waters.

The HRE Pond site was chosen for implementation of the Frozen Soil Barrier Demonstration Project to verify the technical feasibility and real costs of deploying a frozen soil barrier at a radiologically contaminated site. Through a competitive procurement process, an innovative freezing system using hybrid thermosyphons was chosen by the DOE for installation at this site.

BACKGROUND

Since 1862, ground freezing has been used to augment soil properties at civil works and mining sites to facilitate construction. (1) Freezing gives load-bearing strength during construction; seals tunnels, mine shafts, and other subsurface structures against flooding from groundwater; and stabilizes soils during excavation. In 1962, the Atomic Energy Commission (AEC) 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. (2) Indeed, upon remediation of the site in 1995, it was found that virtually no transport of radionuclides into the permafrost had occurred. (3) 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. Thermosyphons have been used as early as 1990 at these sites to either create or maintain permafrost barriers.

Generally, soil refrigeration for ground freezing is performed using a series of concentric pipes 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. In fact, this system of ground freezing was patented in 1883. (1) 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. (4)

Thermosyphons are passive heat removal devices that 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. (5) In cold-

regions 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. (6) 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) 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.

DEMONSTRATION SITE CONDITIONS

The geology in the demonstration area is predominately limestone and shale capped by clay-sized residual soils. These soils are the result of in-place weathering and were not deposited via a transport mechanism. The soil profile gradually turns to rock with depth, and the rock becomes more competent with depth. The depth to limestone in the area is highly variable. Local geologists describe the top of the limestone layer as being speckled with pillars of limestone rising up into the overlying shale. Generally competent bedrock is found at a depth of 4.5 meters below the surface but because of the variability of the limestone pillars, it may be found between 1.5 and 7.5 meters below the surface. Groundwater is abundant at the site and quite shallow as evidenced by the numerous springs and seeps in the area. The groundwater table exhibits dynamic responsiveness to precipitation events. Piezometers in the area have monitored groundwater level rises of over one meter in two hours. (7)

The cap on the HRE Pond was installed in a conventional manner using a 200 millimeter minimum thickness of free draining crushed limestone base course to support the asphalt pavement. Prior to any construction in 1996, this cap was in relatively good shape, with a few long thermal cracks. Some of the cracks were as wide as 75 millimeters.

A pre-barrier tracer test was performed to ascertain hydraulic pathways beneath the asphalt cap. The waterborne tracers rapidly moved across the site due to the very conductive crushed limestone beneath the asphalt cap. It became apparent that one of the mechanisms for transporting contaminants out of the pond area was by near surface flushing caused by rain and storm events. The fill around the HRE Reactor building, located up gradient from the capped pond, is a large catch area for water that moved downhill toward the pond. Substantial quantities of water flowed beneath the asphalt cap and across the top of the pond interior, moving contaminants from the interior of the pond toward the small stream that exists to the south of the pond.

INSTALLED FREEZING SYSTEM

The freezing system installed for this project utilized a series of hybrid thermosyphons embedded vertically around the concerned area of subsurface contamination. These units were designed to freeze from the ground surface to the bedrock and to lock the base of the frozen barrier into the bedrock, thereby using the bedrock as the base of the containment vessel. A system of surface insulation and a waterproof membrane was installed to provide a top and seal for the containment vessel. A temperature monitoring and data collection system was installed to provide barrier and systems status via a remote phone link.

The array of 50 hybrid thermosyphons was installed vertically around the rim of the original HRE impoundment. The 150mm diameter thermosyphons were installed on 1.8 meter centers to a depth of approximately 9.1 meters below grade. Installation was accomplished using 250mm diameter auger and air rotary methods. The upper stratum of residuum was excavated with the augers and the rock material was penetrated with a fully contained air rotary drilling technique. Drilling activities were continuously monitored by an experienced health physics technician to insure no personnel would be contaminated and to categorize the drill cuttings for proper disposition after excavation. The thermosyphons were placed into the drilled holes and the annulus between the thermosyphon and the in situ material was backfilled with quartz sand. The pavement was then patched with a cold mix asphalt product.

The thermosyphons were fitted with internal heat exchangers designed to condense the carbon dioxide working fluid. Carbon dioxide was chosen as the working fluid for the thermosyphons because of previous experience of the thermosyphon manufacturer. Carbon dioxide is the predominate and most reliable working fluid used in commercial thermosyphons for ground freezing and subgrade refrigeration. (Long & Yarmak)

To limit heat transfer to the upper portion of the frozen soil barrier, a 6.1 meter wide strip of extruded polystyrene insulation was installed along the midline of the barrier. The insulation was placed in three; 50.8mm layers for a total thickness of approximately 150mm. This was to insure that the barrier would freeze completely to the top of the old asphalt during any part of the year. To preclude surface water from infiltrating the top of the containment vessel, a spray applied polyurea membrane was installed over the top of the old pond. This membrane was effective in sealing all the penetrations in the pavement and providing a new clean surface on which to work on. Approximately 32,000 kilograms of concrete pavers and curbs were used on the membrane to provide resistance to wind uplift and provide a nonskid foot traffic surfaces.

An active refrigeration system was installed above grade to cool the heat exchangers in each of the thermosyphons. This system utilizes two 22.4 kilowatt air-cooled condensing units that are configured to operate at suction pressures as low as -40°C with R-404a refrigerant. These units are typical of what might be used at a small meat packing plant to cool the blast freezer. The refrigerant is one of the newer "zero ozone-depletion" compounds for low temperature refrigeration. Each of the condensing units is plumbed to 25 thermosyphons such that one condensing unit drives every other thermosyphon in the array.

The R-404a is expanded in the heat exchanger in each of the thermosyphons and returned to the condensing units via copper suction piping. A thermal expansion valve is utilized to modulate the flow of active refrigerant to each thermosyphon. Quarter turn ball valves are installed to isolate each of the thermosyphons or each of the major piping runs should maintenance be required. All active refrigerant piping is insulated to minimize heat gain from ambient conditions and clad to preclude damage from animals or the elements. There were no requirements for secondary containment of the piping due to the fact that the refrigerant posed no threat to the barrier or its components should a leak occur.

There are eight thermowells installed vertically at varying distances from the centerline of the barrier to monitor soil temperatures and verify the barrier thickness. Either 7 or 8 thermistors were installed in each well. Soil temperatures are determined by standard resistance measurements of these instruments. A 100-ohm platinum RTD is installed on the external surface of each thermosyphon at approximately mid-depth to monitor operating temperatures. Additional performance data is collected from heat flux sensors and pressure transducers located on four thermosyphons in the array. Pressure transducers are also installed on the main suction lines feeding each of the condensing units. These instruments are all hard wired to a commercial data logger installed in an environmentally controlled enclosure at the site. Instrumentation conduits outnumber the refrigeration piping lines at the project site. Additionally, a number of alarm contacts are wired to the data logger to accurately indicate the operating conditions at the site. The data is accessed remotely via modem or downloaded at the site with a portable PC. Likewise, changes to the programming of the data logger may be performed via modem. The downloaded data is in spreadsheet form, compatible with most major spreadsheet software.

The entire system was installed without occurrence. There were no safety-related incidents or compromises. Waste minimization practices were stringently followed. No containerized waste was stored on-site.

OPERATION OF THE FREEZING SYSTEM

The system was activated in mid-September of 1997 with the two refrigeration condensing units driving the 50 thermosyphons at approximately -32°C . The frozen cylinders began coalescing in mid-October and completely joined at the surface of the asphalt pavement on November 1, 1997. The barrier reached its design thickness of 3.66 meters in mid January of 1998. Once the design thickness was achieved, the condensing units were put onto an alternating run schedule to minimize the power consumption at the site. Maintenance freezing requires significantly less energy than initial frezedown. The condensing units are alternately cycled for 24 hours periods. The air cooling coils and refrigeration compressors in each condensing unit are controlled to provide appropriate run times to keep the suction side of the active system at -32°C . These controls unload the system so that only the equipment required to keep the suction side at -32°C is running. When outdoor temperatures are below freezing, and the heat load on the system is low, the entire system will shut down. This allows efficient heat removal from the soil with the standard commercial low-temperature refrigeration units. There are no operators required on-site for normal system operation. If required, the system may be run at -40°C without any modification to the equipment package.

Maintenance of system components is required only in the event of a mechanical failure associated with the condensing units. These are off-the-shelf items and can readily be repaired by a qualified refrigeration service technician. There is no secondary waste generated by the operation and maintenance of the system.

In late September of 1998, a power outage was simulated at the site. The refrigerant feed to the array of thermosyphons was stopped for a period of eight days while the data logger continued collecting temperature data. Ambient air temperatures during this period averaged between 32°C and 35°C. The barrier lost less than 2 percent of its thickness during this period with the maximum loss at the top of the barrier just beneath the surficial insulation. The centerline of the barrier beneath the insulation remained frozen for the whole of the eight-day test period.

EVALUATION OF THE FROZEN BARRIER

The US EPA Superfund Innovative Technology Evaluation (SITE) program using an independent sampling and data analysis plan evaluated the integrity of the frozen barrier. Waterborne tracers were used to verify that the area inside the impoundment was hydraulically isolated from the outside of the impoundment. Unique tracers were injected both inside the impoundment and outside the impoundment. The tracer injected outside the impoundment was never detected inside the impoundment. The tracer injected inside the impoundment was essentially contained with the exception of an anomalous breach in the northwest corner of the impoundment due to the presence of an abandon subsurface pipeline.

Piezometers were installed in various groundwater monitoring wells around the impoundment and in within the impoundment. The Piezometers in wells external to the impoundment exhibited the same rapid response to rain and storm events that were observed in the pre-barrier evaluation. The instruments within the barrier exhibited no response to rain and storm events. Water levels within the barrier gradually diminished due to moisture being drawn to the frozen wall.

The conclusion of the independent integrity study is that the barrier is performing as planned and that it has hydraulically isolated the interior of the impoundment.

DEPLOYMENT OF FROZEN BARRIERS

Frozen barriers are well suited to the control a variety of contaminants including radionuclides, DNAPL's, 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 ground water, 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-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 (even though relatively low) 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, ⁹⁰Sr 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.

Although there are numerous developed and embryonic technologies 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.

DEMONSTRATION PROJECT COST

The contract price to install the Frozen Soil Barrier Demonstration Project was \$1,252,778. This cost included the design, site preparation, freezing equipment purchase & installation, membrane installation, health & safety, and first year maintenance for the project. The project coordination & management and health & safety costs totaled approximately 30% of the total project price. These costs were required due to the relatively new technology being installed within a radioactively contaminated area. The installation crew had to be protected from contamination from other sources as well as from the HRE Pond. In fact, the contamination external to the HRE Pond confined the work area so concurrent tasks were nearly impossible to perform on the small site. We estimate that the same number of site coordination and safety personnel could have handled a project 2.5 to 3 times the size of that installed at ORNL.

The surficial membrane installed at the site to manage surface water and provide a top to the containment “box” cost \$94,500 or approximately 8% of the contract price. That component was required to contain contaminants within the barrier and preclude a net influx of water into interior of the “box” formed by the barrier. Otherwise, the bathtub-like container would have overflowed at some future date. This membrane is not an integral part of the frozen soil barrier system. Some type of surface treatment would have been required for most any barrier system installed at this site.

The monitoring system installed for this demonstration project required hard conduit to be run to each of the 59 monitoring locations to meet the ORNL site specific construction code. There are 125 discrete monitoring points, of which, only half are required for monitoring a typical frozen barrier installation. The other points were installed for the demonstration only, to either provide additional data or to test the instrumentation. The costs associated with installing this data collection system were at least 3 times more than required for a system that would have provided the required data to verify proper operation of the barrier.

This barrier is 91 meters long, 9.1 meters deep and has a design thickness of 3.66 meters. This gives a cross-sectional area of 836 square meters, a frozen volume of 3,058 cubic meters and a contained volume of 4,778 cubic meters. On a design volume of frozen soil created basis, this barrier cost \$409.60 per cubic meter. Based on the local rate of \$0.052 per kWh for power, the electricity cost to establish the barrier was \$3500 or approximately \$1.06 per cubic meter of frozen soil formed. The maintenance cost for the barrier is estimated to be approximately \$10.59 per cubic meter of frozen soil per year including monitoring and preventative maintenance. Cost for power only to run the refrigeration units is approximately \$15 or less per day.

The cost of installation of the barrier was representative for a barrier of this size considering the fact that this was a demonstration project with some subsurface complexity at a small site within a contaminated area. For larger, deeper, and less problematic settings, the unit costs will be reduced. With present technologies, the absolute minimum costs for deploying a frozen barrier are on the order of \$24.40 per cubic meter of frozen material. This minimum cost is from a project in Ontario, Canada where a 3.5 kilometer barrier was installed to provide a groundwater cutoff at a non-contaminated site. Costs, of course, will vary significantly from site to site, with different applications, and with different subsurface conditions. Based on our experience at Oak Ridge and recent bidding on large-scale projects, capital installation costs are predicted to be in the range of \$35 to \$176 per cubic meter of frozen soil. The lower end of the cost range is representative of projects above \$25,000,000 with minimal requirements for protection of workers from hazardous substances and the majority of freezing occurring at a depth greater than 6 meters. The upper end of the cost range is for projects at least \$5,000,000 with moderate requirements for worker protection from hazardous substances. Surface water cutoff requirements can increase the costs from 5 to 30 percent depending upon the project. Small scale projects, such as that performed for this demonstration are predicted to cost in the range of \$176 to \$318 per cubic meter of frozen soil. Annual operations and maintenance costs are predicted to be in the range of \$0.70 to \$1.77 per cubic meter of frozen soil depending upon the level of surveillance required.

CLOSURE

The Frozen Soil Barrier Demonstration Project was a successful project for the DOE to prove the feasibility and costs of implementing a frozen barrier at a radiologically contaminated site. The complex site geology was a factor but not an impediment to the deployment. The independent integrity verification by the US EPA showed the area surrounded by the barrier to be hydraulically isolated from the area outside of the barrier. The cost of operation of the frozen barrier is low enough to be nearly forgotten in the annual budgeting process.

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