Frozen Soil Barrier Technology - Facts about the Oak Ridge National Laboratory Barrier – 14554

Elizabeth Phillips*, Edward Yarmak**
* U.S. Department of Energy
** Arctic Foundations, Inc.

DISCLAIMER

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ABSTRACT

In 1997, a frozen soil barrier was constructed and operated by Environmental Management at the Oak Ridge National Laboratory (ORNL). The barrier operated for six years and data regarding its operation was collected by the Department of Energy (DOE) and the contractor, Arctic Foundations, Inc. (AFI). With the recent announcement that a frozen soil barrier would be used at the Fukushima Nuclear Plant to contain contaminated groundwater from reaching the Pacific Ocean, international experts have weighed in on whether the technology would solve the problem. Presentation of the facts and issues from the Oak Ridge project will inform the scientific and regulatory communities of the factors necessary for a successful project at a radioactively contaminated site.

INTRODUCTION

The DOE, Oak Ridge Office of Environmental Management, is located in East Tennessee, and has remediation responsibility for three major sites that were part of the Manhattan Project. These sites are the Y-12 National Nuclear Security Complex, ORNL, and the East Tennessee Technology Park. These sites were placed on the Environmental Protection Agency (EPA) National Priority List in 1989. There are several hundred hazardous and radioactive waste disposal and storage sites across these three sites that are scheduled for complete cleanup by 2047. Remediation has taken place since the early 1980's and many of the sites have already been cleaned up under Resource Conservation and Recovery Act (RCRA) and Comprehensive Environmental Response, Compensation and Liability Act (CERCLA). After careful evaluation, a former earthen pond at the Homogeneous Reactor Experiment (HRE) Site at ORNL was chosen for the frozen soil barrier demonstration project. The 1,200 m^3 (316,000 gallon) pond, meant for low-level liquid waste, also received highly contaminated fission products. The pond was operated from 1957-1961 and was backfilled and paved in 1970.

PROJECT OBJECTIVES

The project objectives were to design and install a subsurface frozen soil barrier around a known source of radiological contamination, evaluate the performance of the frozen soil barrier system, and maintain the barrier to isolate contaminants from further migration away from the source. In order to meet these objectives, a multi-disciplinary project team was formed. The team consisted of a DOE project manager, AFI, Tennessee Department of Environment and

Conservation (TDEC), Environmental Protection Agency Superfund Innovative Technology Evaluation (EPA SITE) Program, Lockheed Martin Energy Research LMER), Lockheed Martin Energy Systems, Bechtel Jacobs Company LLC, Cambrian Groundwater, Tetra Tech EM Inc., and SAIC. This project was part of the Subsurface Contaminants Focus Area portfolio.

The project team installed the frozen soil barrier at ORNL in 1997. Arctic Foundations, Inc. was selected to install the barrier using a technology they developed and used in Alaska, Canada, Greenland, Russia, and other locations in cold climates to keep permafrost frozen.

Artificially frozen soil barriers have been used since 1862 in the mining and construction industries. The technology has been used in a variety of settings, including high-rise, dam, tunnel, and highway construction. Unlike conventional barriers for groundwater containment, frozen barriers are self-healing if ground movement occurs. The process has been adapted as a potential technology for the hazardous and radioactive waste containment industry, since it has shown to immobilize clean groundwater; therefore, the next step was to use it to immobilize contaminated soil and groundwater.

The technology is applicable to many types of conditions, but factors to consider are waste type, topography, overall site hydrogeology, soil moisture content, subsurface structures, soil types, and thermal conductivity. The freezing pipes can be installed in a “V” or “U” configuration to ensure complete encapsulation and isolation of waste. This type of installation is accomplished by placing the freezing pipes within closely spaced directional boreholes. Standard drilling or driving techniques are normally used for freeze pipe installation. In certain geological settings, where downward migration of contaminants is limited by a very low permeability clay or bedrock unit, and when such a unit occurs at a shallow depth, freezing pipes can be installed in a vertical position with the bottom of the pipes anchored in the unit, which acts as a basal bottom confining layer.

AFI used an innovative thermoprobe design for the embedded freezing pipes at this project. Conventional thermoprobes, known generically as thermosyphons, remove heat passively whereby soil can be frozen and remain frozen without the use of an external power supply when deployed in a cold climate. This project used “hybrid thermosyphons”, which constitute a closed, two-phase system that can be used in an active or passive mode. The active mode is used in climates where the ambient air temperature is above freezing and includes the use of an active refrigeration unit. The hybrid thermosyphon design used for this project is shown on Figure 1.

SITE DESCRIPTION

The HRE Pond Site is located in Melton Valley, north of the main ORNL complex. A tributary stream was receiving Sr-90, Cs-137, and H-3 contaminated groundwater from the site and it flowed into Melton Branch, to White Oak Creek, to White Oak Lake. The soil was about 10 meters deep and the top of bedrock contained a permeable, weathered layer that created a preferential flow path for groundwater. Water level data collected from on-site standpipes, piezometers, and monitoring wells indicated that groundwater at the site exhibits significant responsiveness to rainfall and storm events. The average depth to groundwater is 2-3 meters below ground surface.

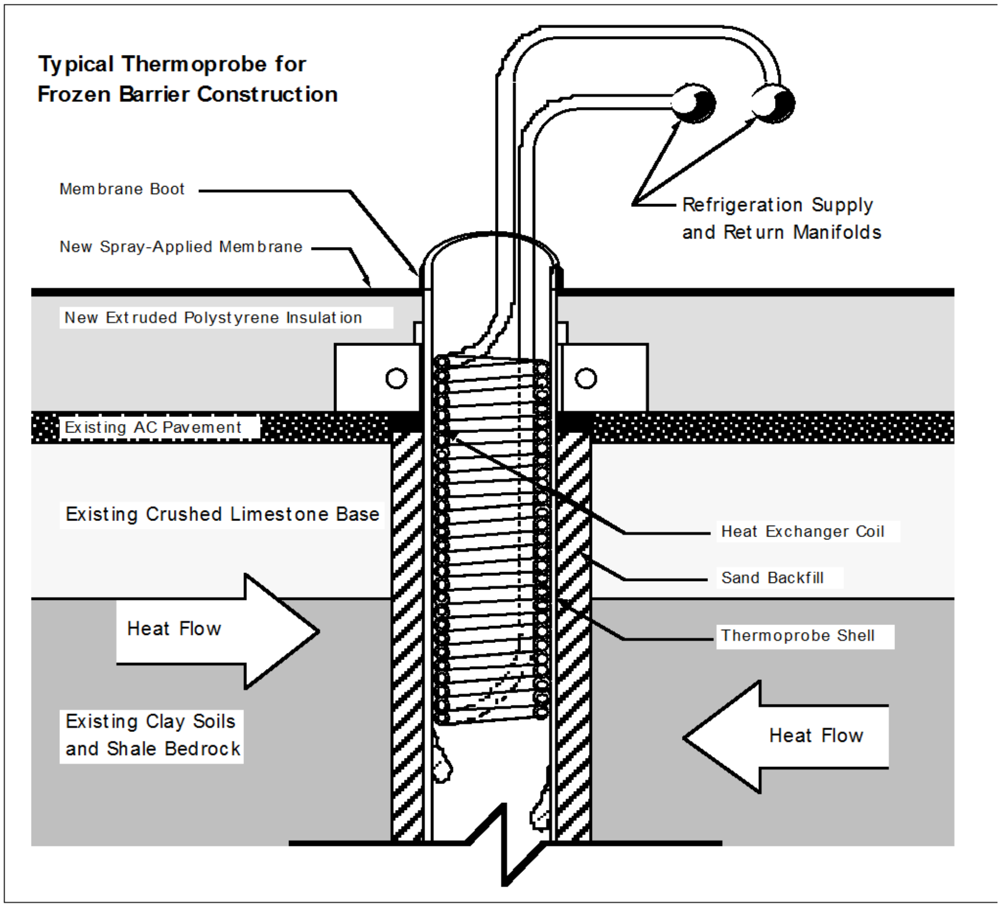

Fig. 1: Hybrid Thermosyphon Design

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 with clay. In 1970, the pond was decommissioned by backfilling with clay and shale materials, and then covering the new surface with a conventional asphalt pavement cap. The cap was installed with a 200 mm (8 inch) minimum thickness, free-draining crushed limestone base course to support the pavement. By April 1997, when site construction began on the frozen soil barrier, the asphalt surface remained in generally good condition except for a few contraction cracks that measured as wide as 75 mm (3 inches).

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 through the crushed limestone base course 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 down gradient of the pond.

TECHNOLOGY DESCRIPTION

The thermoprobes were installed around the edge of the pond, spaced about 1.8 meters apart. Fifty thermoprobes, 9.1 m in length, were installed, and eight additional boreholes were outfitted with temperature monitoring devices. A 25-meter by 27-meter box was formed around the pond. The barrier design used the top of the bedrock as the base of the barrier. An insulated cover was used to ensure that the barrier would freeze completely to the asphalt cap surface and a spray-applied poly-urea membrane was installed to prevent rainwater intrusion into the interior region of the barrier. The barrier design is shown on Figure 2.

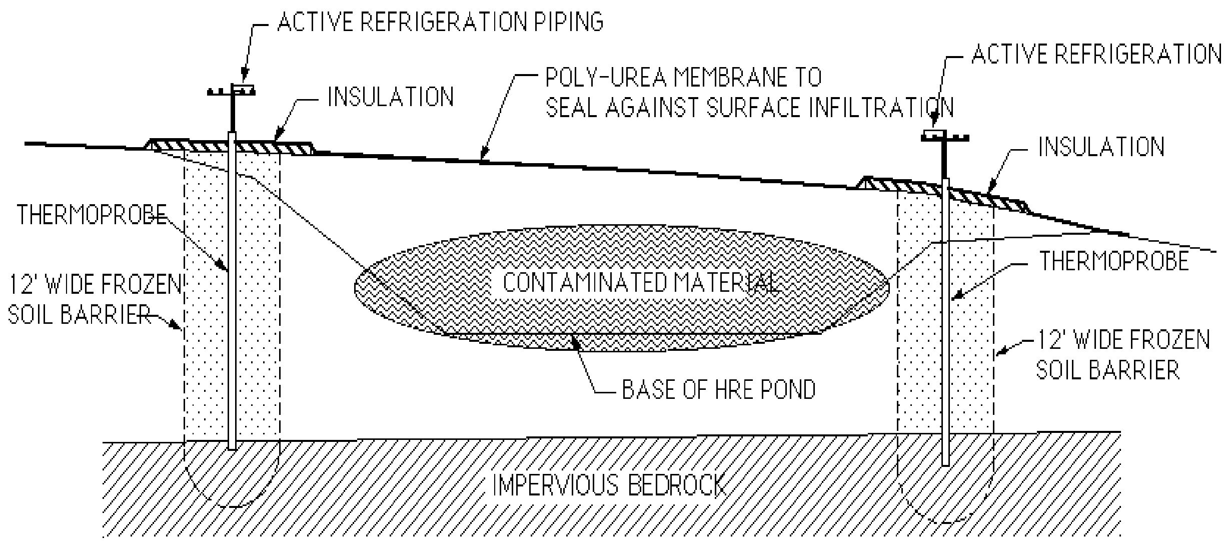

Fig. 2: HRE Pond Frozen Barrier Design

Once installed, the thermoprobes were connected to the powered refrigeration unit, where the active coolant circulates within a closed system to remove heat from the thermoprobe. The type of working fluid used depends on the specific waste application, site conditions, and the desired soil temperatures. For this demonstration, R404A was used for the active coolant in the system because it is relatively benign environmentally and is appropriate for the low temperature refrigeration work. The passive refrigerant is carbon dioxide, the most widely used and lowest maintenance working fluid for the thermoprobes. When the soil adjacent to the pipes reaches 0°C, frozen pore water bonds soil particles together as an impermeable mass. Additional cooling is applied until the frozen area builds outward to the design thickness. Thickness and temperature of the barrier wall are varied to suit site conditions. For this project, the design thickness of the barrier wall was 4 meters thick. The completed barrier is shown on Figure 3.

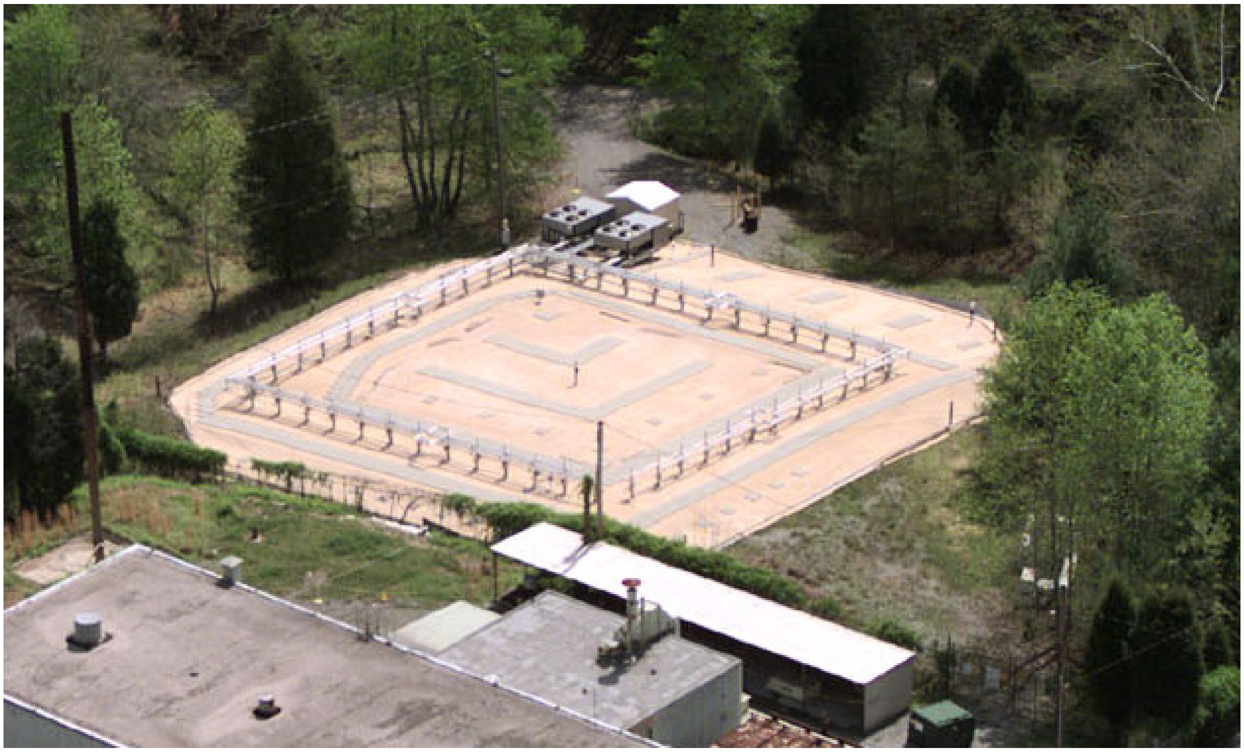

Fig. 3: Completed Barrier

The project plan was to conduct pre-barrier installation studies to define groundwater flow, design and install the system, operate the barrier, and record operating parameters such as electric power usage, temperature changes, and subterranean growth of barrier, and to verify the barrier was isolating the pond. The EPA SITE program and LMER scientists conducted the pre- and post-barrier verification studies and have published a separate report of their findings.

The pre-barrier groundwater studies used three types of fluorescent dye and helium gas tracers to confirm that the pond was hydraulically connected to adjacent wells, springs, and surface water. An electromagnetic geophysical survey was also conducted and indicated three subsurface anomalies; the most important one was at the northwest corner of the site. Later in the project, that anomaly was identified as the inlet pipe to the pond that had not been removed before closure. Also, groundwater monitoring revealed extreme groundwater level response to storm events inside and outside the impoundment.

DISCUSSION

Safety

Safety was of paramount importance on this project, as it is on all projects undertaken within the DOE complex. Although the genesis probably stems from over fifty years of dealing with radiological issues, safety was the highest priority in every aspect of site construction; radiological or not.

Well before the commencement of site work, a qualified consultant with experience working at radiologically contaminated sites was contracted to provide health and safety personnel and related professional services and equipment. A Health & Safety Officer was identified to assist in the preparation of a Site Safety Plan that was subsequently approved by DOE. All site management personnel were trained and certified with 40 hours of Hazardous Waste Operations and Emergency Response (HAZWOPER) training, 8 hours of HAZWOPER supervisory training, and 24 hours of radiological worker training. Similar training was also required of all other personnel who worked on the site. In addition, all personnel were required to have General Employee Training (GET) at ORNL in order to be badged for entry onto the site. Medical examinations were also required of all personnel who could be potentially exposed to radioactivity. These involved a general pre-physical examination, radiological pre- and post-bioassays, and full body counts at ORNL.

Due to the high potential that radioactive cuttings would be produced during the thermoprobe installation, a procedure for handling and disposing of these materials was well established. To support the construction activity, however, the site was defined in terms of a buffer zone and an exclusion zone. These remained in effect until after the asphalt cap was covered with a new and clean membrane. Entry into these areas was restricted to personnel who were properly safety qualified and clothed and protected with personal protective equipment (PPE). Departure from these areas required removal of all PPE at the exit points to avoid the transport of contamination. All PPE was left within the area was discarded as radiological waste. All site personnel were also equipped with personal thermoluminescent dosimeters (TLDs) that were worn continuously while on site.

Other safety procedures were also in effect depending on the activities underway. These included such things as hoisting and rigging procedures, requirements for hot work permits, etc.

The project was entirely successful from a safety perspective, as there was not a single accident, incident, or occurrence from start to finish.

System Operation

The system began operation in September 1997 and operated for 6 1/2 years. The refrigeration condensing units driving the thermoprobes were run at approximately -32°C (-25°F). The barrier was formed within seven weeks from startup, and electrical power usage to form the barrier was 33,000 kW-hours. The barrier walls reached the 3.66 m (12 ft.) design thickness within 18 weeks after start up, and cumulative electrical power usage was 72,000 kW hours. The total volume of frozen soil was 3,060 m^3 (108,000 ft^3), and the total volume of material contained within the frozen barrier was 4,780 m^3 (168,750 ft^3). An eight-day simulated power outage was conducted during operation when ambient air temperatures averaged between 32°C to 35°C (90°F and 95°F), and the barrier lost less than 2% of its thickness with the centerline of the barrier remaining frozen up to the base of the insulation during that test. On December 31, 1999, the average barrier thickness was 7.8 m (25.6 feet), over twice the design thickness.

Post Barrier Studies

The EPA SITE Program, TDEC, Cambrian Groundwater, and LMER personnel performed the barrier verification testing. Groundwater level fluctuations within the pond damped out with the establishment of the barrier. The zone within the frozen soil barrier behaved as if it was isolated hydraulically from the surrounding area. The tracer dye injected outside the impoundment was not transported into the isolated zone.

Operation Life

The barrier was decommissioned on April 16, 2004, and had only diminished approximately 10% by the end of the summer of 2004. The monitoring system was not disabled when the barrier was turned off and Figure 5 is the record of the barrier thaw until the power was cut to the monitoring system. Note that the top of the barrier was still frozen to the base of the insulation for a month after the refrigeration power was turned off. The bulk of the barrier was still frozen when Bechtel Jacobs Company LLC excavated the soil in April 2005. The thermoprobes were in pristine condition and showed no signs of rusting or degradation. The system used an average of 97,900 kWh per year for the period it was in operation (648,189 kWh total when turned off on April 16, 2004). The total power consumption for the site was monitored and shown on Figure 4. Figures 6, 7, 8, and 9 show photos of the barrier system taken during the total site remediation project performed in 2004 and 2005.

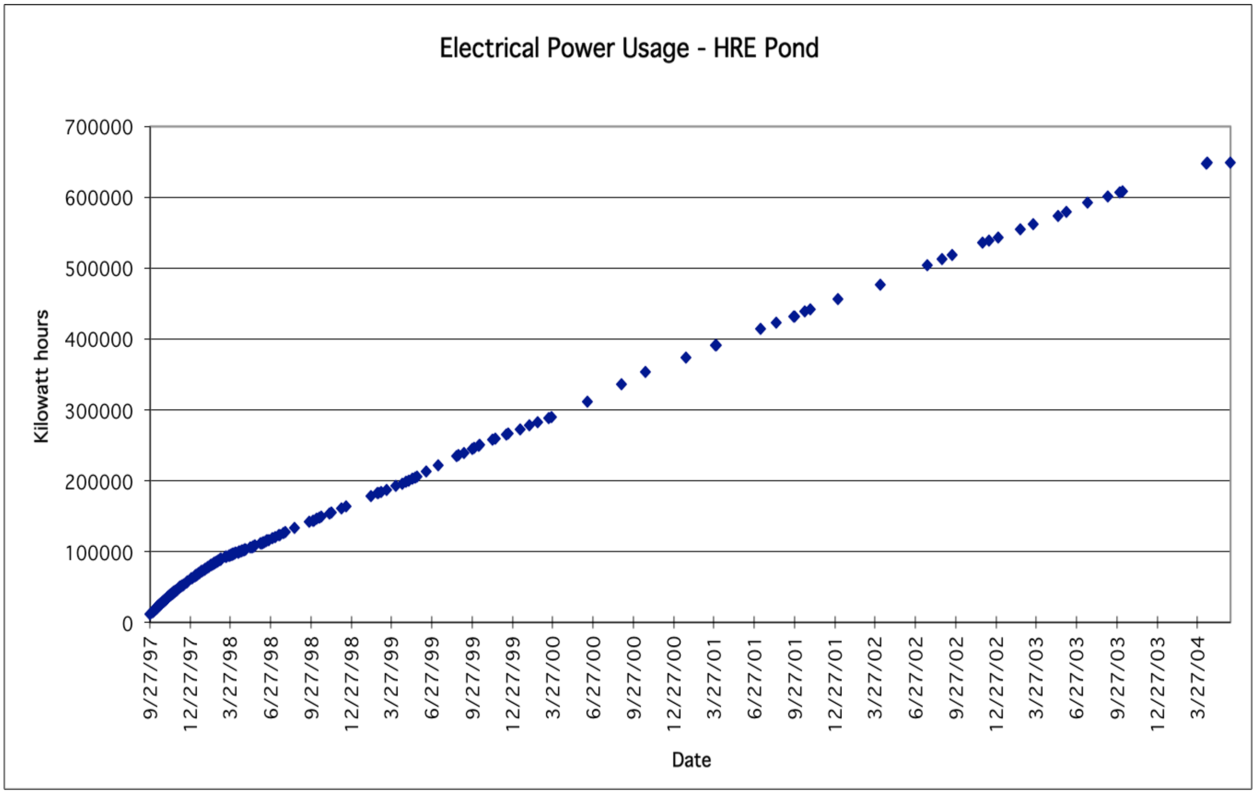

Fig. 4: Electrical Power Usage at HRE Pond

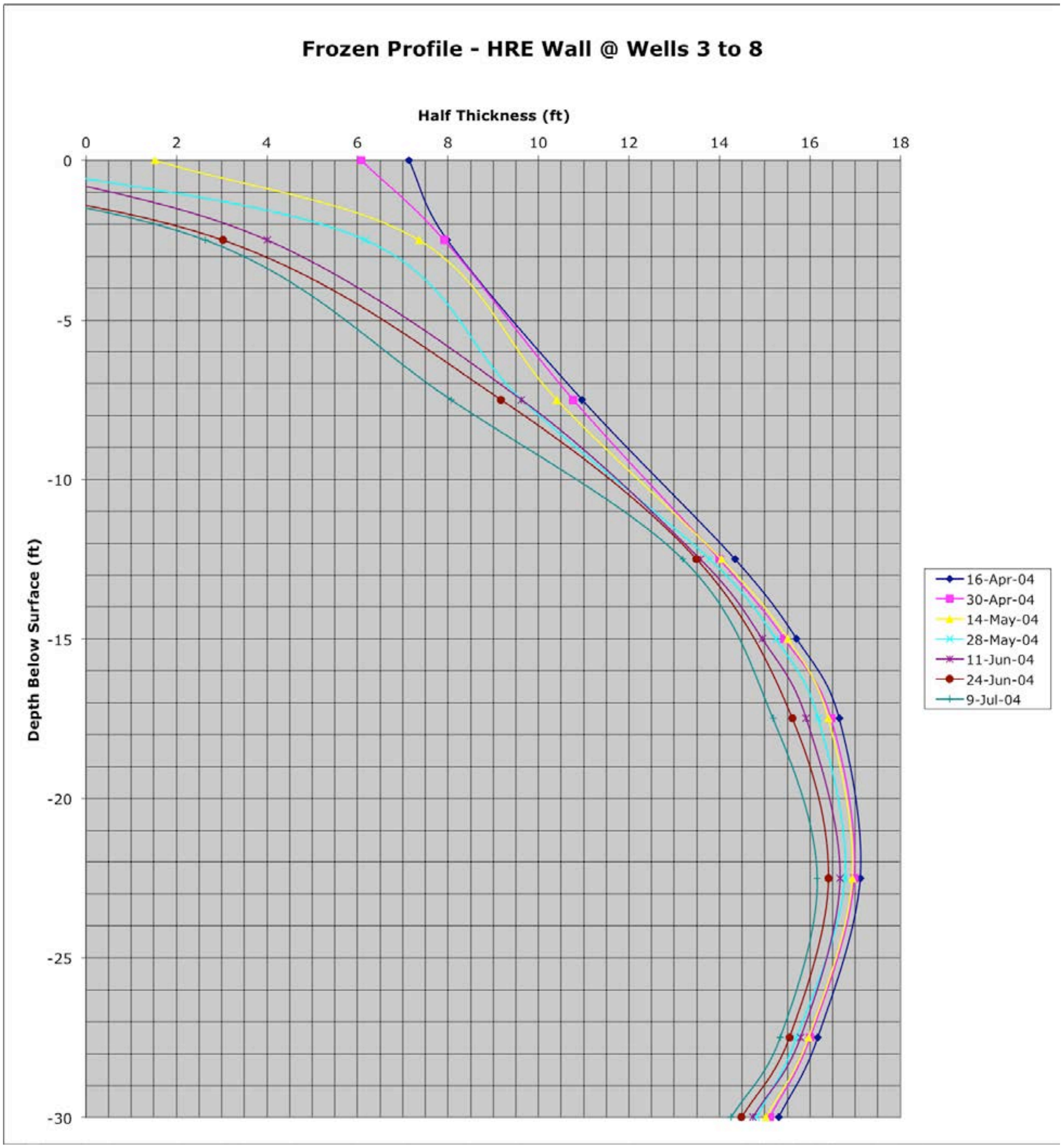

Fig. 5: Frozen Barrier Thaw from April 16 to July 9, 2004

CONCLUSIONS

The frozen soil barrier worked as designed in this climate, hydrologic setting, and for the HRE contaminants. An important recommendation is to adequately characterize the site and understand the geology, hydrogeology, and subsurface structures. A multi-disciplinary team of experienced professionals should be utilized to install the barrier. Prior to implementing a full-scale barrier, best practices dictate a pilot test be performed in a clean area to see if it is suitable for the site. If the pilot test is successful, a larger barrier can be created in a contaminated area. The system can be used as a temporary or more permanent solution and will not harm the environment if it is later thawed and removed.

The total cost of the project was $1,809,000. This includes design, installation, start-up, operation, ORNL engineering and site support, infrastructure upgrades, and pre-and post-barrier verification studies. Electrical power to maintain the barrier was 268 kW hours per day at a cost of less than $15 per day. In hindsight, the system could have been run by solar power after the initial freezedown. The barrier effectively isolated the HRE pond and a reduction of 80% of Sr-90 was measured in the downgradient tributary to the creek.

Several lessons learned were collected from this project. This barrier was installed in a relatively shallow site in a humid climate where rainfall averages over 1.27 m (50 inches) per year and the water table is shallow. An understanding of the site geology and hydrology is imperative. Pre-installation site characterization will identify most subsurface anomalies that may impact the installation of an impervious barrier. Also, on-going groundwater collection and pumping operations in nearby facilities induced local groundwater responses that affected barrier verification studies. These operations were identified after verification began and resulted in more data analysis than was originally planned.

Other important facts to take into consideration are that this barrier was created with existing commercially available technology. The design of the system hardware is mature and of known reliability. The refrigeration plant was oversized for this demonstration in order to achieve rapid freezedown. Also, two refrigeration units were used in case one had unexpected maintenance issues or down time. Capital equipment costs can therefore be traded against barrier formation time. While proprietary hybrid thermosyphon technology was used for this project, other technologies can be used to create a frozen barrier. While bedrock was utilized as the bottom of this barrier, not all geologic situations would support this design. One of the identified project risks was an alternate design in case the integrity of the barrier at the bedrock interface could not be verified. Local subcontractors were utilized for drilling and piping and health and safety/health physics support. Scientists familiar with the site conditions and radioactive contamination were utilized to support the project and conduct verification studies.

Fig. 6: Exposed Frozen Soil Thawing in December 2004

Fig. 7: March 2005 Site Remediation

Fig. 8: March 2005, Thermoprobes are in Good Shape

Fig. 9: May 2005, Excavation Nearly Complete

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