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Creation of an artificial frozen barrier using hybrid thermosyphons

A.M. Wagner *

Cold Regions Research and Engineering Laboratory, Fairbanks, USA

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ABSTRACT

Standard containment technologies for remediation of subsurface contaminants include slurry walls, reactive barriers, sheet piling, and grouting. Another less common technique is freezing contaminants in situ. Artificial freezing techniques can be used to create a frozen barrier that restricts migration of aqueous phase contaminants and, therefore, can provide subsurface containment at a variety of facilities, including underground tanks, nuclear waste sites, groundwater plumes, and in situ waste treatment areas. Frozen barriers are formed by using a series of subsurface freezing pipes. The adjacent soil forms a frozen column the length of the freezing pipe; and the diameter of the frozen soil column increases with time at a rate depending upon the specific soil properties, moisture content, and thermal conditions at a given site and refrigeration rate (i.e., pipe temperature). The barrier is completed once the increasing diameters of the frozen soil columns merge together, which is referred to as "freezing to closure". A study was performed in Fairbanks, Alaska, to investigate how quickly a barrier can be created during the summer using actively cooled hybrid thermosyphons. Freezing to closure occurred after 42 days, the barrier was 1 m thick after approximately 49 days, and temperatures were below −3 °C at the core of the barrier (in between the thermosyphons) after 60 days. The active system was turned off in the fall, and passive cooling of the ground continued through the winter. By the beginning of the following March, the frozen barrier was 3.8 m thick.

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1. Introduction

In the United States, groundwater contamination became recognized as a major issue in the 1970s (NRC, 1994). Large-scale groundwater cleanup operations for federal sites began when the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and the Resource Conservation and Recovery Act (RCRA) were implemented in the 1980s. At many contaminated sites, reaching cleanup goals, as required by the CERCLA and RCRA, has proved difficult and not feasible within a realistic timeframe using pump-and-treat systems (NRC, 1994). However, when used in parallel with other technologies, the efficiency of groundwater cleanup techniques, such as pump-and-treat systems, improves. Examples of such technologies are soil vapor extraction, in situ bioremediation, bioventing, air sparging, and in situ chemical treatment. These technologies all require the circulation of fluids and a continuous energy input for pumping water or air (NRC, 1994). Passive systems, such as intrinsic bioremediation, physical containment, and in situ reactive barriers, are alternative techniques that require no power inputs in mild climates. In cold regions, passive or active heating may be needed when using reactive barriers and during bioremediation.

Physical containments such as slurry walls and sheet pile walls are both established subsurface containment technologies (Pearlman, 1999). Slurry walls have been used for isolating hazardous waste and for preventing the migration of pollutants since the late 1970s and early 1980s (USEPA, 1998). A vertical wall is either keyed into a low permeability formation at deeper depths or installed to intercept flow in the upper part of the aquifer. These walls are installed either up-gradient or down-gradient of a contaminated zone or in a circumferential configuration (USEPA, 1984). The placement of up-gradient walls serves to divert clean groundwater from flowing into a contaminated site. Down-gradient walls function as a barrier to capture contaminants, allowing treatment of the contaminants with extraction wells. Interior and exterior extraction wells can be used in conjunction with barriers to maximize containment and to reduce leakage outside the barrier (USEPA, 1996). Additionally, the cost of pumping decreases when vertical walls work in combination with pump-and-treat systems (Bayer et al., 2005). Site specific factors, such as hydrology and geology, dictate the selection of a suitable vertical barrier for a site. For example, slurry walls are more effective in softer soils and grout curtains work well in fractured rock (Rumer and Ryan, 1995). Sheet piling, grouting, and slurry walls are all permanent structures that are difficult and expensive to remove.

An alternative technology that can be removed once remediation is completed is artificial frozen barriers (Andersland et al., 1996a; Dash, 1991). In 1963, F. H. Poetsch patented artificial ground freezing; and it is primarily used for excavation, tunneling, and underground construction (Hass and Schafers, 2005). Recently, artificial ground freezing has

* Tel.: +1 907 361 5459; fax: +1 907 361 5142.
E-mail address: Anna.M.Wagner@usace.army.mil.

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also been used for containment of contaminants by installing subsurface pipes around the contaminated zone and creating a frozen barrier. Once the frozen soil of the adjacent pipes merges, or "freezes to closure," the barrier is complete. The time for the barrier to close depends on soil characteristics, soil moisture, liquid coolant, pipe diameter, pipe temperature, and spacing of the pipes. Containment beneath the contaminated soil is also possible by installing the pipes at an angle, forming more of a cone of containment. Alternatively, contaminated soil can be frozen completely to form an entire block of frozen material.

For a frozen barrier to be successful, the geology, hydrology, and groundwater conditions need to be suitable (Braun et al., 1979; Sanger and Sayles, 1979). For example, one needs information such as thermal and mechanical characteristics of the soil in addition to contaminant characteristics. The placement of the wall should be outside of the contaminated zone for contaminant-free frozen soil (Andersland et al., 1996a). Thawing of a frozen barrier can occur at a site where the groundwater flow has a high velocity. One method to minimize ice erosion is to design a fully ice-saturated barrier, which entails introducing water to increase the water content of the soil (Andersland et al., 1996b). Andersland and Ladanyi (1994) recommend groundwater velocities less than 1.2 m s^{-1} for the wall to reach freezing to closure. Installing pipes at a closer spacing or installing another row of pipes to increase the total width of the barrier can also minimize ice erosion (Braun et al., 1979). The frozen barrier must also remain at temperatures that are less than the freezing point depression of the contaminant (Andersland et al., 1996b). Designing the refrigeration system to operate at an appropriate temperature can accommodate for the freezing point depression of the contaminant (Johnson et al., 2000).

It is widely known that some pore water remains unfrozen in frozen soil and that the hydraulic conductivity decreases with a decreasing temperature. Nixon (1991) summarized the hydraulic conductivity from nine frozen, fine-grained soils. A study by Smith (1985) reported the highest hydraulic conductivity was for Inuvik Clay with a value of 4.5×10^{-9} cm s^{-1} at a temperature of −0.2 °C that decreased one order of magnitude to 3.5×10^{-10} cm s^{-1} at about −1 °C. Horiguchi and Miller (1983) studied silts and reported values in the range of 10^{-10} to 10^{-11} cm s^{-1}. In another study, McCauley et al. (2002) measured the hydraulic conductivity in ice-rich soils as slightly higher at 10^{-9} cm s^{-1} at a temperature of −4 °C. As a comparison, the industry-accepted permeability for soil-bentonite slurry walls is 10^{-7} cm s^{-1} (USEPA, 1998). In general, the hydraulic conductivity for cement-bentonite slurry trench walls ranges from 10^{-5} to 10^{-6} cm s^{-1}; and for soil-bentonite slurry walls, the range is between 10^{-7} and 10^{-8} cm s^{-1} (Rumer and Ryan, 1995). Grout barriers have a permeability of approximately 5×10^{-6} cm s^{-1} (USEPA, 1998). Hydraulic conductivities for sheet piling barriers are slightly lower with hydraulic conductivities of 10^{-8} to 10^{-10} cm s^{-1} (Smyth et al., 1997). This indicates that frozen barriers have a comparable or lower hydraulic conductivity to other vertical barriers. To assure a low hydraulic conductivity and to decrease the unfrozen water content for the frozen barrier, the core should be designed to have a temperature well below freezing (<−3 °C).

Traditionally, low hydraulic conductivity was thought to be the most important solute transport process through vertical barriers. More recently, there have been indications that molecular diffusion also plays a major role in contaminant transport (Manassero and Shackelford, 1994). In fact, Daniel and Shackelford (1988) and Gerber and Fayer (1994) state that molecular diffusion becomes the dominant transport mechanism of contaminant migration for materials with hydraulic conductivities lower than 10^{-8} cm s^{-1}. For unfrozen nonreactive (non-adsorbed) and reactive solutes, molecular diffusion ranges from 1.0 to 18×10^{-6} cm^2 s^{-1} for saturated soils and 0.54 to 25×10^{-6} cm^2 s^{-1} for unsaturated soils (Shackelford, 1991). The values for unsaturated soils are about 10–20 times greater than for saturated soils. In general, molecular diffusion depends on the properties of the fluid and solute. Temperature also changes the molecular diffusion rate where, for some solutes, at 5 °C the coefficient is about half its 25 °C value (Freeze and Cherry, 1979). The molecular diffusion through a frozen material is lower than through an unfrozen material. For example, the molecular diffusion of sodium ions in an unfrozen, silty clay is between 2.5 and 3.5×10^{-6} cm^2 s^{-1} (Crooks and Quigley, 1984) whereas it is about an order of magnitude less (1×10^{-7} cm^2 s^{-1} at −3 °C) in a typical frozen silt soil (Murrman, 1973).

The most common artificial freezing techniques are circulating coolant systems and expendable refrigerant systems (Braun et al., 1979). The circulating coolant system circulates a calcium chloride solution at about −20 °C to −40 °C (Smoltczyk, 2003). Expendable refrigerant systems use liquid nitrogen (LN_2) as the coolant (Karol, 2003), which evaporates at about −195 °C. Because of its high cost, freezing with LN_2 is only feasible when an immediate frozen wall is needed, where there is a high groundwater flow, where smaller volumes of soil need containment, or when only short periods of operation are needed (Stoss and Valk, 1979).

Using two freezing techniques, containment of contaminants was demonstrated in Oak Ridge, Tennessee, where air temperatures vary from lows of −1 °C to highs of 32 °C. The first demonstration, a "V-shaped" containment, was demonstrated in 1994 at a nonhazardous site using conventional freezing with calcium chloride as the coolant (USDOE, 1995). The freezing pipes were installed at a 45° angle in a staggered double-rowed configuration with a distance between the pipes of 2.4 m. The containment area was 17 × 17 m, and it extended to a depth of 8.5 m. The soils were a combination of silty clay and clayey silt with average moisture content ranging from 26.5 to 33.9%. Below 2.4 m, inside the containment area, a 1.8 m sand layer was added to ensure an adequate flow path during the tracer test. The barrier thickness was about 3.7–4.6 m within the sand layer and 1.5–2.7 m in the clay-dominated areas. Diffusion studies using Rhodamine-WT as the tracer confirmed barrier integrity.

The second freezing technique demonstrated was of a hybrid thermosyphon system that was installed 1997 to contain and immobilize radiologically contaminated material at Oak Ridge National Laboratory (ORNL) Tennessee (USDOE, 1999). Using thermosyphons to freeze the ground is more energy efficient than using conventional freezing

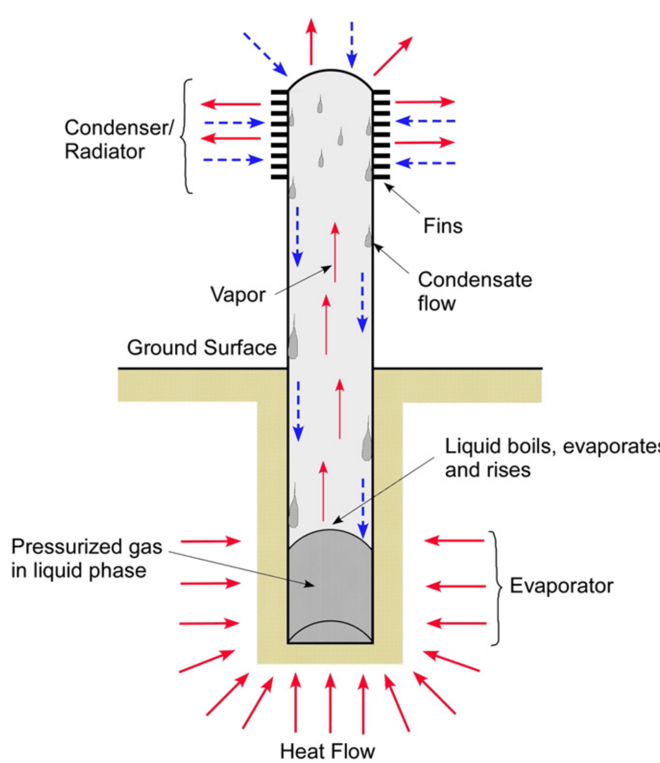

Fig. 1. Illustration of a passive thermosyphon.