The Environmental Effects of Ground-Source Heat Pumps–A Preliminary Overview

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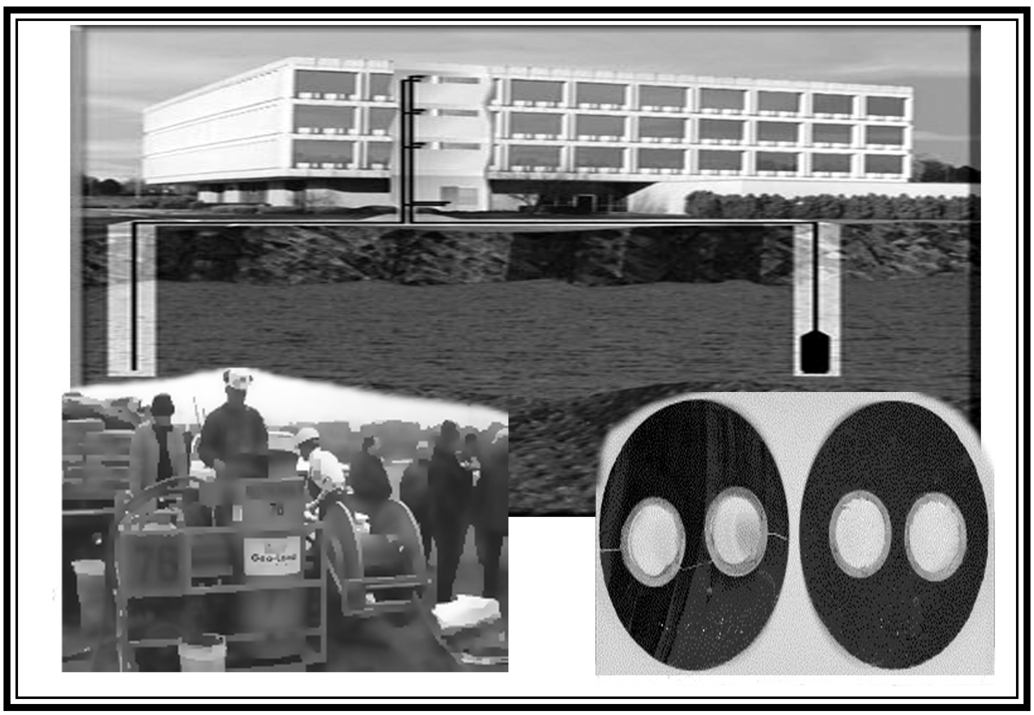

ILLINOIS DEPARTMENT OF NATURAL RESOURCES

ISGS Illinois State Geological Survey

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INTRODUCTION

Ground-source or geothermal heat pumps are a highly efficient, renewable energy technology for space heating and cooling. This technology relies on the fact that, at depth, the Earth has a relatively constant temperature, warmer than the air in winter and cooler than the air in summer. A geothermal heat pump can transfer heat stored in the Earth into a building during the winter, and transfer heat out of the building during the summer. These types of geothermal heat pumps are suitable for use throughout Illinois and the Midwest. Special geologic conditions, such as hot springs, are not needed for successful application of geothermal heat pumps.

A geothermal heat pump includes three principle components– an earth connection subsystem, heat pump subsystem, and heat distribution subsystem. The earth connection subsystem usually includes a closed loop of pipes that is buried, horizontally (Figure 1) or vertically (Figure 2). A fluid is circulated through these pipes, allowing heat but not fluid to be transferred from the building to the ground. The circulating fluid is generally water or a water/antifreeze mixture. Less commonly, the earth connection system includes an open loop of pipes connected to a surface water body or an aquifer, that directly transfers water between the heat exchanger and water source (pond or aquifer). For heating, the heat pump subsystem removes heat from the circulated fluid, concentrates it, and transfers it to the building. For cooling, the process is reversed. The heat distribution subsystem is the conventional ductwork used to distribute heated or cooled air throughout a building.

The U.S. Department of Energy (USDOE) estimated that over two-thirds of the nation's electrical energy and greater than 40% of natural gas consumption is used inside buildings. In residential and commercial buildings, space heating and cooling and water heating consume greater than 40% of electrical power. The U.S. Environmental Protection Agency (USEPA) estimated that geothermal heat pumps can reduce energy consumption by up to 44% compared to air-source heat pumps and up to 72% compared to conventional electrical heating and air conditioning. For most areas of the U.S., geothermal heat pumps are the most energy efficient means of heating and cooling buildings (USGAO, 1994).

For vertical, closed loop systems, heat exchange between the fluid and ground depends upon the thermal properties of the material in the borehole. The borehole may be backfilled with soil cuttings or grout. In Illinois, the borehole must be backfilled with bentonite grout or neat cement. Standard bentonite grout has a thermal conductivity that is lower than most soils or geologic materials (0.43 BTU/ hr ft °F vs 0.8 to 1.8 BTU/ hr ft °F), thus it acts as an insulator around the heat exchange pipes (Smith and Perry, 1999). Thermally enhanced bentonite grouts have been developed and have thermal conductivities of 0.85 to 1.4 BTU/ hr ft °F (Rafferty, 2003), while retaining low hydraulic conductivity ($<10^{-7}$ cm/sec), based on technical data from manufacturers. To boost the thermal conductivity of grouts, manufacturers mix silica sand and bentonite, and at times other materials such as cement and superplasticizer.

Figure 1. Residential geothermal heat pump with horizontal loop piping (from Geothermal Heat Pump Consortium)

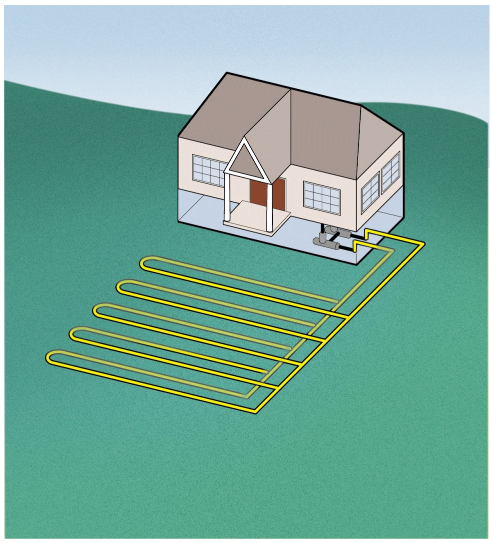
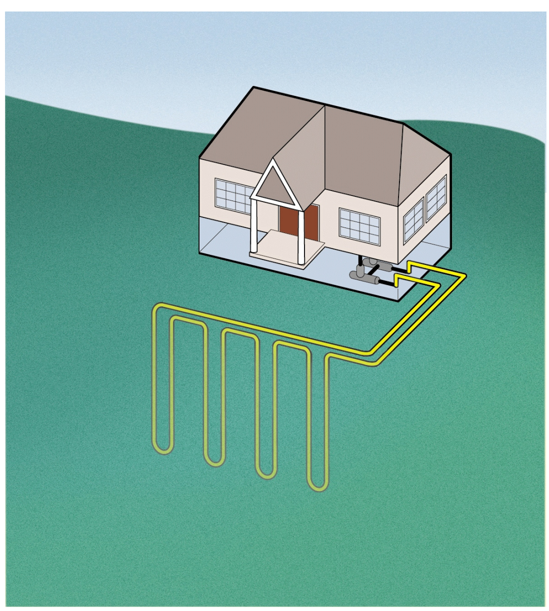


Figure 2. Residential geothermal heat pump with vertical loop piping (from Geothermal Heat Pump Consortium)



ENVIRONMENTAL ASSESSMENT

Geothermal heat pumps can have positive and negative environmental effects. The USDOE and USEPA have encouraged the use of these heat pumps because of their energy efficiency, as discussed above. Increased energy efficiency for such a major use of energy will reduce the amount of fossil fuels burned, greenhouse gases such as carbon dioxide (CO_2) generated, and other air pollutants (NO_x and SO_2) emitted (USEPA, 1997).

Heat Pump Antifreeze

A potential negative effect of all geothermal heat pumps is the release of antifreeze solutions to the environment. Antifreeze solutions are required in colder climates to prevent the circulating fluid from freezing. Antifreeze chemicals include methanol, ethanol, potassium acetate, propylene glycol, calcium magnesium acetate (CMA), and urea. These chemicals are generally mixed with water when used as a heat exchange fluid. These chemicals can be released to the environment via spills or corrosion of system components. In Illinois, closed-loop wells are regulated by the Illinois Department of Public Health under the Illinois Water Well Construction Code (Appendix). Approved antifreezes include methanol, ethanol, propylene glycol, calcium chloride, or ethylene glycol. These antifreezes must be mixed with water, at concentrations of 20% or less.

Geothermal heat pumps for a single family residence and the antifreezes for these units were evaluated by Heinonen et al. (1996). These authors evaluated total energy consumption, corrosion due to the antifreeze, and the operational and environmental effects of six antifreeze solutions (methanol, ethanol, potassium acetate, propylene glycol, CMA, and urea). These authors excluded salt solutions, such as sodium and calcium chloride, from their study because they pose serious potential corrosion problems. The differences in total energy consumption for these antifreezes were considered minimal. Heinonen et al. (1996) recommended that propylene glycol was a good choice based on its low health, fire, and environmental risks (Table 1). Unfortunately, these authors did not assess the leak potential of these antifreezes in the plastic pipe (e.g., HDPE & CPVC SDR-11) commonly used for the ground loop.

Table 1. Cost and Risk Factors for Heat Pump Antifreeze (from Heinonen et al., 1996)

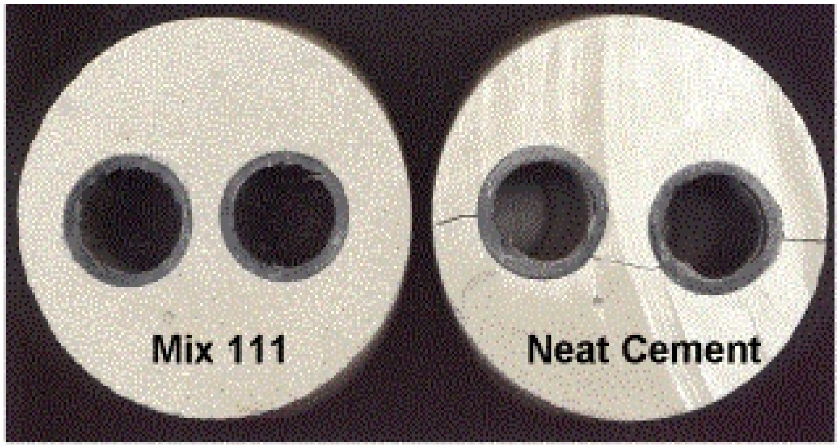
Factor	Antifreeze					
	Methanol	Ethanol	Propylene Glycol	Potassium Acetate	CMA	Urea
Life Cycle Cost	3	3	2	2	2	3
Corrosion Risk	2	2	3[a]	2	2	1
Leakage Risk	3	2	2[a]	1[b]	1	1
Health Risk	1	2	3	3	3	3
Fire Risk	1[c]	1[c]	3	3	3	3
Environmental Risk	2	2	3	2	2	3
Risk of Future Use	1	2	3	2	2	2

Notes:
Ratings– 1 means potential problems and caution required, 2 means minor potential for problems, 3 means little or no potential problems
a) DOWFROST HD
b) GS-4
c) Pure fluid only. Diluted antifreeze (25% solution) is rated 3.

Vertical Boreholes

Geothermal heat pumps with vertical boreholes may pose environmental threats. If these boreholes are not properly grouted or the grout fails, groundwater could be contaminated by surface water infiltration, interaquifer flow, or antifreeze leakage. These boreholes are usually grouted with bentonite, neat cement, or a mixture of these materials. Laboratory tests of the hydraulic conductivity of grout materials range from 10^{-10} to 10^{-7} cm/sec. Hydraulic conductivity values of 10^{-7} cm/sec are considered impermeable. For the grout and conductor pipe systems, values of hydraulic conductivity of 10^{-8} to 10^{-7} cm/sec have been reported (Allan and Philappacopoulus, 1999).

The low hydraulic conductivity of grout/pipe system can be compromised by poor bonding between the grout and the borehole or poor bonding between the grout and the heat conductor pipe (Allan and Philappacopoulus, 1999). The bond between the grout and conductor pipe is considered more likely to be compromised (Philappacopoulus and Berndt, 2001) and can fail by thermal contraction of the conductor pipe. Because the grout and pipe have significantly different coefficients of thermal expansion, the conductor pipe can contract from the grout at low temperatures, forming a conductive pathway for contaminant transport (Figure 3). Neat cement grouts with water/cement ratios of 0.4 to 0.8 failed in this manner during lab experiments where low temperature fluids were pumped through the pipe (Allan and Philappacopoulus, 1999). A thermally enhanced grout (Mix 111) did not fail, maintaining hydraulic conductivities of less than 10^{-7} cm/sec during these experiments. Mix 111 is a mixture of cement, water, silica sand, and small amounts of superplasticizer and bentonite



Grout/U-loop Specimens after Thermal Cycling

Figure 3. Cracking of neat cement grout after thermal cycle testing of grout and U-loop pipe samples (from Brookhaven National Laboratory).

and has high thermal conductivity (1.4 BTU/hr ft °F). The bond between the grout and borehole can be compromised by dessication of the geologic materials near the borehole, as the heat from the borehole lowers the moisture content of the geologic materials and these materials contract. In areas with thick unsaturated zones, the bentonite grout may dry out over time, compromising the seal.

To improve heat exchange, some advocate the use of spacers which moves the heat conductor pipe to the side of the borehole, putting it in contact with the geologic materials. However, the use of spacers appears to increase the environmental risk of antifreeze leaking into groundwater, by reducing or removing the bentonite between the heat conductor pipe and geologic materials.

The risk of groundwater contamination is primarily controlled by the low hydraulic conductivity of the grout. Thus, grouts must be mixed and placed according to manufacturer's specifications and those procedures defined by industry groups such as the International Ground Source Heat Pump Association, Electric Power Research Institute (EPRI and NRECA, 1997), and the National Ground Water Association (McCray, 1997).

Antifreeze & Grout Compatibility

The hydraulic conductivity of bentonite grouts can be altered by changes in the pore fluid, especially some of the fluids used as antifreeze. Salt solutions such as calcium chloride and magnesium chloride solutions, at concentrations used for antifreeze applications, can increase the hydraulic conductivity of bentonite by approximately three orders of magnitude (Jo et al., 2001). Pure organic liquids such as ethanol and heptane also can increase the hydraulic conductivity of bentonite and other clays by two to three orders of magnitude (Anandarajah, 2003). Mixtures of ethanol and water, up to 60% ethanol solutions, were found to decrease the hydraulic conductivity of bentonite while 100% ethanol solutions (pure ethanol) increased the hydraulic conductivity of bentonite by more than two orders of magnitude (Petrov et al., 1999). The causes of this behavior involve differences in fluid viscosity and clay mineralogy, which are beyond the scope of this report. In summary, some antifreeze solutions, if leaked from piping, will alter the hydraulic conductivity of bentonite grouts which are designed to contain any leakage. Additional research is needed for some antifreeze solutions, such as CMA and propylene glycol, because data for their potential to alter the hydraulic conductivity of bentonite grouts is not known.

SUMMARY

USEPA (1997) concluded that, despite potential environmental problems, geothermal heat pumps pose little if any serious environmental risk when best management practices are applied during the installation, operation, and decommissioning of these systems. Grout selection and installation is a vital step in protecting groundwater quality or minimizing the environmental effects of geothermal heat pumps, especially those from vertical boreholes. Neat cement grouts crack and lose hydraulic integrity when exposed to thermal stresses and should not be used for grouting geothermal wells. Bentonite grouts appear to be an acceptable alternative to neat cement grouts. Thermally enhanced grouts appear to be a better option than spacers for improving the thermal connection between the borehole and geologic materials. Spacers reduce the amount of grout between the heat conductor pipe and groundwater, thus they appear to pose a higher risk for groundwater contamination. Finally, additional research is needed on the topic of compatibility of antifreeze solutions and bentonite grouts.

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USGAO, 1994. Geothermal energy: outlook limited for some uses but promising for geothermal heat pumps, U.S. General Accounting Office RECD-94-84.

SOURCES OF ADDITIONAL INFORMATION

Brookhaven National Lab– developers of grout "Mix 111", www.bnl.gov/est/ghp111.htm

Electric Power Research Institute– www.epri.com, EPRI and the National Rural Electric Cooperative Association produced several reports on cement and bentonite grouting in 1997 and 1998. Some of this material also has been released through the International Ground Source Heat Pump Association.

Geo-Heat Center– http://geoheat.oit.edu/ This site has a focus on western U.S geothermal issues.

Geothermal Heat Pump Consortium– www.ghpc.org/home.htm

International Ground Source Heat Pump Association– www.igshpa.okstate.edu

National Ground Water Association, Geothermal Energy Interest Group– www.ngwa.org

U.S. Department of Energy (USDOE)– www.eere.energy.gov/geothermal

U.S. Environmental Protection Agency, Energy Star program–
http://134.67.99.43/Estar/consumers.nsf/content/ghp.htm

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APPENDIX: Illinois Water Well Construction Code/ Closed-Loop Wells

SECTION 920.180 CLOSED-LOOP WELLS
Construction. Each closed-loop well shall be grouted as required in Section 920.90(h). Closed-loop wells shall not be located closer than 200 feet from a water well, except when the well is a private water system well and when the owner is the same for both the water well and the closed-loop well, in which case the water well shall not be closer than 75 feet from the closed-loop well.

Piping Pressure. The liquid in the closed-loop piping shall be maintained under pressure. The equipment shall be designed to shut down if there is any pressure loss in the system. The system must be pressure tested at a minimum pressure of 20 pounds per square inch by the installer after installation to ensure that there are no leaks in the piping or in the equipment system.

Coolant. The solution used as coolant or the liquid which is pumped through the closed-loop well piping must be methanol, ethanol, propylene glycol, calcium chloride or ethylene glycol. These chemicals may be used only in concentrations of 20% or less. When copper piping is utilized, the coolant shall be hydrochlorofluorocarbon-22, or any equivalent refrigerant with less ozone depletion potential.

Piping. All plastic piping shall be watertight and shall conform to ASTM D2666-89, D2447-89, D3035-91. All copper piping system and joints shall be watertight and conform to UL 1995. All joints in plastic piping shall be heat fusion welded.

Abandonment. All vertical piping in closed-loop wells which is abandoned shall be physically disconnected from the horizontal piping and sealed with neat cement grout or any bentonite product manufactured for water well sealing by pressure grouting. All horizontal piping which is abandoned shall be removed or the coolant must be drained from the piping and disposed of off-site in accordance with State and local laws.

Horizontal Piping Distances to Water Wells. Horizontal piping in a closed-looped system shall not be closer than 25 feet to any water well.

Distances to Sources of Contamination. Closed-loop wells shall not be closer to the sources of contamination listed in Section 920.50(b)(1) than the distances to water wells specified in this Section.

(Source: Amended at 22 Ill. Reg. 3973, effective April 1, 1998)