Geology and Drilling Methods for Ground-Source Heat Pump System Installations: An Introduction for Engineers

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PREFACE

This document attempts to establish the following key points:

1. Ground-source heat pump systems are increasingly deployed for commercial heating, ventilating, and air-conditioning (HVAC) systems in offices, schools, health care facilities, stores, and factories. Low operating and maintenance costs mean that these systems generally have attractive life-cycle costs. First costs may be higher where the local design and installation infrastructure are poorly developed.

2. Design and installation of ground-source and groundwater-source heat pumps are straightforward engineering exercises. This manual is intended to help the designer understand the driller's tools, techniques, and the ground they penetrate. It includes an introduction to geology, hydrogeology, soil development, and other conditions that impact the feasibility and economics of ground-source heat pump system installation.

3. The first design step is *site characterization* (Chapters 3, 8, and 9). Adequate geological and hydrological resources are easily obtained and mastered.

4. Drilling is a simple but sophisticated technology suite (Chapter 4). Understanding the needs and knowledge of the driller will help the design engineer get the best heat exchanger for the site. Most drills use a rotary action to displace material by scraping, cutting, or crushing; some use percussion or vibration instead. Chips (cuttings) are removed and the drill is cooled by air with foam or by water with additives such as clay.

5. *Vertical closed loop* (Chapter 5) systems are more common today than groundwater heat pump (GWHP) systems. Closed-loop systems use ground loops (also called *borehole heat exchangers (BHEx)*) to exchange heat between the building and the earth. The individual heat exchange loop is typically 150-300 ft (45-90 m) deep. The hole is usually 4-6 in. (10-15 cm) in diameter. After drilling, a prefabricated *U-bend* of high density polyethylene pipe is pushed to the bottom of the hole. A *tremie* (pipe) is used to pump backfill (generally grout or cement) into the borehole, filling the hole from bottom to top. The grout aids heat transfer between the system and the ground and protects groundwater from possible contamination from surface fluids. A single borehole heat exchanger (BHEx) is typically rated at 6,000-24,000 Btuh (1.8-7.0 kW) peak heat exchange. The cost of the heat exchanger is usually about $1000 ± $300 per ton ($1750 ± $425 per kW) of exchange capacity. The land over the heat exchanger remains available for other uses.

6. *The horizontal ground-coupled heat pump system,* installed in trenches or pits, is one common closed-loop variant. They are usually restricted to small buildings, such as houses, because the heat exchange capability is limited to about 20 ton/acre (175 kW/hectare). Another variation, the *surface water heat pump system (pond loop),* may have higher heat exchange capability. In these systems, coils of copper or HDPE pipe are installed in a pond or lake for heat exchange. "Pond" systems may cost as little as $600/ton ($1000/kW), including the cost of excavating the pond.

7. *Groundwater* systems[1] (Chapter 6) usually comprise one or more *production wells* and their pumps;

1. Commonly called "open loop" systems, sometimes called "pump and dump," particularly when the water that has passed through the system is rejected to the surface instead of being injected back into the aquifer.

a *plate-frame heat exchanger* to isolate the ground water from building water; an interior circulating loop that carries heat exchange fluid to the heat pumps; and a disposal system, which may use storm sewers, surface water bodies, or injection wells (Chapter 6). Groundwater systems have been used for decades and are increasingly deployed in larger commercial applications. Where enough groundwater of sufficient quality is available, open-loop systems cost less than closed-loop systems. Systems that are 300 tons (1000 kW) and larger typically cost less than $500/ton ($900/kW), with sizes declining below $175/ton ($300/kW) for a 300 ton (525 kW) systems drawing water from 200 ft (60 m).

8. *Standing column wells* (chapter 6) are a type of open-loop system, notable for injecting water back into the production well.

9. Systems that exchange heat with "raw" water destined for a water treatment plant, treated sewage effluent, or other "targets of opportunity" use design methods similar to those for groundwater systems (Chapter 7).

10. Because ground and groundwater heat exchangers may penetrate aquifers (ground or rock with potable water production potential), drilling is regulated, and care must be taken to protect the resource (Chapters 5-7). Fortunately, this is readily done, and the measures that protect groundwater generally improve thermal performance too.

11. In addition to groundwater-source and ground-source heat pump systems, there are many other "environmental heat exchange" systems that warrant consideration (Chapter 7). Comprehensive site characterization can include such opportunities as surface water, "raw" water, and treated sewage.

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This paper is dedicated to all the loopers, designers, and self-described “geo-junkies” who admitted me to their number and shared their hard-won wisdom with me.

Part 1: Geology, Hydrology, and Site Characterization

Chapter 1
INTRODUCTION

Ground-source and related heat pump systems[1] are increasingly deployed for commercial heating, ventilating, and air-conditioning (HVAC) systems in offices, schools, health care facilities, stores, and factories.[2] Low operating and maintenance costs mean that these systems generally have attractive life-cycle costs. A recent study found an average return on investment (ROI[3]) of 19%—after excluding the system that cost less than the alternative (and thus had an "infinite" ROI. [ASHRAE 1998, p. viii]). Ground-source systems today may cost \$2/ft^2 (\$21/m^2) more than conventional systems where the systems are not well known. However, in areas with competitive infrastructure and experienced designers, GSHP systems often cost less than systems offering comparable amenity (in terms of ventilation, occupant control, and flexibility).

Designers are sometimes concerned that the installed costs of ground-source systems have varied greatly. ASHRAE (1998) reports on nine cases, with HVAC costs that ranged from \$2.65/ft^2 to \$16.35/ft^2 (\$8.70/m—\$53.50/m),[4] a six-fold difference. In the same study, the conventional systems used as benchmarks had slightly greater capital cost variability. The lesson is simple: Good engineers can design outstanding systems that are economical to install and operate. Poorly designed systems often will cost more because of the tendency to compensate for inexperience with lots of redundancy and superfluous features. For GSHP systems, these features may include overly elaborate energy management systems, borehole heat exchangers that are too large, or clumsy handling of ventilation air. As Kavanaugh and Rafferty state: "It is not hard to put together a GSHP system for \$15/ft^2 (\$160/m^2), but only the best can build a problem-free system for \$10/ft^2 (\$110/m^2) (Kavanaugh and Rafferty 1997, preface). Clearly, prices for HVAC systems vary with time, location, and contract type, so the absolute values are less important than the point that good design leads to value for the client.

Design and installation of ground-source heat pumps are engineering exercises (see ASHRAE 1995, Kavanaugh and Rafferty 1997, and IGSHPA 1998 for basic design information). Design of ground-source heat pump systems for commercial buildings differs slightly from that of traditional heating, ventilating, and air-conditioning (HVAC) equipment. In contrast to the central chillers and boilers of most conventional systems, GSHP systems typically employ unitary heat pumps distributed throughout the building like water loop heat

1. For basic terminology, see the *1999 ASHRAE Handbook—HVAC Applications*, Chapter 31, "Geothermal Energy." According to the Handbook, "ground-source heat pump" is the generic term, including ground-coupled (GCHP), groundwater (GWHP), and surface water (SWHP) systems. They are also called "geothermal heat pumps" and "GeoExchange Systems (GX)." This paper also mentions closely related variants that use treated sewage and other media.
2. The web sites of the Geothermal Heat Pump Consortium, Washington, D.C., <www.ghpc.org>, and the International Ground Source Heat Pump Association, Stillwater, Okla., <www.igshpa.okstate.edu>, often have useful case studies and other reference material; <www.ghpc.org> has a list of commercial installations in its members-only area. Designers also may wish to review the Federal Energy Management Program web site, http://www.eren.doe.gov/femp/. A guide specification is located at <http://www.eren.doe.gov/femp/financing/specs.html>. The GeoHeat Center of the Oregon Institute of Technology <http://geoheat.oit.edu/> is a valuable resource, particularly the suggestions in the newsletter, *Outside the Loop*, available at <http://geoheat.oit.edu/otl/index.htm>.
3. "The Return on Investment (ROI) is that internal rate of return which would prevail if the present worth of the energy savings over the life of the investment just equaled the initial investment." (ASHRAE 1998, p. viii)
4. Throughout this book, conversions from inch-pound to metric are rounded to the precision implied by the inch-pound units.

pump systems. Although this simplifies many aspects of design relative to variable air volume (VAV) and other systems, it requires the engineer to specify the ground-source portion of the system. Chapters 5 through 7 discuss various types of ground heat exchangers. For commercial structures, almost all systems are GWHP, GCHP, or SWHP installations.[5]

The ability to exchange heat with the ground depends on local geology. Thus, Chapter 2 provides an introduction to geology, hydrogeology, soil development, and other conditions that impact the feasibility and economics of borehole heat exchanger (BHEx) and open-loop system installation. This is the basis for discussing a unique design step for ground-coupled systems, *site characterization* (Chapter 3). This is the systematic effort to evaluate heat exchange options by feasibility, first cost, and implications for life-cycle cost. Site characterization starts with calculating building loads and annual energy needs. The designer then quickly reviews the location for unconventional opportunities such as large, nearby waste water or raw water streams. He or she then compares open-loop, pond loop, and ground-source alternatives, using readily available local geological and hydrogeological information. The third step is testing the hypotheses with a water well (open-loop), geotechnical evaluation (pond loop, horizontal closed loop), or test boring(s) with thermal conductivity test(s) for closed-loop vertical.

Trade allies can help with site characterization. Allies include local drillers and "loopers" (contractors who both drill the boreholes and install closed-loop borehole heat exchangers), manufacturers' representatives, and local ground and groundwater experts. Because drilling is novel to many designers, Chapter 4 attempts to help the designer understand the driller's tools and techniques.

Where are ground-source systems (in the broad sense of the term) applicable?

- The prototypical approach, the *ground-coupled heat pump system,* can be installed anywhere that drilling conditions (technical and regulatory) allow.
- *Groundwater heat pump systems* work where there is enough groundwater. A subset, *standing column well systems,* is applicable where the local rock is competent.[6] Standing column wells are generally installed where groundwater quality is excellent but wells do not produce large volumes of water.
- *Allied "opportunistic" systems* have been used with success where other heat sinks are available. These include treated sewage, "raw" water en route from well to treatment plant, and other solutions.

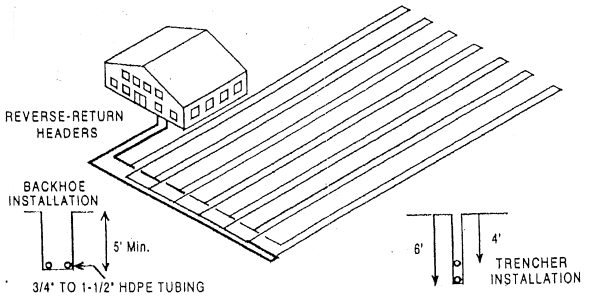


Figure 1-1 Horizontal ground-coupled heat pump, GCHP, or closed-loop system (Kavanaugh and Rafferty 1997).

The most common approaches can be divided into closed loop and open loop. Both types scale down well to small sizes. At small and intermediate sizes, closed-loop systems may require less maintenance. Where suitable groundwater is available and accessible, open-loop systems may be more efficient, because the seasonal variation of heat exchanger water temperature is small. At the largest sizes, open-loop systems will be less expensive where a suitable water supply can be developed.

- *Horizontal ground-coupled (closed-loop) systems* (Figure 1-1) are common for residential applications. Because they are installed with back hoes and similar equipment, installation is inexpensive where soil depths are adequate (about 2 m, or 6 ft). Heat exchange is limited to about 175 kW/hectare (20 tons/acre). Although most systems are < 35 kW (10 tons), a horizontal heat exchanger that approaches 1000 kW (300 ton) has been installed for a heating-dominated school in Wolfsburg, Nova Scotia.[7] Cost

5. All of these categories exchange heat between water and the heat pump refrigerant; they differ in the source of the water. A third category, now emerging, is more common in residential and light commercial applications. These are *direct GeoExchange systems,* rated under ARI 870. They use copper tubes buried in the ground to carry refrigerant for heat exchange.

6. *Competent* means strong enough that the walls will not collapse, even without casing. In competent rocks, the entire column (in a single aquifer) can exchange groundwater with the surrounding rocks.

7. The economics were particularly favorable for three reasons: (1) A great deal of earth moving was required to recontour the site, establish ball fields, etc., so the incremental effort to scrape below finished grade, install the heat exchanger, and then backfill was small. (2) As a school installation, enough land was available. The location is not expected to show the high cooling loads of many U.S. applications.

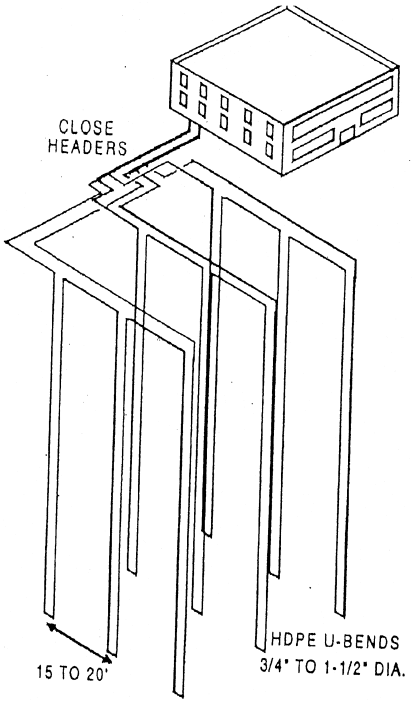


Figure 1-2 Vertical ground-coupled heat pump (GCHP) or closed-loop system (Kavanaugh and Rafferty 1997).

is roughly proportional to size, although very large systems can be quite inexpensive if done in conjunction with site grading.

- *Vertical ground-coupled (closed-loop) systems* (Figure 1-2) are very common for residential systems and commercial systems up to about 3500 kW (1000 tons). The largest systems in the U.S. may be the roughly 5600 kW (1600 ton) system at Richard Stockton College, N.J. and the Birdville High School, Fort Worth, Tex. (1250 boreholes, each 300 ft [90 m] deep). Above a minimum size corresponding to a small installation with relatively high mobilization costs, the price is roughly proportional to size.
- *Surface-water (closed-loop) systems* (Figure 1-3) are increasingly popular. Installation costs may be low, down to $600/ton ($170/kW) including the pond construction, and many clients find that the ponds themselves have esthetic value in suburban settings. Some pond systems are built as part of storm water management systems.
- *Groundwater (open-loop) systems* (Figure 1-4) with separate supply and rejection wells or other disposal are generally integrated with the potable water supply in residential and light commercial

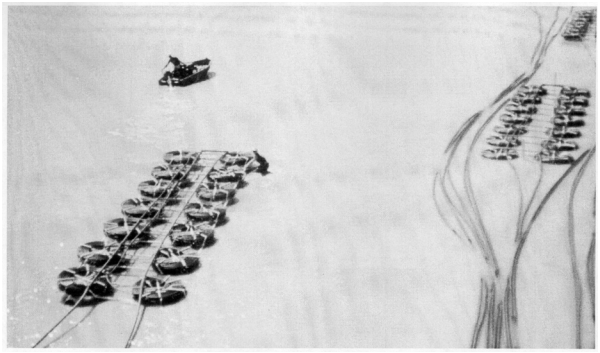


Figure 1-3 Surface-water heat pump (SWHP), or pond loop. Installation at Great River Medical Center, West Burlington, Iowa. (Pictures by Steve White, 1998, Performance Pipe, a division of Chevron Phillips Chemical Company.)

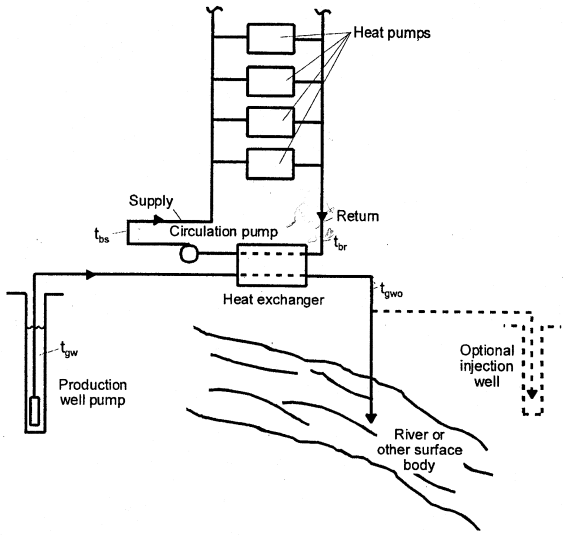


Figure 1-4 Open-loop heat pump system, showing production well and disposal system (Kavanaugh and Rafferty 1997).

sizes, making cost allocation arbitrary. Where sufficient quantity of water is available and the regulatory structure is conducive to it, larger systems often cost much less than other alternatives. The largest U.S. system is probably the Galt House East, Louisville, Ky., at about 14,000 kW (4000 tons). Its designer estimates that the system costs about $140/kW ($500/ton) *less* than alternative HVAC systems that would provide the same amenity.[8]

- *Standing column well systems* (Figure 1-5), open-loop systems that return water to the supply well, are cost-effective for small to moderately sized

8. M. Pinckley, personal communication.

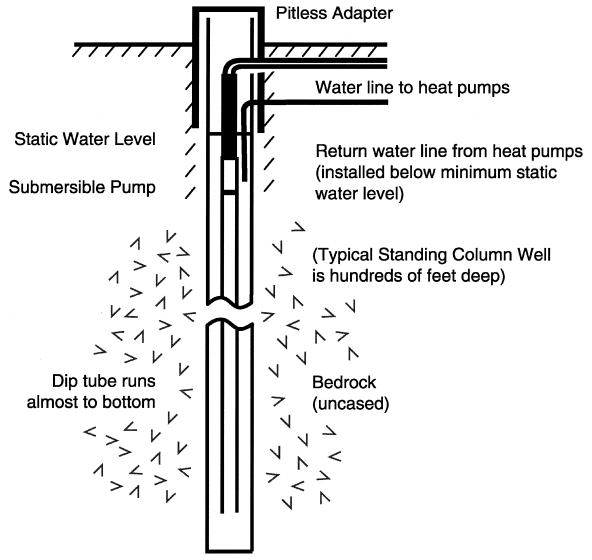


Figure 1-5 Schematic of standing column well.

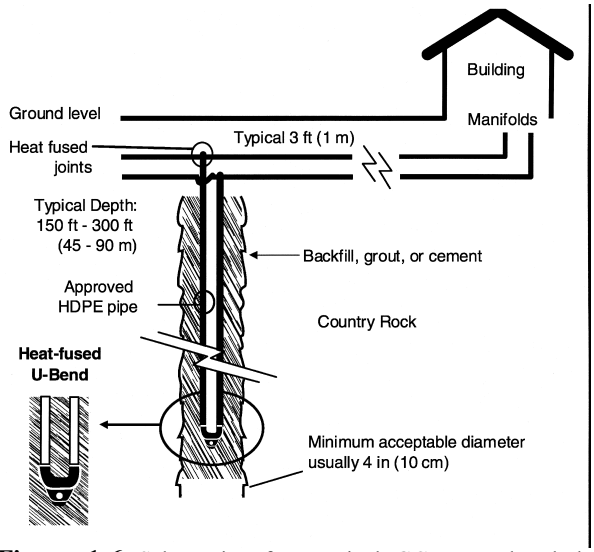


Figure 1-6 Schematic of a vertical GCHP, or borehole heat exchanger, from GHPC.

installations (up to several hundred kW, or 100-200 tons). They are favored where there is competent rock (typically igneous or high-grade metamorphics), poorly producing aquifers, and excellent water quality. They are generally used where the aquifer does not support high production rates; separate supply and return wells are conventionally used where production is higher.

Closed-Loop Systems and Variants

Vertical closed-loop systems (Chapter 5) may be more common today than GWHPs. Most closed-loop systems use borehole heat exchangers (BHEx) to swap heat between the building and the earth. The individual BHEx (Figure 1-6) is typically 45 m to 90 m (150 ft to 300 ft) deep. The hole is usually 10 cm to 15 cm (4 in. to 6 in.) in diameter. After drilling, a prefabricated U-bend of high-density polyethylene pipe (HDPE; IGSHPA 1997, Appendix C) is generally pushed to the bottom of the hole with a tremie (Figure 1-7). The tremie is a pipe used to pump backfill (generally grout or cement) into the borehole, filling the hole from bottom to top. Grout protects groundwater from contamination by surface fluids. Thermally enhanced grout also enhances heat transfer between the system and the ground. A single BHEx is typically rated at a peak capacity of 6,000 to 24,000 Btuh (1.7 to 7 kW) of heat exchange. The cost of the heat exchanger is usually about $1000 ± $300 per ton ($280 ± $85/kW) of exchange capacity. The land over the heat exchanger remains available for other uses.

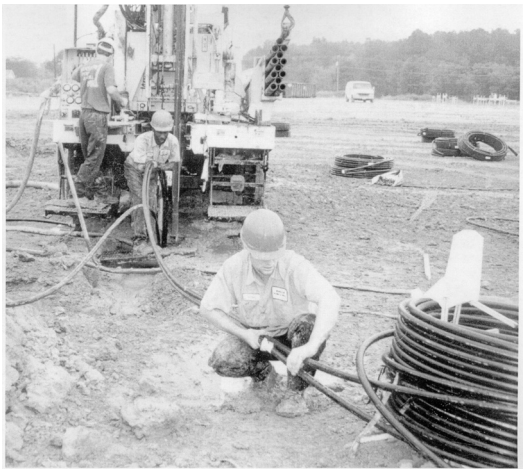


Figure 1-7 Photograph of conventional insertion of U-bend heat exchanger in vertical heat exchange borehole. Note that the two heat exchanger legs are accompanied by the tremie used to inject grout. (Photo by Winslow Pump and Well, Hollywood, Md.)

One common closed-loop variant is the horizontal field (Figure 1-1), installed in trenches or pits. These are usually restricted to small buildings, such as houses, because the heat exchange capability is limited to about 175 kW/hectare (20 tons/acre). Another variation, the surface-water heat pump system[9] (Figure 1-3), has higher heat exchange capability. In these systems, coils of HDPE pipe are installed in a pond or lake for heat

9. Colloquially referred to as a *pond loop.*

exchange. Installations with 80 tons of heat exchange per acre of pond (700 kW/hectare) have been reported.[10] Pond loop systems may cost as little as $600/ton ($170/kW), including the cost of excavating the pond.

For commercial-scale buildings, the most important closed-loop variant may be the hybrid system (Figure 1-8). Because cooling loads generally exceed heating loads in larger buildings, and because ground heat exchangers are more expensive as heat rejectors than closed-circuit fluid coolers, designers often combine a ground loop sized to the heating load (heat extracted) with a fluid cooler sized to the difference between heat extracted and heat rejected[11] (Kavanaugh and Rafferty 1997, Chapter 4, p. 49).

Open-Loop Systems and Variants

Open-loop systems (Chapter 6) usually comprise one or more production wells and their pumps; a plate-frame heat exchanger to isolate the groundwater and prevent its contamination; an interior circulating loop that carries heat exchange fluid to the heat pumps; and a disposal system, which may use surface waters, storm sewers, or injection wells (Kavanaugh and Rafferty, 1997, Chapter 6). Groundwater systems are increasingly deployed in larger commercial applications (ASHRAE 1998). Where enough groundwater of sufficient quality is available, open-loop systems cost less than closed-loop systems. Systems 300 ton and larger typically cost less than $500/ton ($140/kW), with sizes declining toward $250/ton ($70/kW) for large systems with relatively shallow (200 ft, 60 m) pumping requirements (Rafferty 1994).

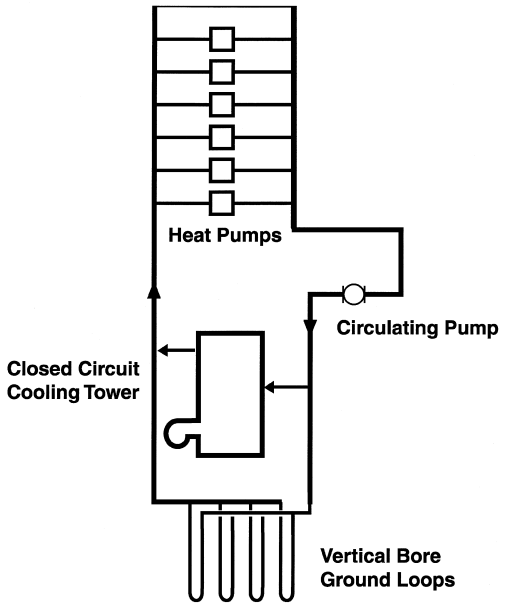


Figure 1-8 Schematic of hybrid GCHP (closed-loop) heat pump system (Rafferty 1995).

Standing column wells are a variety of open-loop heat exchanger, notable for injecting water back into the production well. These systems inject water to the same well from which it was withdrawn. In a typical installation, water is carried from near the bottom of a deep well to a submersible pump below the standing water level. From there it is pumped to the building. The water is returned to the groundwater through a return pipe that terminates below the standing water level, ensuring that the water never "sees" air. Heat exchange with the water descending to the intake is high. To increase capacity, most systems are designed to "bleed" some water, typically 10%-15%, to avoid heating or cooling the water supply too much. The concept is that the inflowing groundwater carries heat much more quickly than conduction through the ground. These systems are most common in New England, but they are expected to spread to other areas where competent rock and good water quality supports their installation.

Water well drilling for service water or open-loop systems is different from closed-loop BHEx installation. For the former, drilling is the first step of a systematic procedure with well-documented consensus standards and regulations (NGWA 1998). Drilling is followed by completion, testing, and pump installation. Drilling and completing a water well take days to months, depending on diameter, depth, and geology. In contrast, the key to BHEx installations is speed. The looper aims for several (5 to 8) completed borehole heat exchangers per day. Although state regulations for BHEx vary, the National Ground Water Association has published an important set of consensus recommendations (NGWA 1998).

Systems that exchange heat with "raw" water destined for a water treatment plant, treated sewage effluent, or other "targets of opportunity" are considered as open-loop installations in this paper, as they are modest extensions of ground-source system designs (Chapter 7).

Trade Responsibilities

The GSHP heat exchanger is part of the mechanical system, generally stamped by the HVAC designer. In

10. Dooley, 1999, personal communication.
11. Note that the loads seen by the ground differ from the building block loads. First, the heat of compression adds to the load in cooling mode but offsets heating load. Second, the monthly or annual heat extracted or rejected is more important to the ground heat exchanger than the peak hourly loads.

most cases, the heat exchanger requires one new trade, to drill the boreholes or install the wells (Chapter 4). Open-loop supply wells are water wells. Injection wells are specialized water wells, constructed under different regulations. Drillers have standard contract forms for them. Closed-loop systems differ, because the installing contractor generally takes responsibility for trenching (for manifolds or headers), drilling, installing the heat exchange U-bends, backfilling, assembling the manifolds, repeated pressure testing, and flushing the system to remove air and debris. Often, the ground heat exchange installer contracts directly with the general contractor or the owner, rather than working as a subcontractor to the mechanical contractor. This requires the design engineer to draw up specifications that precisely delineate the responsibilities of each party. Generally, these specifications center on manifolding in the mechanical room and the responsibility for flushing, purging, and antifreeze (if required).

To aid designers of large systems, particularly for federal government installations, the Oak Ridge National Laboratory has prepared a set of guide specifications in the very detailed CSI format.[12] Some designers will simplify and adapt these for commercial jobs. In the meantime, Appendix B gives sources for specifications for pieces of closed- and open-loop systems.

12. Under "financing" at the FEMP web site http://www.eren.doe.gov/femp/financing/specs.html.

Goals of This Primer

We hope that this primer will help you understand the unique element of the GSHP system—the connection to the environment. This connection replaces the boiler and cooling tower of the conventional water-source heat pump system. Efficient design and capable installation of this heat exchange system, whether ground-coupled, groundwater, or other, is the key to a successful ground-source design practice.

This primer attempts to help the designer see the world through the driller's and looper's eyes, so the practical engineer will understand the driller's tools, techniques, and the ground they penetrate. This requires some background information about geology, hydrogeology, soil development, and other conditions that impact the feasibility and economics of GSHP installation (Chapter 2). Although this primer can provide some basic background to understand systems, for actual design the engineer should consult the available textbooks (ASHRAE 1995; Kavanaugh and Rafferty 1997). They treat design from the engineer's perspective, offering key information on borehole sizing and spacing and on design methods to avoid long-term thermal changes induced by unbalanced heating and cooling loads.