CHAPTER 34

GEOTHERMAL ENERGY

THE use of geothermal resources can be subdivided into three general categories: high-temperature (>300°F) electric power production, intermediate- and low-temperature (<300°F) direct-use applications~~, and ground-source heat pump applications (generally <90°F)~~. This chapter covers only direct use (including wells, equipment, and applications) ~~and ground-source heat pumps. Design aspects of the building heat pump loop may be found in Chapter 9~~ of ~~the 2012 *ASHRAE Handbook—HVAC Systems and Equipment*.~~

1. RESOURCES

Geothermal energy is the thermal energy in the earth's crust: thermal energy in rock and fluid (water, steam, or water containing large amounts of dissolved solids) that fills the pores and fractures in the rock, sand, and gravel. Calculations show that the earth, originating from a completely molten state, would have cooled and become completely solid many thousands of years ago without an energy input beyond that of the sun. It is believed that the ultimate source of geothermal energy is radioactive decay within the earth (Bullard 1973).

Through plate motion and vulcanism, some of this energy is concentrated at high temperature near the surface of the earth. Energy is also transferred from deeper parts of the crust to the earth's surface by conduction and by convection in regions where geological conditions and the presence of water allow.

Because of variation in volcanic activity, radioactive decay, rock conductivities, and fluid circulation, different regions have different heat flows (through the crust to the surface), as well as different temperatures at a particular depth. The normal increase of temperature with depth (i.e., the normal geothermal gradient) is about 13.7°F per 1000 ft of depth, with gradients of 5 to 27°F per 1000 ft being common. Areas that have higher temperature gradients and/or higher-than-average heat flow rates constitute the most interesting and viable economic resources. However, areas with normal gradients may be valuable resources if certain geological features are present.

Geothermal resources of the United States are categorized into the following types:

Igneous point resources are associated with magma bodies, which result from volcanic activity. These bodies heat the surrounding and overlying rock by conduction and convection, as allowed by the rock permeability and fluid content in the rock pores.

Hydrothermal convection systems are hot fluids near the earth's surface that result from deep circulation of water in areas of high regional heat flow. A widely used resource, these fluids rise from natural convection between hotter, deeper formations and cooler formations near the surface. The passageway that provides for this deep convection must consist of adequately permeable fractures and faults.

Geopressured resources, present wid ely in the Gulf Coast of the United States, consist of regional occurrences of confined hot water in deep sedimentary strata, where pressures of greater than 10,000 psi are common. This resource also contains methane, which is dissolved in the geothermal fluid.

Radiogenic heat sources exist in various regions as granitic plutonic rocks that are relatively rich in uranium and thorium. These plutons have a higher heat flow than the surrounding rock; if the plutons are blanketed by sediments of low thermal conductivity, an elevated temperature at the base of the sedimentary section can result. This resource has been identified in the eastern United States.

Deep regional aquifers of commercial value can occur in deep sedimentary basins, even in areas of only normal temperature gradient. For deep aquifers to be of commercial value, (1) basins must be deep enough to provide usable temperature levels at the prevailing gradient, and (2) permeability in the aquifer must be adequate for flow.

Thermal energy in geothermal resources exists primarily in the rocks and only secondarily in the fluids that fill the pores and fractures. Thermal energy is usually extracted by bringing to the surface the hot water or steam that occurs naturally in the open spaces in the rock. Where rock permeability is low, the energy extraction rate is low. In permeable aquifers, fluid produced may be injected back into the aquifer at some distance from the production well to pass through the aquifer again and recover some of the energy in the rock. Figure 1 indicates geothermal resource areas in the United States.

Temperature

The temperature of fluids produced in the earth's crust and used for their thermal energy content varies from below ~~40°F~~ 60 to 680°F. As indicated in Figure 1, local gradients also vary with geologic conditions. The lower value represents fluids used as the low-temperature energy source and sink for heat pumps, and the higher temperature represents an approximate value for the HGP-A well at Hilo, Hawaii.

The following classification by temperature is used in the geothermal industry:

High temperature	$t > 300°F$
Intermediate temperature	$195°F < t < 300°F$
Low temperature	60°F < 195°F

Electric generation is generally not economical for resources with temperatures below about 300°F, which is the reason for the division between high- and intermediate-temperature. However, binary (organic Rankine cycle) power plants, with the proper set of circumstances, have demonstrated that it is possible to generate electricity economically above 230°F. In 1988, there were 86 binary plants worldwide, generating a total of 126.3 MW (Di Pippo 1988).

The preparation of this chapter is assigned to TC 6.8, Geothermal Energy Utilization.

1.2 PRESENT USE

Discoveries of concentrated radiogenic heat sources and deep regional aquifers in areas of near-normal temperature gradient indicate that 37 states in the United States have economically exploitable direct-use geothermal resources (Interagency Geothermal Coordinating Council 1980). The Geysers, in northern California, is the largest single geothermal development in the world. The U.S. Department of Energy created a database of geothermal system data (including ground resource data) for practitioners to share data about installations (NGDS 2014).

The total electricity generated by geothermal development in the world was 7974 MW in 2000 (Lund et al. 2001). Direct application of geothermal energy for space heating and cooling, water heating, agricultural growth-related heating, and industrial processing represented about 51.6×10^9 Btu/h worldwide in 2000. In the United States in 2000, direct-use installed capacity amounted to 12.9×10^9 Btu/h, providing 19.3×10^{12} Btu/yr.

The major uses of geothermal energy in the United States are for heating greenhouse and aquaculture facilities. The principal industrial use is for food processing.

1.3 RENEWABILITY

Geothermal energy is a renewable resource (see the section on Nonrenewable and Renewable Energy Sources in Chapter 34 of the 2013 *ASHRAE Handbook—Fundamentals* for discussion). Quantification of the source may be required for renewable portfolio standards, utility programs, etc.; to do this, measure or calculate the electric or thermal energy that is either generated from, or avoided by, use of the geothermal resource.

Geothermal energy ultimately comes from a variety of sources, ~~including earth heat and solar energy~~. Direct-use and higher-temperature geothermal resources may be considered renewable, because the heat removed is replaced by natural processes: heat is generated deep in the earth and transferred to more shallow depths. The geothermal resource must be carefully managed however, and can eventually be depleted if used at too high of a rate.

~~Geothermal heat pumps (GHPs) also use these sources (albeit in a more complex, indirect fashion) for building heating, cooling, and domestic hot water. Because this method of using geothermal energy does require electricity input, quantification of the renewable portion of GHP operation is to be based on the amount of electric and thermal energy that is avoided by use of GHPs. Attempts at quantifying this avoidance have been made (European Union 2013), but more work is needed before a more specific methodology can be published here.~~

2. DIRECT-USE SYSTEMS DESIGN

A major goal in designing direct-use systems is capturing the most possible heat from each gallon of fluid pumped. System owning and operating costs are composed primarily of well pumping and well capitalization components; maximizing system Δt (i.e., minimizing flow requirements) minimizes well capital cost and pump operating cost. In many cases, system design can benefit from connecting loads in series according to temperature requirements. Direct-use system design is covered in detail in Anderson and Lund (1980) and Rafferty (1989a).

Direct-use systems can be divided into four subsystems: (1) production, including the producing wellbore and associated wellhead equipment; (2) transmission and distribution to transport geothermal energy from the resource site to the user site and then distribute it to the individual user loads; (3) user system; and (4) disposal, which can be either surface disposal or injection back into a formation.

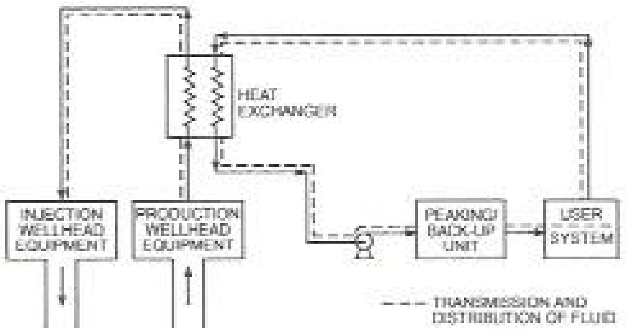


Fig. 3 Geothermal Direct-Use System with Wellhead Heat Exchanger and Injection Disposal

In a typical direct-use system, geothermal fluid is produced from the production borehole by a lineshaft multistage centrifugal pump. When the geothermal fluid reaches the surface, it is delivered to the application site through the transmission and distribution system.

In the system in Figure 3, geothermal fluid is separated from the heating system by a heat exchanger. This secondary loop is especially desirable when the geothermal fluid is particularly corrosive and/or causes scaling. The geothermal fluid is pumped directly back into the ground without loss to the surrounding surface.

2.1 COST FACTORS

The following characteristics influence the cost of energy delivered from geothermal resources:

- Well depth
- Distance between resource location and application site
- Well flow rate
- Resource temperature
- Temperature drop
- Load factor
- Composition of fluid
- Ease of disposal

Many of these characteristics have a major influence because the cost of geothermal systems is primarily front-end capital cost; annual operating cost is relatively low.

Well Depth

The cost of the wells is usually one of the larger items in the overall cost of a geothermal system, and increases with resource depth. Compared to many geothermal areas worldwide, well depth requirements in the western United States are relatively shallow; most larger geothermal systems there operate with production wells of less than 2000 ft, and many at less than 1000 ft.

Distance Between Resource Location and Application Site

Direct use of geothermal energy must occur near the resource. The reason is primarily economic; although geothermal (or secondary) fluid could be transmitted over moderately long distances (greater than 60 miles) without great temperature loss, such transmission is generally not economically feasible. Most existing geothermal projects have transmission distances of less than 1 mile.

Well Flow Rate

Energy output from a production well varies directly with the fluid flow rate. The energy cost at the wellhead varies inversely with the well flow rate. A typical good resource has a production rate of 400 to 800 gpm per production well; however, geothermal direct-use wells have been designed to produce up to 2000 gpm.

Resource Temperature

The available temperature is fixed by the prevailing resource. The temperature can restrict applications. It often requires a reevaluation of accepted application temperatures, which were developed for uses served by conventional fuels for which the application temperature could be selected at any value in a relatively broad range. Most existing direct-use projects use fluids in the 130 to 230°F range.

Temperature Drop

Because well flow is limited, power output from a geothermal well is directly proportional to the temperature drop of the geothermal fluid connected to the system. Consequently, a larger temperature drop reduces operating (pumping) and capital (well and production pump) costs.

Cascading geothermal fluid to uses with lower temperature requirements can help achieve a large temperature difference (Δt). Most geothermal systems are designed for a Δt between 30 and 50°F, although one system was designed for a Δt of 100°F with a 190°F resource temperature.

Load Factor

Defined as the ratio of the average load to the design capacity of the system, the load factor effectively reflects the fraction of time that the initial investment in the system is working. Again, because geothermal cost is primarily initial rather than operating cost, this factor significantly affects a geothermal system's viability. As the load factor increases, so does the economy of using geothermal energy. The two main ways of increasing the load factor are (1) to select applications where it is naturally high, and (2) to use peaking equipment so that the geothermal design load is not the application peak load, but rather a reduced load that occurs over a longer period.

Composition of Fluid

The quality of the produced fluid is site specific and may vary from less than 1000 ppm TDS to heavily brined. Fluid quality influences two aspects of the design: (1) material selection to avoid corrosion and scaling effects, and (2) disposal or ultimate end use of the fluid.

Ease of Disposal

The costs associated with disposal, particularly when injection is involved, can substantially affect development costs. Historically, most geothermal effluent was disposed of on the surface, including discharge to irrigation, rivers, and lakes. This method of disposal is considerably less expensive than constructing injection wells.

Geothermal fluids sometimes contain chemical constituents that make surface disposal problematic. Some of these constituents are listed in Table 1.

Most new, large geothermal systems use injection for disposal to minimize environmental concerns and ensure long-term resource reliability. If injection is chosen, the depth at which the fluid can be injected affects well cost substantially. Many jurisdictions require the fluid be returned to the same or similar aquifers; thus, it may be necessary to bore the injection well to the same depth as the production well. Direct-use injection wells are considered Class V wells under the U.S. Environmental Protection Agency's Underground Injection Control (UIC) program. Water wells, along with terminology relating to the technology, are discussed in the section on Groundwater Heat Pumps. in Chapter XX, Ground Source Heat Pumps

Table 1 Selected Chemical Species Affecting Fluid Disposal

Species	Reason for Control
Hydrogen sulfide (H_2S)	Odor
Boron (B^{3+})	Damage to agricultural crops
Fluoride (F^-)	Level limited in drinking water sources
Radioactive species	Levels limited in air, water, and soil

Source: Lunis (1989).

Direct-Use Water Quality Testing

Low-temperature geothermal fluids commonly contain seven key chemical species that can significantly corrode standard materials of construction (Ellis 1989). These include

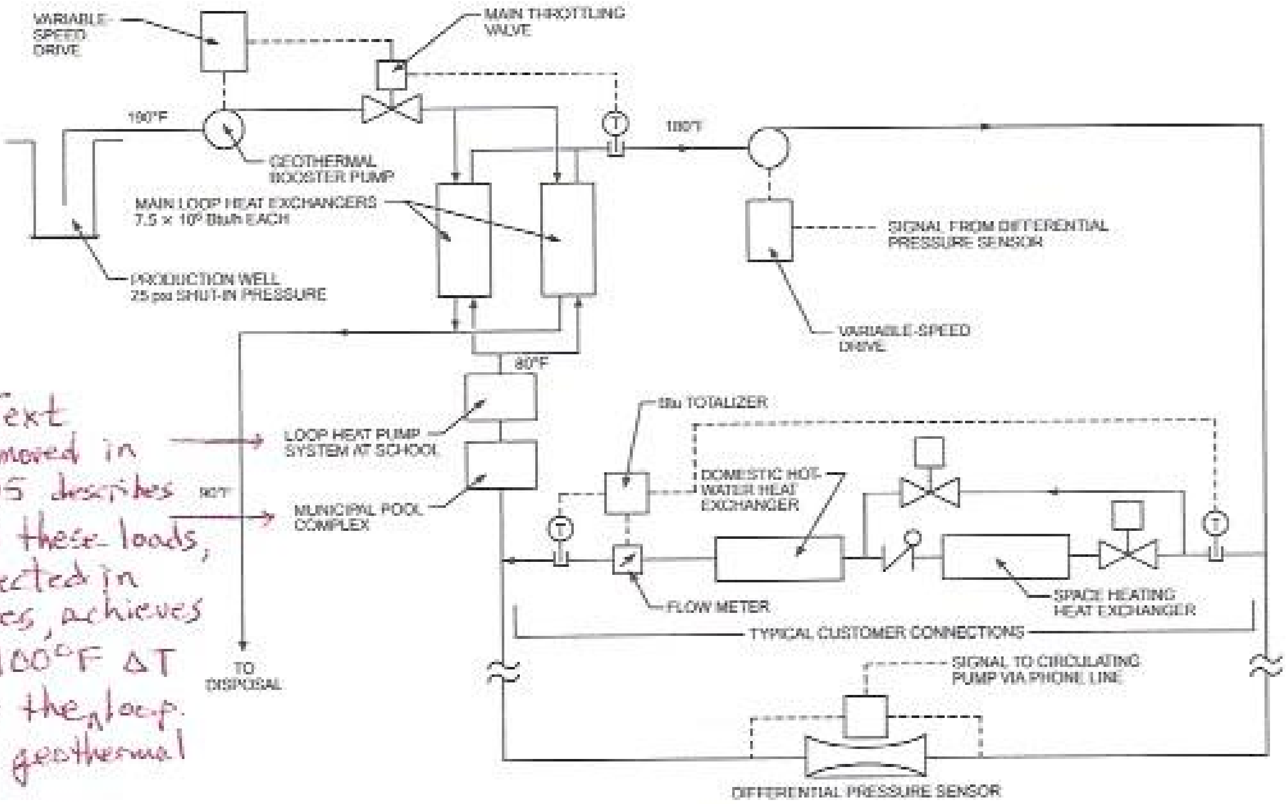
- Oxygen (generally from aeration)
- Hydrogen ion (pH)
- Chloride ion
- Sulfide species
- Carbon dioxide species
- Ammonia species
- Sulfate ion

The principal effects of these species are summarized in Table 2. Except as noted, the described effects are for carbon steel. Kindle

Table 2 Principal Effects of Key Corrosive Species

Species	Principal Effects
Oxygen	• Extremely corrosive to carbon and low-alloy steels; 30 ppb shown to cause fourfold increase in carbon steel corrosion rate. • Concentrations above 50 ppb cause serious pitting. • In conjunction with chloride and high temperature, <100 ppb dissolved oxygen can cause chloride-stress corrosion cracking (chloride-SCC) of some austenitic stainless steels.
Hydrogen ion (pH)	• Primary cathodic reaction of steel corrosion in air-free brine is hydrogen ion reduction. Corrosion rate decreases sharply above pH 8. • Low pH (5) promotes sulfide stress cracking (SSC) of high-strength low-alloy (HSLA) steels and some other alloys coupled to steel. • Acid attack on cements.
Carbon dioxide species (dissolved carbon dioxide, bicarbonate ion, carbonate ion)	• Dissolved carbon dioxide lowers pH, increasing carbon and HSLA steel corrosion. • Dissolved carbon dioxide provides alternative proton reduction pathway, further exacerbating carbon and HSLA steel corrosion. • May exacerbate SSC. • Strong link between total alkalinity and corrosion of steel in low-temperature geothermal wells.
Hydrogen sulfide species (hydrogen sulfide, bisulfide ion, sulfide ion)	• Potent cathodic poison, promoting SSC of HSLA steels and some other alloys coupled to steel. • Highly corrosive to alloys containing both copper and nickel or silver in any proportions.
Ammonia species (ammonia, ammonium ion)	• Causes stress corrosion cracking (SCC) of some copper-based alloys.
Chloride ion	• Strong promoter of localized corrosion of carbon, HSLA, and stainless steel, as well as of other alloys. • Chloride-dependent threshold temperature for pitting and SCC. Different for each alloy. • Little if any effect on SSC. • Steel passivates at high temperature in 6070 ppm chloride solution (pH = 5) with carbon dioxide. 133,500 ppm chloride destroys passivity above 300°F.
Sulfate ion	• Primary effect is corrosion of cements.

Source: Ellis (1989).
Note: Except as indicated, described effects are for carbon steel.



Text removed in 1995 describes how these loads, connected in series, achieves a 100°F ΔT for the loop geothermal

Fig. 7 Closed Geothermal District Heating System
(Rafferty 1989a)

energy demand density, and load factor. For those resources that cannot heat water to the required temperature, preheating is usually possible. Whenever possible, the domestic hot-water load should be placed in series with the space-heating load to reduce system flow rates and increase Δt.

Space Cooling

Geothermal energy has seldom been used for cooling, although emphasis on solar energy and waste heat has created interest in cooling with thermal energy. The absorption cycle is most often used, and lithium bromide/water absorption machines are available in a wide range of capacities. Temperature and flow requirements for absorption chillers run counter to the general design philosophy for geothermal systems: they require high supply water temperatures and a small Δt on the hot-water side. Figure 8 illustrates the effect of reduced supply water temperature on machine performance. The machine is rated at a 240°F input temperature, so derating factors must be applied if the machine is operated below this temperature. For example, operation at a 200°F supply water temperature results in a 50% decrease in capacity, which seriously affects the economics of absorption cooling at a low resource temperature.

Coefficient of performance (COP) is less seriously affected by reduced supply water temperature. The nominal COP of a single-stage machine at 240°F is 0.65 to 0.70; that is, for each ton of cooling output, a heat input of 12,000 Btu/h divided by 0.65, or 18,460 Btu/h, is required.

Most absorption equipment is designed for steam input (an isothermal process) to the generator section. When this equipment is operated from a hot-water source, a relatively small Δt must be used. This creates a mismatch between building flow requirements for space heating and cooling. For example, assume a 200,000 ft² building is to use a geothermal resource for heating and cooling. At 25 Btu/h·ft² and a design Δt of 40°F, the flow requirement for heating is 250 gpm. At 30 Btu/h·ft², a Δt of 15°F, and a COP of 0.65, the flow requirement for cooling is 1230 gpm.

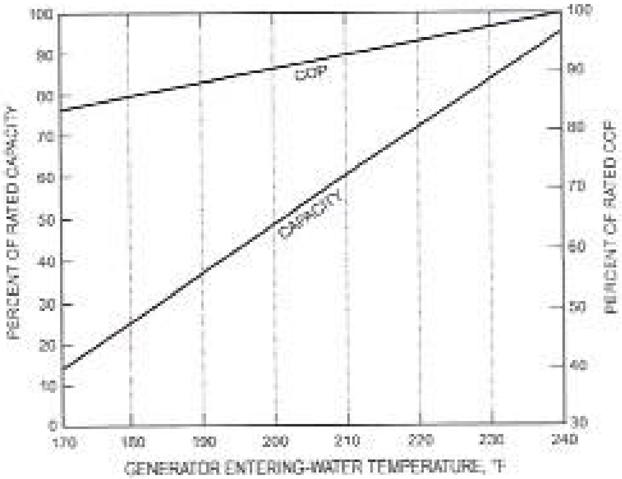


Fig. 8 Typical Lithium Bromide Absorption Chiller Performance Versus Temperature
(Christen 1977)

Some small-capacity (3 to 25 ton) absorption equipment has been optimized for low-temperature operation in conjunction with solar heat. Although this equipment could be applied to geothermal resources, the prospects are questionable. Small absorption equipment generally competes with packaged direct-expansion units in this range; absorption equipment requires a great deal more mechanical auxiliary equipment for a given capacity. The cost of the chilled-water piping, pump, and coil; cooling-water piping, pump, and tower; and hot-water piping raises the capital cost of the absorption equipment substantially. Only in large sizes (>10 tons) and in areas with high electric rates and high cooling requirements (>2000 full-load hours) would this type of equipment offer an attractive investment to the owner (Rafferty 1989a).

2.4 INDUSTRIAL APPLICATIONS

Design philosophy for the use of geothermal energy in industrial applications, including agricultural facilities, is similar to that for space conditioning. However, these applications have the potential for much more economical use of the geothermal resource, primarily because they (1) operate year-round, which gives them greater load factors than possible with space-conditioning applications; (2) do not require extensive (and expensive) distribution to dispersed energy consumers, as is common in district heating; and (3) often require various temperatures and, consequently, may be able to make greater use of a particular resource than space conditioning, which is restricted to a specific temperature. In the United States, the primary non-space-heating applications of direct-use geothermal resources are dehydration (primarily vegetables), gold mining, and aquaculture.

New Chapter starts here

~~3.~~ GROUND-SOURCE HEAT PUMPS

Ground-source heat pumps were originally developed in the residential arena and are now widely applied in the commercial sector. Many of the installation recommendations and design guides appropriate to residential design must be amended for large buildings. Kavanaugh and Rafferty (1997) provide a more complete overview of design of ground-source heat pump systems. Kavanaugh (1991) and OSU (1988a, 1988b) provide a more detailed treatment of the design and installation of ground-source heat pumps, but their focus is primarily residential and light commercial applications. Comprehensive coverage of commercial and institutional design and construction of ground-source heat pump systems is provided in CSA *Standard* C448.

3.1 TERMINOLOGY

The term **ground-source heat pump (GSHP)** is applied to a variety of systems that use the ground, groundwater, or surface water as a heat source and sink. The general terms include **ground-coupled (GCHP), groundwater (GWHP),** and **surface-water (SWHP) heat pumps.** Many parallel terms exist [e.g., **geothermal heat pumps (GHP), geo-exchange,** and **ground-source (GS) systems**] and are used to meet a variety of marketing or institutional needs (Kavanaugh 1992). See Chapter 9 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment* for a discussion of the merits of various other nongeothermal heat sources/sinks.

This chapter focuses primarily on the ground heat exchanger portion of GSHP systems, although the heat pump units used in these systems are unique to GSHP technology as well. GSHP systems typically use extended-range water-source heat pump units, in most cases of water-to-air configuration. Extended-range units are specifically designed for operation at entering water temperatures between 23°F in heating mode and 104°F in cooling mode. Units not meeting the extended-range criteria are not suitable for use in GSHP systems (except for some groundwater heat pump systems). Some applications can include a free-cooling mode when water-loop temperatures fall near or below 55°F. This includes groundwater loops, deep-surface-water loops, and interior core zones of ground-coupled loops when perimeter zones require heating. This is typically accomplished by inserting a water coil in the return air stream before the refrigerant coil.

Ground-Coupled Heat Pump Systems

The GCHP is a subset of the GSHP and is often called a closed-loop heat pump. A GCHP system consists of a reversible vapor compression cycle that is linked to a closed ground heat exchanger (also called a ground loop) buried in soil (Figure 9). The most widely used unit is a water-to-air heat pump, which circulates a water or a water/antifreeze solution through a liquid-to-refrigerant heat exchanger and a buried thermoplastic piping network. Heat pump units often include desuperheater heat exchangers (shown on the left in Figure 9). These devices use hot refrigerant at the compressor outlet to heat water. A second type of GCHP is the direct-expansion (DX) GCHP, which uses a buried copper piping network through which refrigerant is circulated.

The GCHP is further subdivided according to ground heat exchanger design: vertical and horizontal. **Vertical GCHPs** (Figure 10) generally consist of two small-diameter, high-density polyethylene (HDPE) tubes placed in a vertical borehole that is subsequently filled with a solid medium. The tubes are thermally fused at the bottom of the bore to a close return U-bend. Vertical tubes range from 0.75 to 1.5 in. nominal diameter. Bore depths normally range from 50 to 400 ft depending on local drilling conditions and available equipment, but can go to 600 ft or more if procedures for deep boreholes are followed (see the section on Pump and Piping System Options). Boreholes are typically 4 to 6 in. in diameter.

To reduce thermal interference between individual bores, a minimum borehole separation distance of 20 ft is recommended when loops are placed in a grid pattern. This distance may be reduced when bores are placed in a single row, the annual ground load is balanced (i.e., energy released in the ground is approximately equal to the energy extracted on an annual basis), or water movement or evaporation and subsequent recharge mitigates the effect of heat build-up in the loop field.

Advantages of the vertical GCHP are that it (1) requires relatively small plots of ground, (2) is in contact with soil that varies very little in temperature and thermal properties, (3) requires the smallest amount of pipe and pumping energy, and (4) can yield the most efficient GCHP system performance. Disadvantages are (1) typically higher cost because of expensive equipment needed to

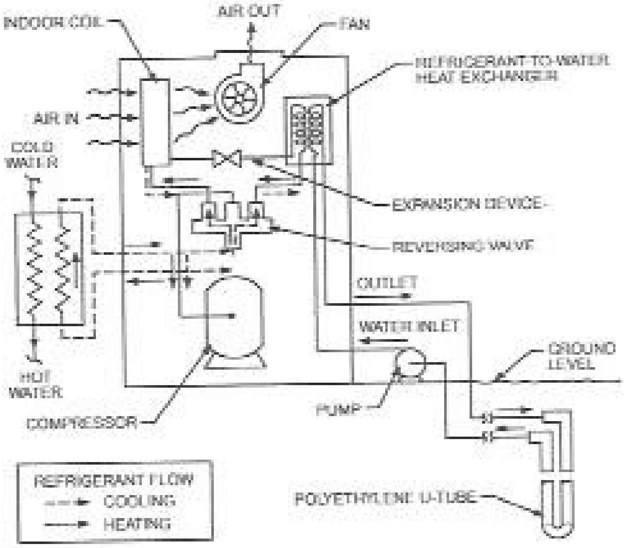


Fig. 9 Vertical Closed-Loop Ground-Coupled Heat Pump System
(Kavanaugh 1985)

separation distance, completion methods, annulus grout/fill, and header arrangements); include subheader circuits (typically 5 to 15 U-tubes on each) with isolation valves to allow air and debris flushing of sections of loop field through a set of full-port purge valves.

9. Determine optimum ground heat exchanger dimensions with Equations (4) and (5) or software; one or more alternatives (depth, number of bores, grout/fill material, etc.) that provide equivalent performance may yield more competitive bids.
10. Iterate to determine optimum operating temperatures, flows, loop field arrangement, depth, bores, grout/fill materials, etc.
11. Lay out interior piping and compute head loss through critical path.
12. Select pumps and control method, determine system efficiency, and consider modifying water distribution system if pump demand exceeds 8% of the system total demand or air distribution system if fan demand exceeds 12% of the system total.

Deliverables from this process that are necessary to adequately describe a GCHP installation include, as a minimum,

- Heat pump specifications at rated conditions
- Pump(s) specifications, expansion tank size, and air separator
- Fluid specifications: system volume, inhibitors, antifreeze concentration (if required), water quality, etc.
- Design operating conditions: entering and leaving ground heat exchanger temperatures, return air temperatures (including wet bulb in cooling), airflow rates, and liquid flow rates
- Pipe header details with ground heat exchanger layout, including pipe diameters, spacing, and clearance from building and utilities
- Bore depth and approximate bore diameter
- Piping material specifications, and visual inspection and pressure testing requirements
- Grout/fill specifications: thermal conductivity and acceptable placement methods to eliminate voids
- Purge provisions and flow requirements to ensure removal of air and debris without reinjecting air when switching to adjacent subheader circuits
- Instructions on connecting to building loop(s) and coordinating building and ground heat exchanger flushing
- If applicable, a drilling report from the thermal properties test borehole that includes the type of equipment used (rig, bit, etc.), drilling fluid (air, foam, drilling mud), depth of hole, description of drilled soil or rock, time needed to drill the borehole, any special conditions encountered.
- Sequence of operation for controls

Thermal Property Testing. In the design of vertical GCHPs, accurate knowledge of soil/rock formation thermal properties is critical. These properties can be estimated in the field by installing a loop of approximately the same size and depth as the heat exchangers planned for the site. The test loop location should be chosen with care, and designed to be used for the eventual full borefield, especially if ~~geothermal~~ GCHP is a likely final system choice (this may require the test loop to meet all local ground heat exchanger standards). Heat is added in a water loop at a constant rate, and data are collected as shown in Figure 14. Inverse methods are applied to find thermal conductivity, diffusivity, and temperature of the formation. These methods are based on the either the line source (Gehlin 1998; Mogensen 1983; Witte et al. 2002), the cylindrical heat source (Ingersoll and Zobel 1954), or a numerical algorithm (Austin et al. 2000; Shonder and Beck 1999; Spitler et al. 1999). More than one of these methods should be applied, when possible, to enhance reported accuracy. Recommended test specifications are as follows (Kavanaugh 2000, 2001):

- Thermal property tests should be performed for 36 to 48 h.
- Heat rate should be 15 to 25 W/ft of bore, which are the expected peak loads on the U-tubes for an actual heat pump system.

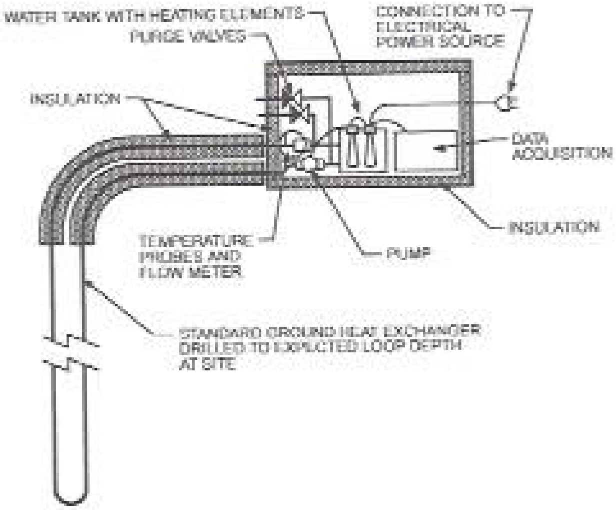


Fig. 14 Thermal Properties Test Apparatus

- Standard deviation of input power should be less than ±1.5% of the average value and peaks less than ±10% of average, or resulting temperature variation should be less than ±0.5°F from a straight trend line of a log (time) versus average loop temperature.
- Accuracy of temperature measurement and recording devices should be ±0.5°F.
- Combined accuracy of the power transducer and recording device should be ±2% of the reading.
- Flow rates should be sufficient to provide a differential loop temperature of 6 to 12°F. This is the temperature differential for an actual heat pump system.
- A waiting period of five days is suggested for low-conductivity soils ($k < 1.0$ Btu/h·ft·°F) after the ground heat exchanger has been installed and grouted (or filled) before the thermal conductivity test is initiated. A delay of three days is recommended for higher-conductivity formations ($k > 1.0$ Btu/h·ft·°F).
- The initial ground temperature measurement should be made at the end of the waiting period by directly inserting a probe inside a liquid-filled ground heat exchanger at three locations, representing the average, or by temperature measurement as liquid exits the loop during the period immediately after start-up.
- Data collection should be at least once every 10 min.
- All aboveground piping should be insulated with a minimum of 0.5 in. closed-cell insulation or equivalent. Test rigs should be enclosed in a sealed cabinet that is insulated with a minimum of 1.0 in. fiberglass insulation or equivalent.
- If retesting a bore is necessary, loop temperature should be allowed to return to within 0.5°F of the pretest initial ground temperature. This typically requires a 10 to 12 day delay in mid- to high-conductivity formations and 14 days in low-conductivity formations if a complete 48 h test has been conducted. Waiting periods can be proportionally reduced if tests were shorter.

Ground Heat Exchanger Sizing. This is perhaps the most critical step in design of a vertical GCHP. Ground-loop design methods must proceed with limited information; a major missing component is long-term, field-monitored data, which are needed to further validate the design method to address effects of water movement and long-term heat storage more fully. The conservative designer can assume no benefit from water movement; designers who assume maximum benefit must ignore annual imbalances in heat rejection and absorption.

Two design methods are presented in the following section. Both methods have been implemented in design software tools, temperature after 10 years of heat extraction at an average rate of 5.2 Btu/h per foot of bore?

Evaluation of the three non-dimensional parameters lead to: r_b/H = 0.0005, B/H = 0.05, t_s = 31.5 years and $\ln(t/t_s)$ = –1.15. According to Figure 19, the resulting g-function is 12.3. Using Equation (13), the borehole wall temperature is then equal to 47.3°F.

The g-functions can be used to determine the design length of a bore field. One possible approach is to use Equations (4) and (5) but with two modifications. First, when g-functions are used, thermal interference among boreholes is implicitly accounted for and t_p can be eliminated. Second, the values of R_{ga}, R_{gm}, and R_{gd} are now based on g-functions. Hence, Equations (10) to (12) take the following forms:

$$R_{ga} = \frac{g_{(t_f)} - g_{(t_f - t_1)}}{2\pi k_g} \tag{14}$$

$$R_{gm} = \frac{g_{(t_f - t_1)} - g_{(t_f - t_2)}}{2\pi k_g} \tag{15}$$

$$R_{gd} = \frac{g_{(t_f - t_2)}}{2\pi k_g} \tag{16}$$

where $g_{(t_f - t_p)}$ is the g-function evaluated at $\ln[(t_f - t_p)/t_s]$ for a given bore field and B/H ratio. Note that determining L (i.e., $n_b \times H$, where n_b is the number of boreholes) is an iterative process because R_{ga}, R_{gm}, and R_{gd} depend on H, which is unknown beforehand. Thus, software tools are often required to accomplish this task. Because g-functions account for 3D heat transfer in the borefield, they are considered to be more accurate than the G-factors, which derive from a radial-only heat transfer model.

Example 3. A building has a cooling block load of 15 tons with a corresponding value of $q_{lc,cond}$ = –225,200 Btu/h. The annual ground imbalance q_a = –10,236 Btu/h, PLF$_m$ = 0.30, and F_{SC} = 1.0. The 3 × 2 bore field has the following characteristics: r_b = 2 in., B = 16.4 ft, and R_b = 0.173 h·ft·°F/Btu. The undisturbed ground temperature is 50°F, the thermal conductivity is 1.93 Btu/h·ft·°F, and the thermal diffusivity is 1.04 ft²/day × 10⁻⁶. Calculate the equivalent thermal resistances R_{ga}, R_{gm}, and R_{gd} for three consecutive heat pulses of 10 years, 1 month, and 6 hours and the total required length if the maximum mean fluid temperature in the borehole is to be kept below 95°F.

From the problem statement, t_f = 3680.25 days, t_2 = 3680 days, and t_1 = 3650 days. After iterations, this leads to $g_{(t_f)}$ = 12.34, $g_{(t_f - t_1)}$ = 3.99, and $g_{(t_f - t_2)}$ = 1.55; and R_{ga} = 0.689 h·ft·°F/Btu, R_{gm} = 0.201 h·ft·°F/Btu, and R_{gd} = 0.128 h·ft·°F/Btu; and

$$L_c = \frac{-10{,}236 \times 0.689 - 225{,}200(0.173 + 0.3 \times 0.201 + 0.128)}{50 - 95} = 1965 \text{ ft}$$

Thus, 321 ft per bore is required with a borehole spacing of 16.4 ft. This represents a length of 131 ft per ton.

Simulation of Ground Heat Exchangers

After the design length has been determined, it is often necessary to evaluate the outlet fluid temperature of a bore field as a function of time, generally on an hourly basis, and estimate the annual heat pump energy consumption. Energy simulation can be used to compute this temperature (they can also be used iteratively to assist in sizing the ground heat exchanger). Some energy simulation programs use the duct ground storage (DST) model introduced by Hellström (1989) to evaluate the outlet fluid temperature of a bore field as a function of time. Yavuzturk and Spitler (1999) describe the calculation method behind the DST model.

The DST model calculates the transient thermal process in densely packed borehole fields. The boreholes are assumed to be evenly distributed within a cylindrical storage region in the ground. Although the DST model was originally intended to simulate borehole thermal energy storage (BTES) systems, it has been used to simulate ground source heat pump systems.

Other energy simulation programs have a g-function-based routine to evaluate the outlet fluid temperature of a bore field as a function of time (Fisher et al. 2006; Liu 2008). The following analysis is intended to give only the salient features of an hourly simulation based on g-functions. As an example, assuming that F_{SC} = 1 and that the borehole length and the inlet fluid temperature are known, and that the heat transfer rates for three consecutive time intervals (0 to t_1, t_1 to t_2, and t_2 to t_3) are given by Q_1, Q_2, and Q_3, then, using temporal superposition, the mean fluid temperature at the end of the third time interval is given by

$$T_m - T_g = \left[\frac{Q_1[g_{(t_3 - 0)} - g_{(t_3 - t_1)}] + Q_2[g_{(t_3 - t_1)} - g_{(t_3 - t_2)}] + Q_3 g_{(t_3 - t_2)}}{2\pi k_g L} + \frac{Q_3 R_b}{L}\right] \tag{17}$$

with $T_m = (T_{in} + T_{out})/2$.

Based on the work of Yavuzturk and Spitler (1999), Equation (17) can be generalized for n time steps as follows:

$$T_m - T_g = \sum_{i=1}^{n} \frac{(Q_i - Q_{i-1})}{2\pi k_g L} g\left(\frac{t_n - t_{i-1}}{t_s}, \frac{r_b}{H}, \frac{B}{H}\right) + \frac{Q_n R_b}{L} \tag{18}$$

Solving Equation (18) can be computationally intensive if the number of time steps is large, because there is no recurrence in the summation term. In other words, the calculations performed at time step $n - 1$ cannot be used at time step n, and the ground loop loading history must be updated at each time step. Load aggregation is typically used to reduce the number of terms in the summation without sacrificing accuracy. It is based on the fact that recent ground loads have a more significant effect on the current mean fluid temperature than distant ground loads. For example, in the case of hourly simulations, the determination of T_m at the end of a year would require a summation of 8760 hourly terms according to Equation (18). One possible alternative is to aggregate (i.e., average) the ground loads of the first 8000 hours, then aggregate the next 730 hours and keep intact the last 30 hours. The summation term would then be reduced to 32 terms. Other aggregation schemes have been proposed by Bernier et al. (2004), Liu (2005), and Yavuzturk and Spitler (1999).

Hybrid System Design

The design methods described previously size the ground loop for the larger of the heating or cooling loads, including a temperature penalty for the amount of imbalance (which can be large in severe climates). An alternative approach for imbalanced buildings is to partially balance the load on the ground, both at peak and annual scale, by adding a supplemental device to help meet the larger of the two peak loads. This is a ~~**hybrid geothermal (or**~~ **hybrid ground-coupled**~~)~~ system. Hybrids can provide several benefits for buildings with a load imbalance. The biggest economic effect is in decreasing the ground heat exchanger size/cost. First-cost savings have been reported of 6 to 16% of total HVAC system cost, with little consequence reported on operating cost (Hackel and Pertzborn 2011; Singh and Foster 1998) because the HVAC systems operates for the vast majority of the year at a fraction of peak design. Table 7 shows that the more balanced loads resulting from hybrids also significantly affect long-term performance too.

In most U.S. commercial buildings, the cooling load is dominant both annually and at the peak because of high internal loads, ventilation heat recovery, and good building envelopes. Heat from compressors, pumps, and fans also plays a factor; in heating mode, this heat is delivered to the building, so less heat is required from the

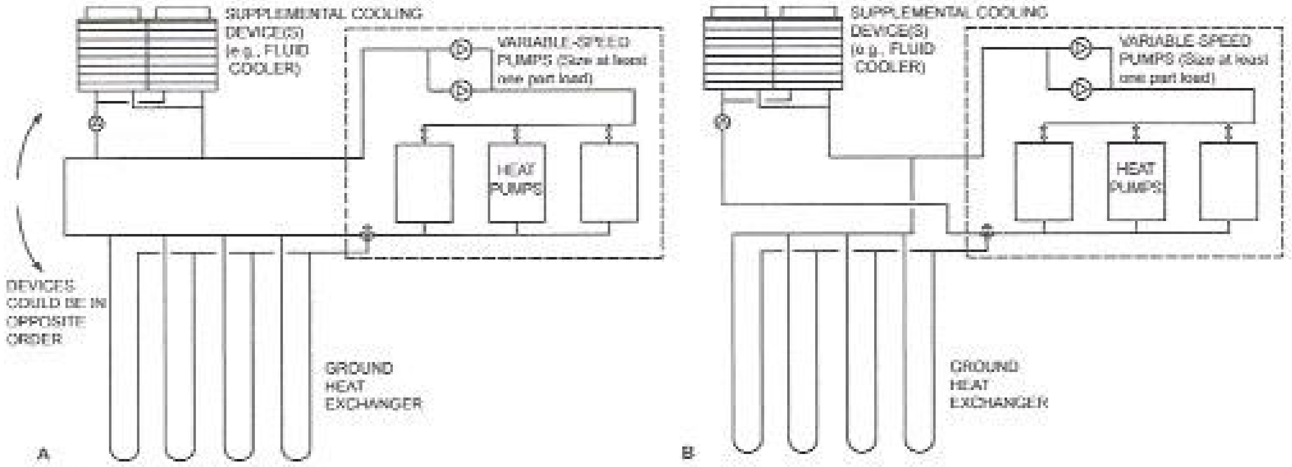


Fig. 20 Hybrid System Configuration Options, (A) Series and (B) Parallel

ground source/sink

ground. As a result, achieving annual thermal balance requires heat pumps in a ~~geothermal~~ system to operate in heating mode 1.6 to 1.8 h for every hour in cooling.

The ideal configuration of the ground heat exchanger and supplemental cooling device in a hybrid depends on many factors, such as climate, building peak load, and building annual loads. Carefully analyze which approach may work best for a specific building. One common configuration for cooling-dominated systems, a series hybrid, is shown in Figure 20A. This approach could also be taken with a closed-circuit cooling tower (i.e., fluid cooler) downstream of the ground heat exchanger (GHX). In general, it is most effective to place the lower-temperature heat sink downstream; an energy model can help determine which order most often results in this scenario throughout the year. As a rule of thumb, in drier climates with warmer ground (e.g., desert southwestern United States) the tower is almost always the lower-temperature sink, whereas in humid climates with moderate-temperature ground (e.g. southeastern United States), the ground is often the lower-temperature sink. The hybrid can also be configured in parallel, as shown in Figure 20B, which is especially desirable if the ground heat exchanger is small in comparison to the building peak cooling load (a series system in this example would require a more complex partial GHX bypass). In either case, there are two guidelines for design and operation of hybrid systems:

- A valve can be used to bypass the ground heat exchanger when the system is balanced; a dead band of 55 to 75°F can be used for this purpose. This valve can be three-way as shown, or two-way where appropriate.
- Cooling towers are optional when they are oversized, use a variable-speed fan, and minimize fan speed across cells.

Control of a cooling-dominated hybrid depends on the configuration. If equipment is placed as shown in Figure 20A, the temperature downstream of the tower can be used to control the use and speed of the tower based on a high limit (some additional savings are possible if the tower is controlled by the Δt between entering fluid and ambient wet-bulb temperatures, though this method depends on a difficult measurement of wet bulb). If the tower is located upstream of the ground heat exchanger, the temperature exiting the tower and the ground heat exchanger should both be used in tower control (to ensure the ground is not being cooled). For parallel configurations (Figure 20B), one practical tower control sequence bases tower operation on a calculation of the average of fluid temperature entering the heat pumps over the previous week (Xu 2007). Xu also suggests a strategy for controlling the parallel three-way valve.

A heating-dominated hybrid with a boiler instead of a cooling tower can use a series configuration, with the boiler downstream of the loop (because of the boiler's high temperature output). The boiler is ideally controlled based on the temperature leaving the heat pumps.

Sizing hybrid components is a bit more complex than standard systems. For cooling dominated hybrids, Kavanaugh and Rafferty (1997) suggest that heat exchanger length for heating L_h be determined using Equation (5) with heating-mode loop temperatures t_{wi} and t_{wo} as low as possible to minimize L_c. A tower with an isolation heat exchanger is sized to meet the capacity difference between the required cooling length L_c from Equation (4) and the heating length L_h. Kavanaugh (1998) revised this method to include an additional iteration to size the ground heat exchanger only after estimating the annual heat rejection from the tower: q_{tower}(rated gpm) − gpm$_{system}$$(L_c - L_h)/L_c$, where L_c is calculated from Equation (5) but based on reduced EFLH$_c$ to account for tower operation rejecting an estimated amount of the annual load. The strategy suggests eliminating long-term ground temperature change with additional tower operation.

A more detailed study (Hackel et al. 2009) included assumptions about typical installation and operating costs to demonstrate an optimized design strategy for cooling dominated hybrids. Based on life-cycle cost, this approach was roughly attractive whenever the peak heating load was less than 80% of the cooling load; savings increased logarithmically as the ratio decreased below 80%. A variety of cases were modeled, and the simplified best-fit regression for the hybrid ground heat exchanger length L_{hyb} in a cooling-dominated scenario was found to be proportional to heating load:

$$L_{hyb} = C_1 \times q_h/(t_g - t_{wi}) \tag{19}$$

where C_1 = 254 ft·h·°F/kBtu, at k = 1.4 Btu/ft·h·°F. For other ground conductivities, the change in ground heat exchanger size is approximately inversely proportional to the change in conductivity. In choosing t_{wi}, Hackel et al. also suggest in cooler climates it is often economical to include antifreeze in the system and allow the entering fluid temperature to drop to 35°F or lower. The supplemental cooling device (closed-circuit tower) should then be sized to meet the fraction of the cooling load that this smaller hybridized ground heat exchanger cannot. The study suggests that the tower should even be oversized slightly and its fan put on variable-speed control, to achieve optimal performance. Furthermore, tower sizing

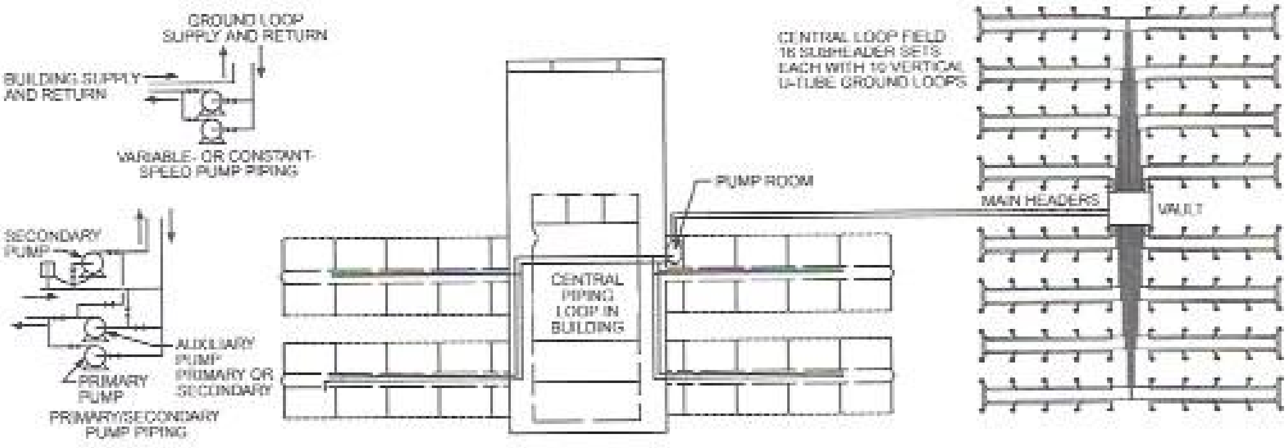


Fig. 23 Central Loop GCHP

Table 10 GCHP Piping Cost Comparison for Two Sample Buildings

	Four-Story Office Building, 40,000 ft^2		Elementary School, 57,000 ft^2	
	Central Loop	Sub-Central Loops (Eight)	Central Loop	Unitary Loops
Vertical loop cost per ft	$6.63	$6.63	$6.63	$6.63
Header and vertical loop cost per ft	$10.57	$9.67	$12.91	$10.71
Vertical loop cost per ton	$1327	$1343	$1300	$1430
Header and vertical loop cost per ton	$2114	$1956	$2530	$2099

(IGSHPA) design and installation standards lists only high-density polyethylene (HDPE), and most recently an exception for cross-linked polyethylene (PEX-a) as approved materials for buried pipe. (IGSHPA 2011). In most cases, this pipe is buried without insulation.

Distribution systems in a building need to be carefully chosen and not solely driven by cost or ease of installation. As with any system, piping materials must be compatible with system design temperatures and with the fluids conveyed. Closed-loop systems typically use potable water and may also include an antifreeze solution and/or water treatment chemicals. With newer refrigerants, care is needed to ensure the piping materials are compatible with the oils used in the refrigeration system and that equipment seals are compatible with the heat transfer fluids conveyed; for instance, polyolester (POE) oil used with R-410A is not compatible with PVC pipe. Consult chemical resistance charts provided by materials manufacturers.

Whether designing a new system or retrofitting an existing one, it is the design engineer's responsibility to size and select the proper piping materials for each application and to select only those materials allowed by code (ICC 2012). In large building systems, the aboveground piping specifications commonly include steel, iron, copper or PVC. Where the hydronic mains are 4 in. or larger, it is often more cost effective to specify steel pipe. Specifying steel pipe may require some type of water treatment to inhibit general corrosion and dielectric isolation when connected to ~~geothermal~~ ground source heat pumps.

Water Quality, Heat Transfer Fluids, and Water Treatment. When engineers introduce dissimilar metals into closed-loop hydronic piping systems, improperly address water treatment requirements for their designs, or are not properly informed of the local groundwater regulations, water quality problems may result. Poor water quality contributes to a decline in mechanical system performance, increased maintenance, and can reduce the useful lifetime of mechanical system components.

The standard working fluid in small residential closed-loop piping systems is either potable water or, in colder regions, an antifreeze solution. Where required, the antifreeze solution is introduced after the ground loop is properly pressure tested, flushed, and purged of debris and air. There has been little problem with or concern about water quality in these GSHP systems, because piping materials have historically been HDPE, copper, or stainless steel hose kits for final connection at the heat pumps.

Quality of potable water can vary, depending upon the source, and rules on its use vary from state to state. The chemistry of this water is one of the contributors to corrosion and water quality problems in closed-loop piping systems, so engineers need to be precise with hydronic piping and water treatment system specifications. Chapter 49 offers some guidance on understanding the consequences of water quality on both open- and closed-loop hydronic systems.

The type of chemical used for water treatment in closed-loop systems is based on several criteria, including the materials being protected, the quality of the water in the piping system, local regulations, and cost. These systems are typically specified to include a rigorous process for cleaning the distribution piping, flushing the piping systems of air and debris, and then adjusting the water quality of the final local water to meet the long-term performance requirements of the building systems. Chemicals used to adjust water quality for these systems are often not acceptable for use when the circulating fluid is also connected to a ground loop. This is not a problem unless there is a pipe failure or problem with the ground loop, but a potential leak is a concern of the regulatory agencies that protect groundwater in each state.

Flush and Purge. To ensure that a ~~geothermal~~ ground source heat pump system provides trouble-free operation, all ground-loop systems must be properly flushed and purged prior to connection to the building piping system (IGSHPA 2011). The current standard of care is defined by IGSHPA as providing a minimum velocity of 2 ft/s through each piping system, and flushing and purging each supply and return circuit in the forward and reverse directions for long enough to remove all debris and air from the system.

Recommendations for Good GSHP Piping System Design.

- Before beginning design, consult the local regulatory agency for guidance on requirements related to the ground-loop portion. In many locations, this may be the Departments of Health or Environmental Services. Drilling for a vertical closed-loop system may not be allowed. Local groundwater conditions may limit the exchanger. The increased capital cost of installing the heat exchanger is only a small percentage of the total cost and, in view of these systems' greatly reduced maintenance requirements, is quickly recovered.

Past GWHP systems sometimes used surface disposal (to rivers, lakes, drainage ditches, etc.) of the groundwater. Injection, in general, should be the standard disposal method because it eliminates the potential for negative effects on the aquifer water level over time and preserves the positive environmental character associated with GSHP systems.

Regardless of the type of equipment installed in the building, the specific components for handling groundwater are similar. Primary items include (1) wells (supply and injection), (2) well pump and controls, and (3) groundwater heat exchanger. Some specifics of these items are discussed in the Direct-Use Systems Design section of this chapter. In addition to those comments, the following considerations apply specifically to unitary GWHP systems using a groundwater isolation heat exchanger.

Design Strategy

An open-loop system design must balance well pumping power with heat pump performance. As groundwater flow increases through a system, more favorable average temperatures are produced for the heat pumps. Higher groundwater flow rates, to a point, increase system EER or COP: increased well pump power is outweighed by decreased heat pump power requirements (because of the more favorable temperatures). At some point, additional increases in groundwater flow result in a greater increase in well pump power than the resulting decrease in heat pump power. The key strategy in open-loop system design is identifying the point of maximum system performance with respect to heat pump and well pump power requirements. Once this optimum relationship has been established for the design condition, the method of controlling the well pump determines the extent to which the relationship is preserved at off-peak conditions. This optimization process involves evaluating the performance of the heat pumps and well pump(s) over a range of groundwater flows. Key data necessary to make this calculation include well performance (flow and drawdown at various groundwater flows) and heat pump performance versus entering water temperatures at different flow rates. Well information is generally derived from well pump test results. Heat pump performance data are available from the manufacturer.

GWHP systems employ the same type of extended-range unitary heat pumps as GCHP systems. Building loop pumping guidelines (see Table 9) in the GCHP portion of this chapter also apply to GWHP systems. In large commercial applications, the head loss associated with the isolation heat exchanger in a GWHP system is typically lower than that of an equivalently sized ground heat exchanger in a GCHP system. A guideline for building loop head loss in a GWHP system can be described as follows:

$$\text{Building loop head loss (ft of water)} = 28 + 0.1d$$

where d = pipeline distance ft from plate heat exchanger outlet to most distant heat pump unit inlet.

This calculation assumes a maximum head loss of 4 ft/100 ft fittings at 25% of total head loss and a heat pump unit head loss of 12 ft. Because of more extensive fittings, retrofits can sometimes exceed this value.

For moderate-efficiency heat pumps (EER of 14.2), efficient loop pump design (7.5 hp/100 tons), and a heat exchanger approach of 3°F, Figure 29 provides curves for two different groundwater temperatures (GWT = 50 and 65°F) and two well pump situations (SWL 75 ft/specific capacity 10 gpm/ft and SWL 300 ft/specific capacity 3 gpm/ft). The curves are plotted for constant well pump head, a situation which does not occur in practice. In reality, well pump head rises with flow but at a rate typically less than that in friction head applications.

Although the four curves show a clear optimum flow, sometimes operating at a lower groundwater flow reduces well/pump capital cost and the problem of fluid disposal. These considerations are highly project specific, but do afford the designer some latitude in flow selection. Generally, an optimum design results in a groundwater flow rate that is less than the building loop flow rate.

The exception to this occurs in the case of groundwater temperatures of less than 47°F and greater than 72°F. In these situations the groundwater flow requirement is influenced more by avoiding excessive heat pump EWT in the cooling mode (groundwater temperatures above 72°F) and heat pump LWTs that could result in freezing conditions in the heating mode (groundwater temperatures less than 47°F). In the case of low water temperatures, some designers have found it advantageous to use antifreeze in the building loop to slightly broaden the allowable loop temperature range.

Table 17 provides design data for a specific example system.

3.4 WATER WELLS

This section includes information on water wells that is generally common to both direct-use and groundwater heat pump (GWHP) systems.

This section remains with either chapter, referenced by the other

Table 17 Example GWHP System* Design Data

Heat Pump EWT, °F	Heat Pump LWT, °F	Heat Pump EER	Ground-water LWT, °F	Ground-water Flow, gpm	Well Pump Head, ft	Well Pump kW	Loop Pump kW	System EER
61.0	72.4	17.6	68.4	289	256	23.7	4.8	11.8
63.0	74.5	17.3	70.5	233	229	17.5	4.8	12.5
65.0	76.5	16.9	72.5	196	210	13.7	4.8	12.9
67.0	78.6	16.5	74.6	169	197	11.4	4.8	13.0
69.0	80.6	16.1	76.6	149	186	9.7	4.8	13.1
71.0	82.7	15.7	78.7	133	179	8.5	4.8	13.0
73.0	84.7	15.3	80.7	120	172	7.5	4.8	12.9
75.0	86.7	15.1	82.7	110	167	6.7	4.8	12.9
77.0	88.8	14.9	84.8	101	163	6.0	4.8	12.8
79.0	90.8	14.6	86.8	94	159	5.5	4.8	12.6
81.0	92.3	14.2	88.9	88	156	5.1	4.8	12.4
83.0	94.9	13.4	90.9	82	153	4.7	4.8	12.2

*Block cooling load 85 tons, 60°F groundwater, 75 ft well static water level, 2 gpm/ft specific capacity, 37 ft surface head losses, 4°F heat exchanger approach, 213 gpm building loop flow at 65 ft head.

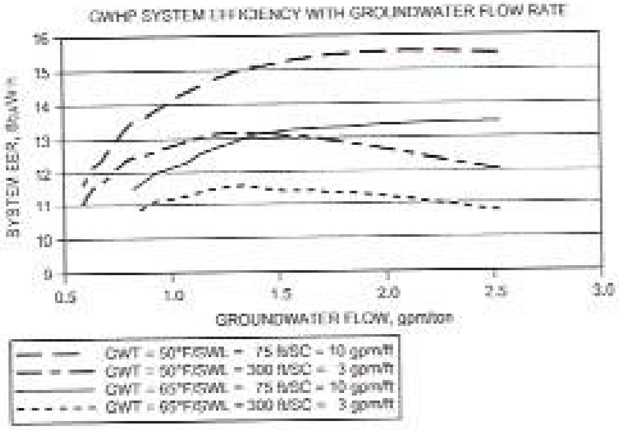


Fig. 29 Optimum Groundwater Flow for Maximum System EER

SWL is static water level in ft, and
SC is specific capacity of well in gpm/ft.
(Kavanaugh and Rafferty 1997)

In a conventional heat-recovery chiller, waste heat is available only when there is a building chilled-water (or conditioning) load. In a groundwater system, a heat source (the groundwater) is available year round. To take advantage of this source during the heating season, the chiller must be loaded in response to the heating load instead of the chilled-water load. That is, the control must include a heating-dominant mode and a cooling-dominant mode. Two general designs are available for this:

- Chiller capacity remains controlled by chilled-water (supply or return) temperature, and groundwater flow through the chilled-water exchanger is varied in response to the heating load
- Chiller capacity is controlled by the heating-water (condenser) loop temperature, and groundwater flow through the chilled-water exchanger is controlled by chilled-water temperature

For buildings with a significant heating load, the former may be more attractive, whereas the latter may be appropriate for conventional buildings in moderate to warm climates.

Standing-Column Systems

In practice, standing-column wells (SCWs) are a trade-off between groundwater systems and ground-coupled systems. They do not require well flow testing of the sort necessary for groundwater systems, and conductive heat transfer can be based on existing closed-loop theory. Though standing-column systems have been applied mostly in the northeastern United States, approximately 60% of the country is underlain by near-surface (<150 ft) bedrock suitable for the systems.

A heating capacity of 350,000 to 420,000 Btu/h or cooling capacity of 30 to 35 tons can be expected from a 1500 ft deep standing-column well. Ideal spacing between SCWs is 50 to 75 ft (Orio et al. 2005) Typically, spacing between standing-column wells is greater than vertical closed-loop (GCHP) boreholes. These estimated capacities assume a 10% advective bleed flow, discussed later in this section. Closer spacing affects well field performance and can be evaluated with design software. Additional information on standing-column systems can be found in Spitler (2002).

The standing-column well combines supply and injection wells into one, and does not depend on the presence or flow of groundwater, beyond that of the typical bleed rate of 10 to 20% of total pumped flow. Standing-column wells are always augmented with a bleed circuit, to monitor the entering water temperature. Well water temperatures that are below or above design limits because of variations in rock conductivity, building anomalies, or nonstandard weather patterns can be restabilized (i.e., brought back to far-field temperatures by overflowing smaller amounts of water on command). This advective flow is a powerful short-term method of warming and cooling well columns that are beyond design limits.

Standing-column wells (Figure 33) consist of a borehole cased in steel or other material until competent bedrock is reached. The casing must be driven 25 to 50 ft into and sealed in competent bedrock. Bedrock sealing requirements vary by state. The remaining depth of the well is then self-supporting through bedrock. For deep commercial SCWs, a tail pipe (porter shroud) is inserted to form a conduit to draw up water, and an annulus to return water downward. This tail pipe is perforated at the bottom to form a diffuser. Water is drawn into the diffuser and up the central riser pipe to the submersible pump. The well pump must be located below the water table in line with the central riser pipe. The tail pipe allows a shorter, reduced-power wire size as well as more accessible well pump service.

The U.S. Environmental Protection Agency (EPA) Underground Injection Control program considers standing-column reinjection well water a Class V water use, type 5A7, noncontact cooling water for ~~geothermal~~ heating and cooling. The EPA and equivalent state agencies regard SCW reinjection as a beneficial use. Permitting or notice may be required, depending on average daily water flow rates. SCWs are serviced by qualified well contractors with minimal familiarization training.

heat pump

type 5A6, direct heat reinjection wells

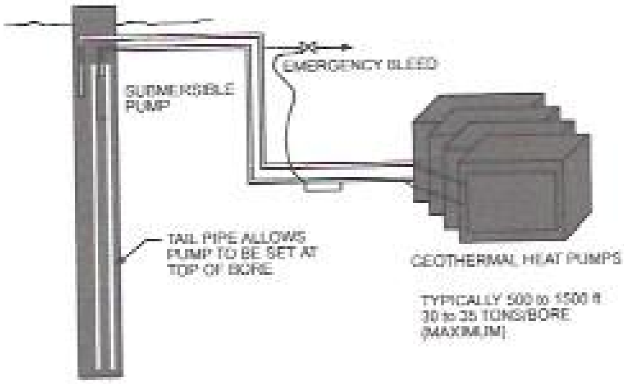


Fig. 33 Commercial Standing-Column Well

3.5 SURFACE WATER HEAT PUMPS

Surface water bodies can be very good heat sources and sinks if properly used. In some cases, lakes can be the very best water supply for cooling. Various water circulation designs are possible; several of the more common are presented here.

In a **closed-loop system**, one or more water-to-water or water-to-air heat pumps are linked to one or more submerged coils or flat plate heat exchangers, referred to as **surface water heat exchangers (SWHEs)**. Heat is exchanged to (cooling mode) or from (heating mode) the lake by the fluid (usually a water/antifreeze mixture) circulating inside the SWHE. The heat pump transfers heat to or from the air in the building.

In an **open-loop system**, water is pumped from the lake through a heat exchanger and returned to the lake some distance from the point at which it was removed.

Thermal stratification of water often keeps large quantities of cold water undisturbed near the bottom of deep lakes. This water is cold enough to adequately cool buildings by simply being circulated through heat exchangers. A heat pump is not needed for cooling, and energy use is substantially reduced. Closed-loop coils may also be used in colder lakes. Heating can be provided by a separate source or with heat pumps in heating mode. As noted previously, precooling or supplemental total cooling are also allowed when water returning to the building is near or below 55°F.

Heat Transfer in Lakes

Heat is transferred to lakes by three primary modes: radiant energy from the sun, convective heat transfer from the surrounding air (when the air is warmer than the water), and conduction from the ground. Solar radiation, which can exceed 300 Btu/h per square foot of lake area, is the dominant heating mechanism, but it occurs primarily in the upper portion of the lake unless the lake is very clear. About 40% of solar radiation is absorbed at the surface (Pezent and Kavanaugh 1990). Approximately 93% of the remaining energy is absorbed at depths visible to the human eye.

Convection transfers heat to the lake when the lake surface is cooler than the air. Wind speed increases the rate at which heat is transferred to the lake, but maximum heat gain by convection is usually only 10 to 20% of maximum solar heat gain. Conduction gain from the ground is even less than convection gain (Pezent and Kavanaugh 1990).

32 Types of Class V Injection Wells

Source: Ground Water Protection Council

Code	*Well Type and Description*	*Risk*	*Potential Contaminants*
	DRAINAGE WELLS		
5F1	Agricultural Drainage Wells – receive irrigation tailwater, other field drainage, animal yard, feedlot, or dairy runoff, etc.	High	Pesticides, nutrients, pathogens, metals transported by sediments, salts
5D2	Storm Water Drainage Wells – receive storm water runoff from paved areas including parking lots, streets, residential subdivisions, building roofs, highways etc.	Low - Moderate	Heavy metals (Cu, Pb, Zn), organics, high levels of coliform bacteria. Contaminants from streets, roofs, landscaped areas (herbicides, pesticides.)
5D3	Improved Sinkholes - receive stormwater runoff from developments in karst topographic areas.	Moderate - High	Variable; pesticides, nutrients, coliform bacteria, or other storm water contaminants
5D4	Industrial Drainage Wells - wells located in industrial areas which are constructed to discharge storm water but are susceptible to spills, leaks, or other chemical discharge.	Moderate - High	Usually organic solvents, acids, pesticides, and various industrial waste constituents.
5G30	Special Drainage Wells - used for disposing water from sources other than direct precipitation, such as landslide control, lake level control, swimming pool drainage, or portable water tank overflow/drainage.	Low - Moderate	Chlorinated and treated water, pH imbalance, algaecides, fungicides, muriatic acid.
	GEOTHERMAL REINJECTION WELLS		
5A5	Electric Power Reinjection Wells - reinject geothermal fluids used to generate electric power (deep wells.)	Moderate	pH imbalance, minerals and minerals in solution (As, Bo, Se), sulfates.
5A6	Direct Heat Reinjection Wells - reinject geothermal fluids used to provide heat for large buildings or developments.	Moderate	Hot geothermal brines with TDS between 2,000 to 325,000 mg/L Co_3, $CaSO_4$, SR and Ba, As.
5A7	Heat Pump/Air Conditioning Return Flow Wells – reinject groundwater used to heat or cool a building in a heat pump system (shallow wells.) **Not injection wells** if they are a closed loop system as many states require.	Low	Potable water with temperatures ranging from 90 to 110 degrees F, may have scale or corrosion inhibitors.
5A8	Groundwater Aquaculture Return Flow Wells – reinject groundwater or geothermal wells used to support aquaculture. Non-geothermal aquaculture disposal wells are also included in this category (such as those used in aquariums.)	Moderate	Used geothermal waters which may be highly mineralized and include traces of arsenic, boron, fluoride, dissolved and suspended solids, animal waste, perished animals and bacteria.

www3.epa.gov/region9/water/groundwater/uic-pdfs/32types-gwpc.pdf