CHAPTER 32

GEOTHERMAL ENERGY

THE use of geothermal resources can be broken down into three general categories: high-temperature (>300°F) electric power production, intermediate- and low-temperature direct-use applications (<300°F), and ground-source heat pump applications (generally <90°F). This chapter covers only the direct-use and ground-source heat pump categories. After an overview of resources, the chapter is divided into two sections. The section on Direct-Use Systems contains information on wells, equipment, and applications. The section on Ground-Source Heat Pumps includes information only on the ground-source portion. Design aspects of the building heat pump loop may be found in Chapter 8 of the 2000 *ASHRAE Handbook—Systems and Equipment*.

RESOURCES

Geothermal energy is the thermal energy within the earth's crust—the thermal energy in rock and fluid (water, steam, or water containing large amounts of dissolved solids) that fills the pores and fractures within 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 the 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 permit.

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. The 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 permitted by the rock permeability and fluid content in the rock pores.

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

Geopressured resources, present widely 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) the basins must be deep enough to provide usable temperature levels at the prevailing gradient, and (2) the permeability within the aquifer must be adequate for flow.

The thermal energy in geothermal resources exists primarily in the rocks and only secondarily in the fluids that fill the pores and fractures within them. 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, the produced fluid 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 to 680°F. As indicated in Figure 1, local gradients also vary with geologic conditions. The lower value represents the fluids used as the low-temperature energy source 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	$t <$ 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 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).

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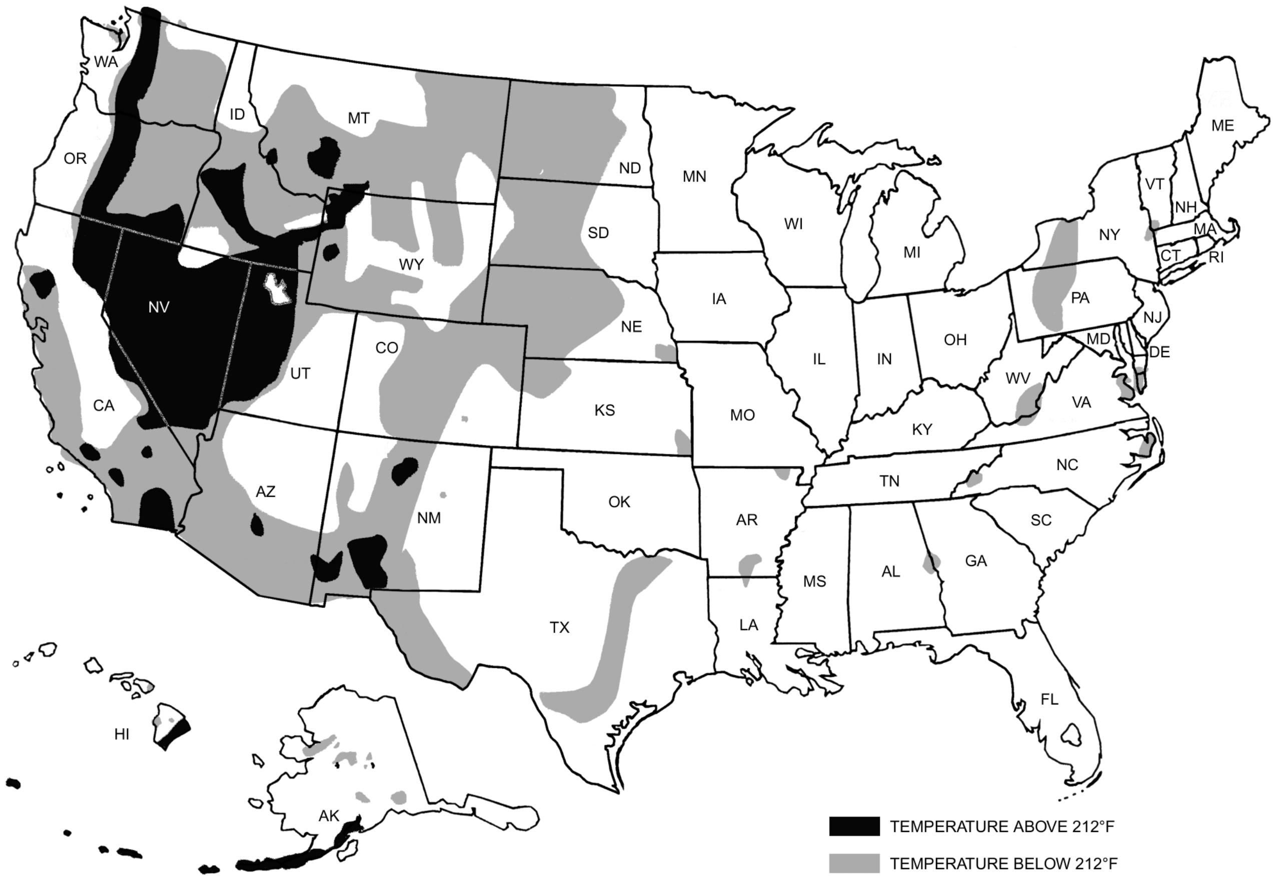

Fig. 1 U.S. Hydrothermal Resource Areas
(Lineau et al. 1995)

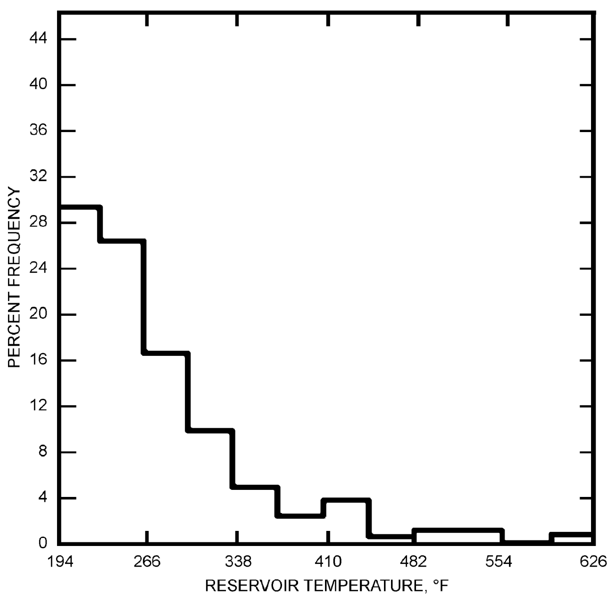

Fig. 2 Frequency of Identified Hydrothermal Convection Resources Versus Reservoir Temperature
(Muffler 1979)

Geothermal resources at the lower temperatures are more common. The frequency by reservoir temperature of identified convective systems above 195°F is shown in Figure 2.

Fluids

Geothermal energy is currently extracted from the earth through the naturally occurring fluids in rock pores and fractures. In the future, an additional fluid may be introduced into the geothermal system and circulated through it to recover the energy. The fluids being produced are steam, hot water, or a two-phase mixture of both. These may contain various amounts of impurities, notably dissolved gases and dissolved solids.

Geothermal resources that produce essentially dry steam are **vapor-dominated**. Although these are valuable resources, they are rare. Hot-water (**fluid-dominated**) resources are much more common and can be produced either as hot water or as a two-phase mixture of steam and hot water, depending on the pressure maintained on the production plant. If the pressure in the production casing or in the formation around the casing is reduced below the saturation pressure at that temperature, some of the fluid will flash, and a two-phase fluid will result. If the pressure is maintained above the saturation pressure, the fluid will remain single-phase. In fluid-dominated resources, both dissolved gases and dissolved solids are significant.

Geothermal fluid chemistry varies over a wide range. In the Imperial valley of California, some geothermal fluids may contain up to 300,000 ppm of total dissolved solids (TDS). Fluids of this character are extremely difficult to accommodate in systems design and materials selection. Fortunately, most low- to moderate-temperature resources are less difficult. In fact most low-temperature fluids contain less than 3000 ppm and many meet drinking water standards. Despite this, even geothermal fluids of a few hundred ppm TDS can cause substantial problems with standard construction materials.

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, a resource area in northern California, is the largest single geothermal development in the world.

The total electricity generated by geothermal development in the world was 7974 MW in 2000 (Lund et al. 2001). The 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 agricultural growth applications are for heating greenhouse and aquaculture facilities. The principal industrial uses of geothermal energy in the United States are for food processing (dehydration) and gold processing. Worldwide, the main applications include space and water heating, space cooling, agricultural growth, and food processing. Exceptions are diatomaceous earth processing in Iceland, and pulp and paper processing in New Zealand.

DIRECT-USE SYSTEMS DESIGN

One of the major goals in designing direct-use systems is capturing the most possible heat from each gallon of fluid pumped. Owning and operating costs for the systems 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 systems can be divided into five subsystems: (1) the production system, including the producing wellbore and associated wellhead equipment, (2) the transmission and distribution system that transports the geothermal energy from the resource site to the user site and then distributes it to the individual user loads, (3) the user system, (4) the disposal system, which can be either surface disposal or injection back into a formation, and (5) an optional peaking/back-up system. None of the 14 major geothermal district heating systems in the United States includes a peaking/back-up component as part of the main distribution system. Back-up is most commonly included in the end user systems and peaking is rarely used.

In a typical direct-use system, the geothermal fluid is produced from the production borehole by a lineshaft multistage centrifugal pump. (For free-flowing wells with adequate quantities of fluid, a pump is not required. However, most commercial operations require pumping to provide the necessary flow.) When the geothermal fluid reaches the surface, it is delivered to the application site through the transmission and distribution system.

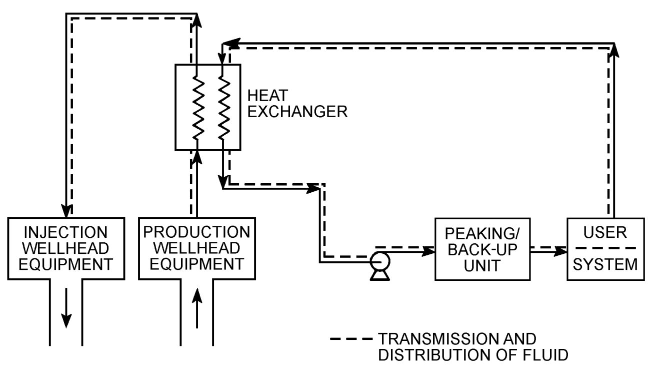

Fig. 3 Geothermal Direct-Use System with Wellhead Heat Exchanger and Injection Disposal

In the system shown in Figure 3, the geothermal production and disposal system are closely coupled, and they are both separated from contact with the equipment by a heat exchanger. This secondary loop is especially desirable when the geothermal fluid is particularly corrosive and/or causes scaling. Then the geothermal fluid is pumped directly back into the ground without loss to the surrounding surface.

COST FACTORS

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

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

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.

Depth of the Resource

The cost of the well is usually one of the larger items in the overall cost of a geothermal system, and the cost increases with the depth of the resource. 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

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

Well Flow Rate

The 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

In geothermal resources, the available temperature is associated with the prevailing resource. A nearly fixed value for a given resource, the temperature may possibly increase with deeper drilling. Natural convection in fluid-dominated resources keeps the temperature relatively uniform throughout the aquifer, but if there are deeper, separate aquifers (producing zones) in the area, deeper drilling can recover energy at a higher temperature.

The temperature can restrict applications. It often requires a reevaluation of accepted application temperatures, which have been developed for uses served by conventional fuels for which the application temperature could be selected at any value within 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, the power output from the geothermal well is directly proportional to the temperature drop of the geothermal fluid. Consequently, a larger temperature drop results in lower energy cost at the wellhead. This concept differs from many conventional and solar energy systems that circulate a heating fluid with a small temperature drop, so a different design philosophy and different equipment are required.

Cascading the geothermal fluid to uses with lower temperature requirements can be advantageous in achieving a large temperature difference (Δt). Most geothermal systems have been designed for a Δt of between 30 and 50°F, although one system was designed for a Δt of 100°F with a 190°F resource temperature.

Load Size

Large-scale applications benefit from economy of scale, particularly in regard to reduced resource development and transmission system costs. For smaller developments, matching the size of the application with the production rate from the geothermal resource is important because the total output varies in increments of one well's output.

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 cost rather than operating cost, this factor significantly affects the viability of a geothermal system. 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 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. The quality of the fluid 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. Most geothermal effluent is disposed of on the surface, including discharge to irrigation, rivers, and lakes. This method of disposal is considerably less expensive than the construction of injection wells. However, the magnitude of geothermal development in certain areas where surface disposal has historically been used (e.g., Klamath Falls, Oregon and Boise, Idaho) has caused the aquifer water level to decline. As a result, regulatory authorities in these and many other areas favor the use of injection in order to maintain reservoir fluid levels.

In addition, geothermal fluids sometimes contain chemical constituents that cause surface disposal to become a problem. Some of these constituents are listed in Table 1.

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).

If injection is required, the depth at which the fluid can be injected affects well cost substantially. Some jurisdictions allow considerable latitude of injection level; others require the fluid be returned to the same or similar aquifers. In the latter case, 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.

Resource Life

The life of the resource has a direct bearing on the economic viability of a particular geothermal application. There is little experience on which to base projections of resource life for heavily developed geothermal resources. However, resources can readily be developed in a manner that will allow useful lives of 30 to 50 years and greater. In some heavily developed, direct-use areas, major systems have been in operation for many years. For example, the Boise Warm Springs Water District system (a district heating system serving some 240 residential users) has been in continuous operation since 1892.

WATER WELLS

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

Terminology

Although moisture exists to some extent at most subsurface locations, below a certain depth there exists a zone in which all of the pores and spaces between the rock are filled with water. This is called the **zone of saturation**. The object of constructing wells is to gain access to **groundwater**, the water that exists within the zone of saturation. An **aquifer** is a geologic unit that is capable of yielding groundwater to a well in sufficient quantities to be of practical use (UOP 1975).

In many projects, the construction of the well (or wells) is handled through a separate contract between the owner and the driller. As a result, the engineer is not responsible for its design. However, because the design of the building system depends on the performance of the well, it is critical that the engineer be familiar with well terminology and test data. The most important consideration with regard to the wells is that they be completed and tested (for flow volume and water quality) prior to final system design.

Figure 4 presents a summary of the more important terms relating to wells. Several references (Anderson 1984; Campbell and Lehr 1973; EPA 1975; Roscoe Moss Company 1985) cover well drilling and well construction in detail.

Static water level (SWL) is the level that exists under static (nonpumping) conditions. In some cases, this level is much closer to the surface than that at which the driller encounters water during drilling. **Pumping water level** (PWL) is the level that exists under specific pumping conditions. Generally, this level is different for different pumping rates (higher pumping rates mean lower pumping levels). The difference between the SWL and the PWL is the **drawdown**. The **specific capacity** of a well is frequently quoted in gpm per foot of drawdown. For example, for a well with a static level of 50 ft that produces 150 gpm at a pumping level of 95 ft, drawdown = 95 – 50 = 45 ft; specific capacity = 150/45 = 3.33 gpm per foot.

For groundwater characterized by carbonate scaling potential, **water entrance velocity** (through the screen or perforated casing) can be an important design consideration. Velocity should be limited to a minimum of 0.1 fps to avoid incrustation of the entrance area, though there is disagreement in the literature on this issue. The **pump bowl assembly** (impeller housings and impellers) is always placed sufficiently below the expected pumping level to prevent

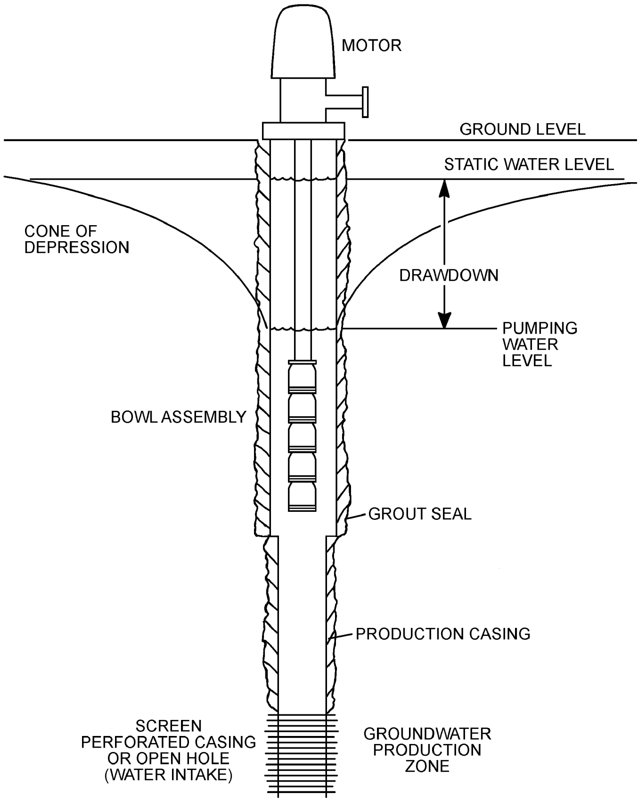

Fig. 4 Water Well Terminology

cavitation at the peak production rate. For the previous example, this pump should be placed at least 115 ft below the casing top (pump setting depth = 115 ft) to allow for adequate submergence at peak flow. The specific net positive suction head (NPSH) required for a pump varies with each application and should be carefully considered in selecting the setting depth.

For the well pump, **total pump head** is composed of four primary components: lift, column friction, surface requirements, and injection head. **Lift** is the vertical distance that water must be pumped to reach the surface. In the example, lift would be 95 ft. The additional 20 ft of submergence imposes no static pump head.

Column friction is calculated from pump manufacturer data in a similar manner to other pipe friction calculations (see Chapter 35 of the 2001 *ASHRAE Handbook—Fundamentals*). Surface pressure requirements account for friction losses through piping, heat exchangers, controls, and injection pressure (if any). Injection pressure requirements are a function of well design, aquifer conditions, and water quality. In theory, an injection well penetrating the same aquifer as the production well will experience a water level rise (assuming equal flows) that mirrors the drawdown in the production well. Using the earlier example, an injection well with a 50 ft static level would experience a water level rise of 45 ft, resulting in a surface injection pressure of 45 − 50 = −5 ft (i.e., a water level that remains 5 ft below the ground surface). Thus no additional pump pressure is requires for injection.

In practice, injection pressure requirements usually exceed the theoretical value. With good (nonscaling) water, careful drilling, and little sand production, injection pressure should be near the theoretical value. For poor water quality, high sand production, or poor well construction, injection pressure may be 30 to 60% higher.

The well casing diameter depends on the diameter of the pump (bowl assembly) necessary to produce the required flow rate. Table 2 presents nominal casing sizes for a range of water flow rates.

Table 2 Nominal Well Surface Casing Sizes

Pump Bowl Diameter, in.	Suggested Casing Size, in.	Minimum Casing Size, in.	Submersible Flow Range (3450 rpm), gpm	Lineshaft Flow Range (1750 rpm), gpm
4	6	5	<80	<50
6	10	8	80 to 350	50 to 175
7	12	10	250 to 600	150 to 275
8	12	10	360 to 800	250 to 500
9	14	12	475 to 850	275 to 550
10	14	12		500 to 1000
12	16	14		900 to 1300

In addition to the production well, most systems should include an injection well to dispose of the fluid after it has passed through the system. Injection stabilizes the aquifer from which the fluid is withdrawn and helps to ensure long-term productivity.

Flow Testing

When possible, well testing should be completed before mechanical design. Only with actual flow test data and water chemical analysis information can accurate design proceed.

Flow testing can be divided into three different types of tests: rig, short-term, and long-term (Stiger et al. 1989). Rig tests are generally shorter than 24 h and are accomplished while the drilling rig is on site. The primary purpose of this test is to purge the well of remaining drilling fluids and cuttings and to get a preliminary indication of yield. The length of the test is generally governed by the time required for the water to run clean. The rate is determined by the available pumping equipment. Frequently the well is blown or pumped with the drilling rig's air compressor. As a result, little can be learned about the production characteristics of the well from a rig test. If the well is air lifted, it may not be useful to collect water samples for chemical analysis because certain chemical constituents may be oxidized by the compressed air.

Properly conducted, short-term, single-well tests of 4 h to 24 h duration yield information about the well flow rate, temperature, pressure, drawdown, and recovery. These tests are used most frequently for direct-use and GWHP applications. The test is generally run with a temporary electric submersible pump or lineshaft turbine pump driven by an internal combustion engine. The work is most often performed by a well pump contractor.

The test should involve at least three production rates, the largest being equal to the design flow rate for the system served. The three points are the minimum required to determine a productivity curve for the well that relates production to drawdown (Stiger et al. 1989). Water level and pumping rate should be stabilized at each point before the flow is increased. In most cases, water level is monitored with a "bubbler" or an electric sounder, and flow is measured using an orifice meter. This short-term test is generally used for small projects and provides information on yield, drawdown, and specific capacity.

Long-term tests of up to 30 days provide information on the reservoir. Normally these tests involve monitoring nearby wells to evaluate interference effects. The data are useful in calculating transmissivity and storage coefficient, reservoir boundaries, and recharge areas (Stiger et al. 1989) but are rarely used for direct-use and GWHP systems.

It is also important to collect background information prior to the test and water level recovery data after pumping has ceased. Recovery data in particular can be used to evaluate skin effect, which is a type of well flow resistance caused by residual drilling fluids, insufficient screen or slotted liner area, or improper filter pack.

Water Quality Testing

Geothermal fluids commonly contain seven key chemical species that produce a significant corrosive effect (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 3. Except as noted, the described effects are for carbon steel. Kindle and Woodruff (1981) present recommended procedures for complete chemical analysis of geothermal well water.

Two of these species are not reliably detected by standard water chemistry tests and deserve special mention. Dissolved oxygen does not occur naturally in low-temperature (120 to 220°F) geothermal fluids that contain traces of hydrogen sulfide. However, because of slow reaction kinetics, oxygen from air in-leakage may persist for some minutes. Once the geothermal fluid is produced, it is extremely difficult to prevent contamination, especially if the pumps used to move the fluid are not downhole submersible or lineshaft turbine pumps. Even if the fluid systems are maintained at positive pressure, air in-leakage at the pump seals is likely, particularly with the low level of maintenance in many installations.

Table 3 Principle Effects of Key Corrosive Species

Species	Principle 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, the described effects are for carbon steel.

Hydrogen sulfide is ubiquitous in extremely low concentrations in geothermal fluids above 120°F. This corrosive species also occurs naturally in many cooler ground waters. For alloys such as cupronickel, which are strongly affected by it, hydrogen sulfide concentrations in the low parts per billion (10^9) range may have a serious detrimental effect, especially if oxygen is also present. At these levels, the characteristic rotten egg odor of hydrogen sulfide may be absent, so field testing may be required for detection. Hydrogen sulfide levels down to 50 ppb can be detected using a simple field kit; however, absence of hydrogen sulfide at this low level may not preclude damage by this species.

Two other key species that should be measured in the field are pH and carbon dioxide concentrations. This is necessary because most geothermal fluids release carbon dioxide rapidly, causing a rise in pH.

Production of suspended solids (sand) from a well should be addressed during the well construction with gravel pack, screen, or both. Proper selection of the screen/gravel pack is based on sieve analysis of the cutting samples from the drilling process. Surface separation is less desirable because a surface separator requires the sand to pass first through the pump, reducing its useful life.

Biological fouling is largely a phenomenon of low-temperature (<90°F) wells. The most prominent organisms are various strains (*Galionella*, *Crenothrix*) of what are commonly referred to as iron bacteria. These organisms typically inhabit water with a pH range of 6.0 to 8.0, dissolved oxygen content of less than 5 ppm, ferrous iron content of less than 0.2 ppm, and a temperature of 46 to 61°F (Hackett and Lehr 1985). Iron bacteria can be identified microscopically. The most common treatment for iron bacteria infestation is chlorination, surging, and flashing. Successful use of this treatment depends on the maintenance of proper pH (less than 8.5), dosage, free residual chlorine content (200 to 500 gpm), contact time (24 h minimum), and agitation or surging. Hackett and Lehr (1985) provide additional detail on treatment.

EQUIPMENT AND MATERIALS

The primary equipment used in geothermal systems includes pumps, heat exchangers, and piping. Although some aspects of these components are unique to geothermal applications, many of them are of routine design. However, the great variability and general aggressiveness of the geothermal fluid necessitate limiting corrosion and scale buildup rather than relying on system cleanup. Corrosion and scaling can be limited by (1) proper system and equipment design or (2) treatment of the geothermal fluid, which is generally precluded by cost and environmental regulations relating to disposal.

Performance of Materials

Carbon Steel. The Ryznar Index has traditionally been used to estimate the corrosivity and scaling tendencies of potable water supplies. However, one study found no significant correlation (at the 95% confidence level) between carbon steel corrosion and the Ryznar Index (Ellis and Smith 1983). Therefore, the Ryznar and other indices based on calcium carbonate saturation should not be used to predict corrosion in geothermal systems, though they remain valid for scaling prediction.

In Class Va geothermal fluids [as described by Ellis (1989); <5000 ppm total key species (TKS), total alkalinity 207 to 1329 ppm as $CaCO_3$, pH 6.7 to 7.6] corrosion rates of about 5 to 20 mil/yr can be expected, often with severe pitting.

In Class Vb geothermal fluids [as described by Ellis (1989); <5000 ppm TKS, total alkalinity <210 ppm as $CACO_3$, pH 7.8 to 9.85], carbon steel piping has given good service in a number of systems, provided the system design rigorously excluded oxygen. However, introduction of 30 ppb oxygen under turbulent flow conditions causes a fourfold increase in uniform corrosion. Saturation with air often increases the corrosion rate by at least 15 times. Oxygen contamination at the 50 ppb level often causes severe pitting. Chronic oxygen contamination causes rapid failure.

In the case of buried steel pipe, the external surfaces must be protected from contact with groundwater. Groundwater is aerated and has caused pipe failures by external corrosion. Required external protection can be obtained by coatings, pipe-wrap, or preinsulated piping, provided the selected material resists the system operating temperature and thermal stress.

At temperatures above 135°F, galvanizing (zinc coating) does not reliably protect steel from either geothermal fluid or groundwater. Hydrogen blistering can be prevented by using void-free (killed) steels.

Low-alloy steels (steels containing not more than 4% alloying elements) have corrosion resistance similar, in most respects, to carbon steels. As in the case of carbon steels, sulfide promotes entry of atomic hydrogen into the metal lattice. If the steel exceeds a hardness of Rockwell C22, sulfide stress cracking may occur.

Copper and Copper Alloys. Copper fan coil units and copper-tubed heat exchangers have a consistently poor performance due to traces of sulfide species found in geothermal fluids in the United States. Copper tubing rapidly becomes fouled with cuprous sulfide films more than 1 mm thick. Serious crevice corrosion occurs at cracks in the film, and uniform corrosion rates of 2 to 6 mil/yr appear typical, based on failure analyses.

Experience in Iceland also indicates that copper is unsatisfactory for heat exchange service and that most brasses (Cu-Zn) and bronzes (Cu-Sn) are even less suitable. Cupronickel often performs more poorly than copper in low-temperature geothermal service because of trace sulfide.

Much less information is available regarding copper and copper alloys in non-heat-transfer service. Copper pipe shows corrosion behavior similar to copper heat exchange tubes under conditions of moderate turbulence (Reynolds numbers of 40,000 to 70,000). An internal inspection of yellow brass valves showed no significant corrosion. However, silicon bronze CA 875 (12-16Cr, 3-5Si, <0.05Pb, <0.05P), an alloy normally resistant to dealloying, failed in less than three years when used as a pump impeller. Leaded red brass (CA 836 or 838) and leaded red bronze (SAE 67) appear viable as pump internal parts. Based on a few tests at Class Va sites, aluminum bronzes have shown potential for corrosion in heavy-walled components (Ellis 1989).

Solder is yet another problem area for copper equipment. Lead-tin solder (50Pb, 50Sn) was observed to fail by dealloying after a few years' exposure. Silver solder (1Ag, 7P, Cu) was completely removed from joints in under two years. If the designer elects to accept this risk, solders containing at least 70% tin should be used.

Stainless Steel. Unlike copper and cupronickel, stainless steels are not affected by traces of hydrogen sulfide. Their most likely application is heat exchange surfaces. For economic reasons, most heat exchangers are probably of the plate-and-frame type, most of which will be fabricated with one of two standard alloys, Type 304 and Type 316 austenitic stainless steel. Some pump and valve trim also are fabricated from these or other stainless steels.

These alloys are subject to pitting and crevice corrosion above a threshold chloride level which depends on the chromium and molybdenum content of the alloy and on the temperature of the geothermal fluid. Above this temperature, the passivation film, which gives the stainless steel its corrosion resistance, is ruptured, and local pitting and crevice corrosion occur. Figure 5 shows the relationship between temperature, chloride level, and occurrence of localized corrosion of Type 304 and Type 316 stainless steel. This figure indicates, for example, that localized corrosion of Type 304 may occur in 80°F geothermal fluid if the chloride level exceeds approximately 210 ppm; Type 316 is resistant at that temperature until the chloride level reaches approximately 510 ppm. Due to its 2 to 3% molybdenum content, Type 316 is always more resistant to chlorides than is Type 304.

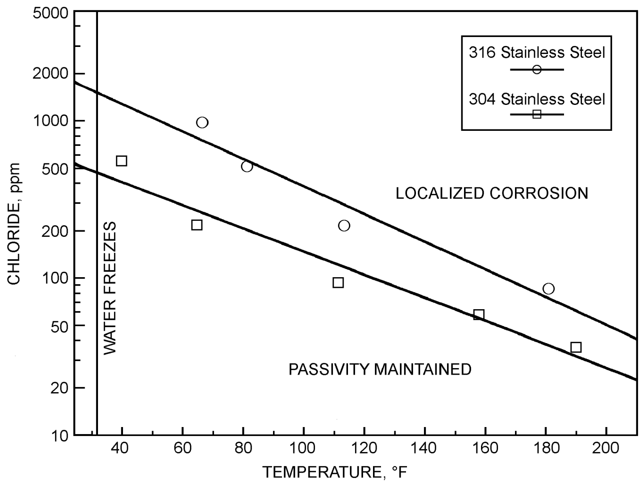

Fig. 5 Chloride Concentration Required to Produce Localized Corrosion of Stainless Steel as Function of Temperature
(Efrid and Moeller 1978)

Aluminum. Aluminum alloys are not acceptable in most cases because of catastrophic pitting.

Titanium. This material has extremely good corrosion resistance and could be used for heat exchanger plates in any low-temperature geothermal fluid, regardless of dissolved oxygen content. Great care is required if acid cleaning is to be performed. The vendor's instructions must be followed. The titanium should not be scratched with iron or steel tools, as this can cause pitting.

Chlorinated Polyvinyl Chloride (CPVC) and Fiber-Reinforced Plastic (FRP). These materials are easily fabricated and are not adversely affected by oxygen intrusion. External protection against groundwater is not required. The mechanical properties of these materials at higher temperatures may vary greatly from those at ambient temperature, and the mechanical limits of the materials should not be exceeded. The usual mode of failure is creep rupture: strength decays with time. Manufacturer's directions for joining should be followed to avoid premature failure of joints.

Elastomeric Seals. Tests on O-ring materials in a low-temperature system in Texas indicated that a fluoroelastomer is the best material for piping of this nature; Buna-N is also acceptable. Neoprene, which developed extreme compression set, was a failure. Natural rubber and Buna-S should also be avoided. Ethylene-propylene terpolymer (EPDM) has been used successfully in gasket, O-ring, and valve seats in many systems. EPDM materials have swollen in some systems using oil-lubricated turbine pumps (Ellis 1989).

Pumps

Production well pumps are among the most critical components in a geothermal system and have in the past been the source of much system downtime. Therefore, proper selection and design of the production well pump is extremely important. Well pumps are available for larger systems in two general configurations: lineshaft and submersible. The lineshaft type is most often used for direct-use systems (Rafferty 1989a).

Lineshaft Pumps. Lineshaft pumps are similar to those typically used in irrigation applications. An above-ground driver, typically an electric motor, rotates a vertical shaft extending down the well to the pump. The shaft rotates the pump impellers in the pump bowl assembly, which is positioned at such a depth in the wellbore that adequate net positive suction head (NPSH) is available when the unit is operating. Two designs for the shaft/bearing portion of the pump are available: open and enclosed.

In the **open lineshaft pump**, the shaft bearings are supported in "spiders," which are anchored to the pump column pipe at 5 to 10 ft intervals. The shaft and bearings are lubricated by the fluid flowing up the pump column. In geothermal applications, bearing materials for open lineshaft designs have consisted of either bronze or various elastomer compounds. The shaft material is typically stainless steel. Experience with this design in geothermal applications has been mixed. It appears that the open lineshaft design is most successful in applications with high (<50 ft) static water levels or flowing artesian conditions. Open lineshaft pumps are generally less expensive than enclosed lineshaft pumps for the same application.

In an **enclosed lineshaft pump**, an enclosing tube protects the shaft and bearings from exposure to the pumped fluid. A lubricating fluid is admitted to the enclosed tube at the wellhead. It flows down the tube, lubricates the bearings, and exits where the column attaches to the bowl assembly. The bowl shaft and bearings are lubricated by the pumped fluid. Oil-lubricated, enclosed lineshaft pumps have the longest service life in low-temperature, direct-use applications.

These pumps typically include carbon or stainless steel shafts and bronze bearings in the lineshaft assembly, and stainless steel shafts and leaded red bronze bearings in the bowl assembly. Keyed-type impeller connections (to the pump shaft) are superior to collet-type connections (Rafferty 1989a).

Because of the lineshaft bearings, the reliability of lineshaft pumps decreases as the pump-setting depth increases. Nichols (1978) indicates that at depths greater than about 800 ft, reliability is questionable, even under good pumping conditions.

Submersible Pumps. The electrical submersible pump consists of three primary components located downhole: the pump, the drive motor, and the motor protector. The pump is a vertical multistage centrifugal type. The motor is usually a three-phase induction type that is filled with oil for cooling and lubrication; it is cooled by heat transfer to the pumped fluid moving up the well. The motor protector is located between the pump and the motor and isolates the motor from the well fluid while allowing pressure equalization between the pump intake and the motor cavity.

The electrical submersible pump has several advantages over lineshaft pumps, particularly for wells requiring greater pump bowl setting depths. The deeper the well, the greater the economic advantage of the submersible pump. Moreover, it is more versatile, adapting more easily to different depths. The breakover point is at a pump depth of 800 ft; the submersible pump is desirable at greater pump depths, and the lineshaft is preferred at lesser depths.

Submersible pumps have not demonstrated acceptable lifetimes in most geothermal applications. Although they are commonly used in high-temperature, downhole applications in the oil and gas industry, the acceptable overhaul interval in that industry is much shorter than in a geothermal application. In addition, most submersibles operate at 3600 rpm, resulting in greater susceptibility to erosion in aquifers that produce moderate amounts of sand. They have, however, been applied in geothermal projects where an existing well of relatively small diameter must be used. At 3600 rpm, they provide greater flow capacity for a given bowl size than an equivalent 1750 rpm lineshaft pump.

Standard "cold-water" submersible motors can be used at temperatures up to approximately 120°F with adequate precautions. These consist primarily of ensuring adequate water velocity past the motor (minimum 3 ft/s), which may require the use of a sleeve, and a small degree of motor oversizing (Franklin Electric 2001)

Well Pump Control. Well pumps can be controlled using variable-speed drives. Historically, vertical turbine pumps have used fluid couplings for this purpose; recently, variable-frequency drive (VFD) has been more common. Submersible pumps can also be controlled using VFD, but special precautions are required. Drive-rated motors are not commonly available for these applications, so external electronic protection should be used to prevent premature motor failure. In addition, the motor manufacturer must be aware that the motor will applied in a variable-speed application. Finally, because of the large static head in many well pump applications, controls should be configured to prevent the pump from operating at no-flow conditions.

Heat Exchangers

Geothermal fluids can be isolated with large central heat exchangers, as in the case of a district heating system, or with exchangers at individual buildings or loads. In both cases, the principle is to isolate the geothermal fluid from complicated systems or those that cannot readily be designed to be compatible with the geothermal fluid. The principal types of heat exchangers used in transferring energy from the geothermal fluid are plate and downhole.

Plate Heat Exchangers. For all but the very smallest applications, plate and frame heat exchangers are the most commonly used design. Available in corrosion-resistant materials, easily cleanable, and able to accommodate increased loads through the addition of plates, these exchangers are well suited to geothermal applications. The high performance of plate heat exchangers is also an asset in many system designs. Because geothermal resource temperatures are often less than those used in conventional hot-water heating system design, minimizing temperature loss at the heat exchanger is frequently a design issue. Approach temperatures of 5°F and less are common.

Materials for plate heat exchangers in direct-use applications normally include Buna-N or EPDM gaskets and 316 or titanium plates. The selection of plates is often a function of temperature and chloride content of the water. For applications characterized by chloride contents of >50 ppm at 200°F, titanium would be used. At lower temperatures, much higher chloride exposure can be tolerated (Figure 5).

Downhole Heat Exchangers. The downhole heat exchanger (DHE) is an arrangement of pipes or tubes suspended in a wellbore (Culver and Reistad 1978). A secondary fluid circulates from the load through the exchanger and back to the plant in a closed loop. The primary advantage of a DHE is that only heat is extracted from the earth, which eliminates the need to dispose of spent fluids. Other advantages are the elimination of (1) pumps with their initial operating and maintenance costs, (2) the potential for depletion of groundwater, and (3) environmental and institutional restrictions on surface disposal. One disadvantage of a DHE is the limited amount of heat that can be extracted from or rejected to the well. The amount of heat extracted depends on the hydraulic conductivity of the aquifer and well design. Because of the limitations of natural convection, only about 10% of the heat output of the well is available from a DHE in comparison to pumping and using surface heat exchange (Reistad et al. 1979). With wells of approximately 200°F and depths of 500 ft, output under favorable conditions is sufficient to serve the needs of up to five homes.

The DHE in low- to moderate-temperature geothermal wells is installed in a casing, as shown in Figure 6.

Downhole heat exchangers with higher outputs rely on water circulation within the well, whereas lower-output DHEs rely on earth conduction. Circulation in the well can be accomplished by two methods: (1) undersized casing and (2) convection tube. Both methods rely on the difference in density between the water surrounding the DHE and that in the aquifer.

Circulation provides the following advantages:

- Water circulates around the DHE at velocities that, in optimum conditions, can approach those in the shell of a shell-and-tube exchanger.

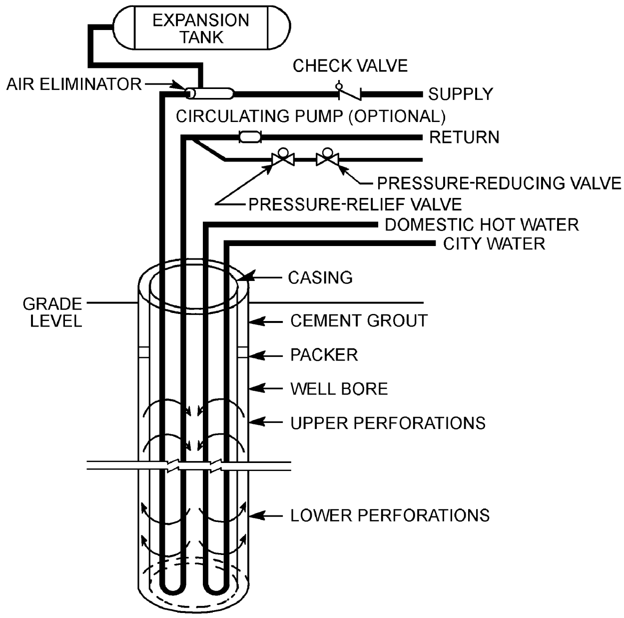

Fig. 6 Typical Connection of Downhole Heat Exchanger for Space and Domestic Hot-Water Heating
(Reistad et al. 1979)

- Hot water moving up the annulus heats the upper rocks and the well becomes nearly isothermal.
- Some of the cool water, being more dense than the water in the aquifer, sinks into the aquifer and is replaced by hotter water, which flows up the annulus.

Figure 6 shows well construction in competent formation (i.e., where the wellbore will stand open without a casing). An undersized casing with perforations at the lowest producing zone (usually near the bottom) and just below the static water level is installed. A packer near the top of the competent formation permits the installation of cement between it and the surface. When the DHE is installed and heat extracted, thermosiphoning causes cooler water inside the casing to move to the bottom, and hotter water moves up the annulus outside the casing.

Because most DHEs are used for space heating (an intermittent operation), the heated rocks in the upper portion of the well store heat for the next cycle.

In areas where the well will not stand open without casing, a convection tube can be used. This is a pipe one-half the diameter of the casing either hung with its lower end above the well bottom and its upper end below the surface or set on the bottom with perforations at the bottom and below the static water level. If a U-bend DHE is used, it can be either inside or outside the convection tube. DHEs operate best in aquifers with a high hydraulic conductivity and that provide the water movement for heat and mass transfer.

Valves

In large (>2.5 in.) pipe sizes, resilient-lined butterfly valves have been the choice for geothermal applications. The lining material protects the valve body from exposure to the geothermal fluid. The rotary rather than reciprocating motion of the stem makes the valve less susceptible to leakage and build-up of scale deposits. For many direct-use applications, these valves are composed of Buna-N or EPDM seats, stainless steel shafts, and bronze or stainless steel disks. Where oil-lubricated well pumps are used, a seat material of oil-resistant material is recommended. Gate valves have been used in some larger geothermal systems but have been subject to stem leakage and seizure. After several years of use, they are no longer capable of 100% shutoff.

Piping

Piping in geothermal systems can be divided into two broad groups: pipes used inside buildings and those used outside, typically buried. Indoor piping carrying geothermal water is usually limited to the mechanical room, and is generally the same as that used in other hydronic applications, except for the materials. Because of the corrosive effects of hydrogen sulfide, copper piping is inappropriate; primarily carbon steel is used for these applications.

For buried piping, many existing systems have used some form of nonmetallic piping, particularly asbestos cement and fiberglass. Asbestos cement is no longer available. With the cost of fiberglass for larger sizes (>6 in.) sometimes prohibitive, ductile iron is frequently used. Available in sizes >2 in., ductile iron offers several positive characteristics: low cost, familiarity to installation crews, and wide availability. It requires no allowances for thermal expansion; tyton joints are used.

Most larger-diameter buried piping is pre-insulated. The basic ductile iron pipe is surrounded by a layer of insulation (typically polyurethane), which is protected by an outer jacket of PVC or PE.

The standard ductile iron product used for municipal water systems is sometimes modified for geothermal use. The seal coat used to protect the cement lining of the pipe is not suitable for the temperature of most geothermal applications; in applications where the geothermal water is especially soft or low in pH, the cement lining should be omitted as well. Special high-temperature gaskets (usually EPDM) are used in geothermal applications. Few problems have been encountered in the use of ferrous piping with low-temperature geothermal fluids unless high chloride concentration, low (<7.0) pH, or oxygen is present in the fluid. Most cases of corrosion failure have resulted from external attack due to soil moisture in buried applications.

RESIDENTIAL AND COMMERCIAL BUILDING APPLICATIONS

The primary applications for the direct use of geothermal energy in the residential and commercial area are space heating, domestic water heating, and space cooling (using the absorption process). Although geothermal space and domestic hot-water heating are widespread, space cooling is rare.

Space Heating

Figure 7 illustrates a system that uses geothermal fluid at 170°F (Austin 1978). The geothermal fluid is used in two main equipment components for heating the buildings: (1) a plate heat exchanger that supplies energy to a closed heating loop previously heated by a natural gas boiler (the boiler remains as a standby unit) and (2) a water-to-air coil used for preheating ventilation air. In this system, proper control is crucial for economical operation.

The average temperature of the discharged fluid is 120 to 130°F. The geothermal fluid is used directly in the preheat terminal equipment within the buildings (this would probably not be the case if the system were being designed today). Several corrosion problems have arisen in the direct use, mainly because of the action of hydrogen sulfide on copper-based equipment parts (Mitchell 1980). Even with these difficulties, the geothermal system appears to be highly cost-effective (Lienau 1979).

Figure 8 shows a geothermal district heating system that is unique in terms of its design based on a peak load Δt of 100°F using a 190°F resource. It is of closed-loop design with central heat exchangers. The production well has an artesian shut-in pressure of 25 psi, so the system operates with no production pump for most of the year. During colder weather, a surface centrifugal pump located at the wellhead boosts the pressure.

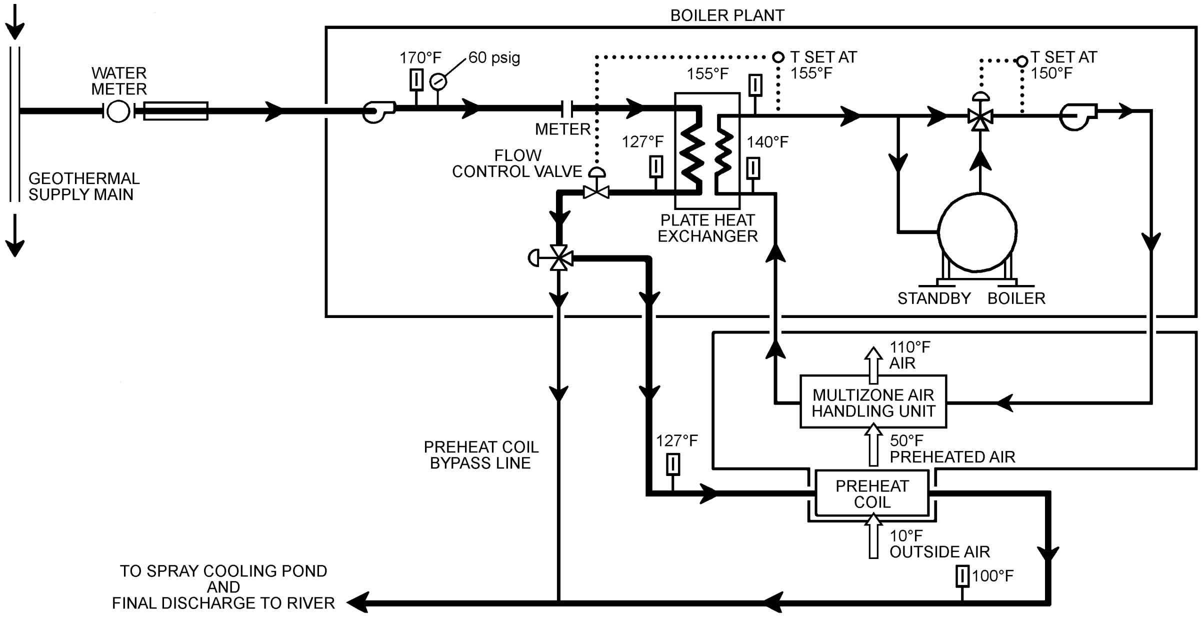

Fig. 7 Heating System Schematic

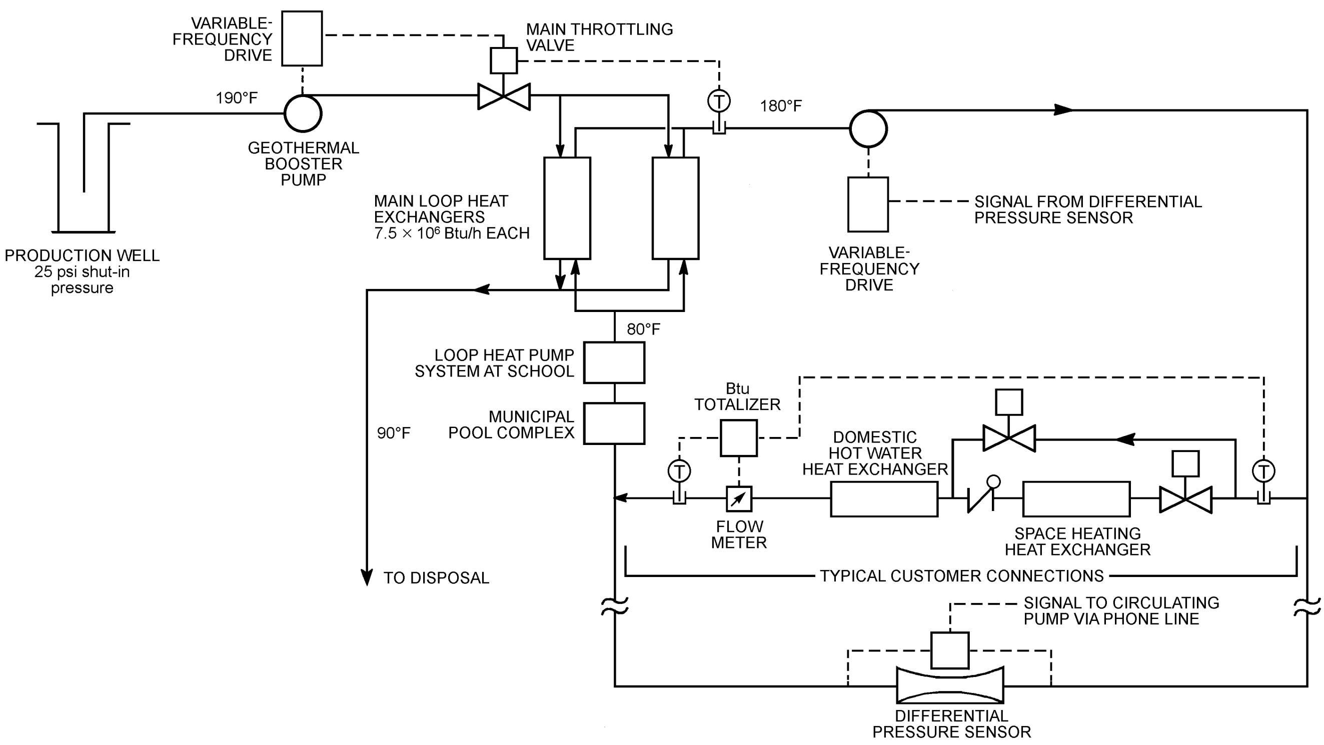

Fig. 8 Closed Geothermal District Heating System
(Rafferty 1989)

Geothermal flow from the production well is initially controlled by a throttling valve on the supply line to the main heat exchanger, which responds to a temperature signal from the supply water on the closed-loop side of the heat exchanger. When the throttling valve has reached the full-open position, the production booster pump is enabled. The pump is controlled through a variable-frequency drive that responds to the same supply-water signal as the throttling valve. The booster pump is designed for a peak flow rate of 300 gpm of 190°F water.

A few district heating systems have also been installed using an open distribution system. In this design, central heat exchangers (as in Figure 8) are eliminated and the geothermal water is delivered to individual building heat exchangers. When more than a few buildings are connected to the system, using central heat exchangers is normally more cost-effective.

The terminal equipment used in geothermal systems is the same as that used in nongeothermal heating systems. However, certain types of equipment are better suited to geothermal design than others.

In many cases, buildings heated by geothermal sources operate their heating equipment at less than conventional temperatures because of the low temperature of the resource and the use of heat exchangers to isolate the fluids from the building loop. Because many geothermal sources are designed to take advantage of a large Δt, proper selection of equipment with respect to the low flow and low temperature is important.

Finned-coil, forced-air systems generally function best in this low-temperature/high Δt situation. One or two additional rows of coil depth compensate for the lower supply-water temperature. Although an increased Δt affects coil circuiting, it improves controllability. This type of system should be capable of using a supply water temperature as low as 110°F.

Radiant floor panels are well suited to the use of very low water temperature, particularly in industrial applications with little or no floor covering. In industrial settings, with a bare floor and a relatively low space-temperature requirement, the average water temperature could be as low as 95°F. For a higher space temperature and/or thick floor coverings, a higher water temperature may be required.

Baseboard convectors and similar equipment are the least capable of operating at low supply-water temperature. At 150°F average water temperatures, derating factors for this design load may be affected. This type of equipment can be operated at low temperatures from the geothermal source to provide base-load heating. Peak load can be supplied by a conventional boiler.

Domestic Water Heating

Domestic water heating in a district space-heating system is beneficial because it increases the overall size of the energy load, the energy demand density, and the 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 commercially 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 9 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 would result in a 50% decrease in capacity, which seriously affects the economics of absorption cooling at a low resource temperature.

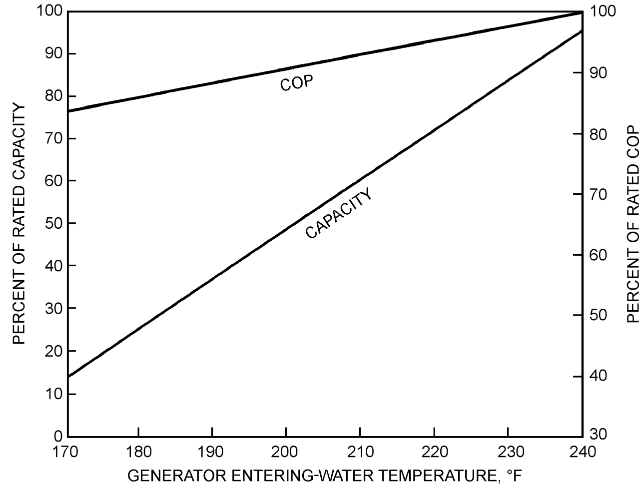

Fig. 9 Typical Lithium Bromide Absorption Chiller Performance Versus Temperature
(Christen 1977)

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 the building flow requirements for space heating and cooling. For example, assume a 200,000 ft^2 building is to use a geothermal resource for heating and cooling. At 25 $Btu/h \cdot ft^2$ and a design Δt of 40°F, the flow requirement for heating is 250 gpm. At 30 $Btu/h \cdot ft^2$, a Δt of 15°F, and a COP of 0.65, the flow requirement for cooling is 1230 gpm.

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 for this are questionable. Small absorption equipment would generally compete with package direct-expansion units in this range; the 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 1989b).

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 (1) they operate year-round, which gives them greater load factors than possible with space-conditioning applications; (2) they do not require an extensive (and expensive) distribution to dispersed energy consumers, as is common in district heating; and (3) they 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.

GROUND-SOURCE HEAT PUMPS

Ground-source heat pumps were originally developed in the residential arena and are now being 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) and Caneta Research (1995) have a more complete overview of ground-source heat pumps. OSU (1988a, 1988b) and Kavanaugh (1991) provide a more detailed treatment of the design and installation of ground-source heat pumps, but the focus of these two documents 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 (1993).

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. Included under the general term are **ground-coupled (GCHP)**, **groundwater (GWHP)**, and **surface water (SWHP) heat pumps**. Many parallel terms exist [e.g., **geothermal heat pumps (GHP)**, earth energy systems, and ground-source (GS) systems] and are used to meet a variety of marketing or institutional needs (Kavanaugh 1992). Chapter 8 of the 2000 *ASHRAE Handbook—Systems and Equipment* should be consulted for a discussion of the merits of various other nongeothermal heat sources/sinks.

Ground-Coupled Heat Pump Systems

The GCHP is a subset of the GSHP and is often called a closed-loop ground-source heat pump. A GCHP refers to a system that consists of a reversible vapor compression cycle that is linked to a closed ground heat exchanger buried in soil (Figure 10). 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. A second type of GCHP is the direct-expansion (DX) GCHP, which uses a buried copper piping network through which refrigerant is circulated. To distinguish them from DX GCHPs, systems using water-to-air and water-to-water heat pumps are often referred to as GCHPs with secondary solution loops.

The GCHP is further subdivided according to ground heat exchanger design: vertical and horizontal. **Vertical** GCHPs (Figure 11) generally consist of two small-diameter, high-density polyethylene (HDPE) tubes that have been 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 range from 50 to 600 ft, depending on local drilling conditions and available equipment.

A minimum borehole separation distance of 20 ft is recommended when loops are placed in a grid pattern. This distance may be reduced when the bores are placed in a single row, the annual heating load is much greater than the annual cooling load, or vertical water movement mitigates the effect of heat buildup in the loop field.

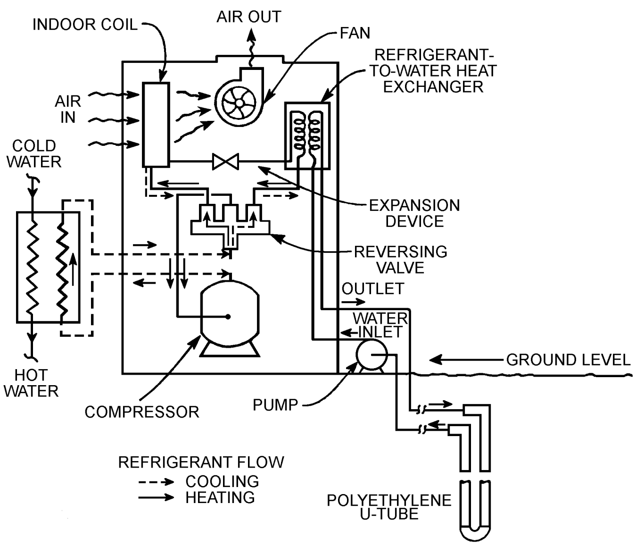

Fig. 10 Vertical Closed-Loop Ground-Coupled Heat Pump System
(Kavanaugh 1985)

The 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 drill the borehole and (2) the limited availability of contractors to perform such work.

Hybrid systems are a variation of ground-coupled systems in which a smaller ground loop is used, augmented during the cooling mode by a cooling tower. This approach can have merit in large cooling-dominated applications. The ground loop is sized to meet the heating requirements. The downsized loop is used in conjunction with the cooling tower (usually the closed-circuit fluid cooler type) to meet the heat rejection load. Use of the tower reduces the capital cost of the ground loop in such applications, but somewhat increases maintenance requirements.

Horizontal GCHPs (Figure 12) can be divided into at least three subgroups: single-pipe, multiple-pipe, and spiral. Single-pipe horizontal GCHPs were initially placed in narrow trenches at least 4 ft deep. These designs require the greatest amount of ground area. Multiple pipes (usually two, four, or six), placed in a single trench, can reduce the amount of required ground area. Trench length is reduced with multiple-pipe GCHPs, but total pipe

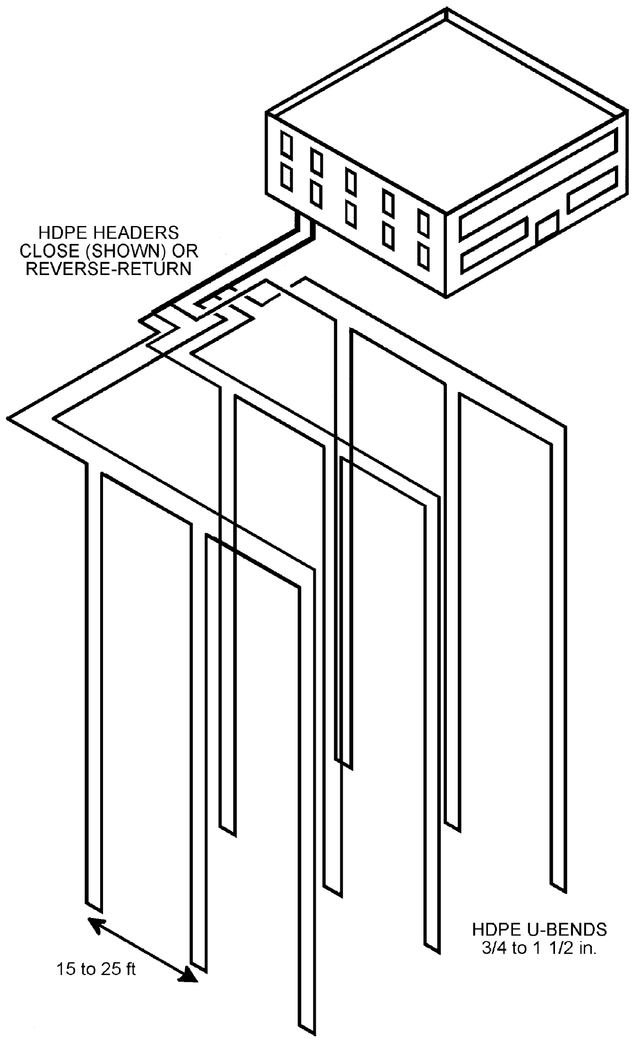

Fig. 11 Vertical Ground-Coupled Heat Pump Piping

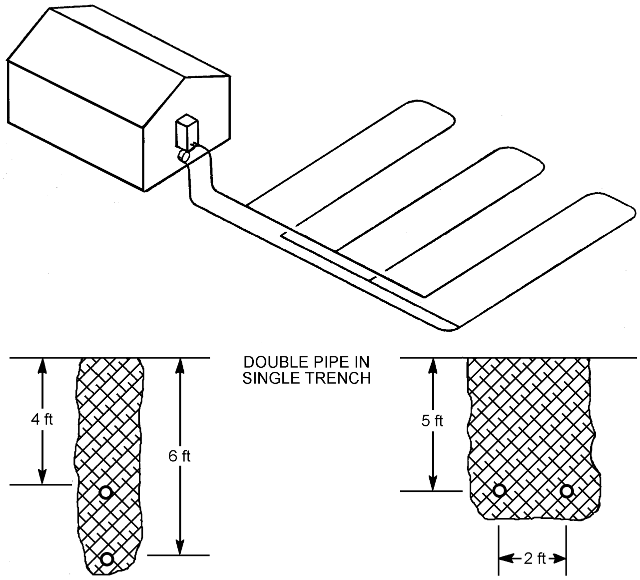

Fig. 12 Horizontal Ground-Coupled Heat Pump Piping

length must be increased to overcome thermal interference from adjacent pipes. The spiral coil is reported to further reduce required ground area. These horizontal ground heat exchangers are made by stretching small-diameter polyethylene tubing from the tight coil in which it is shipped into an extended coil that can be placed vertically in a narrow trench or laid flat at the bottom of a wide trench. Recommended trench lengths are only 20 to 30% of single-pipe horizontal GCHPs, but trenches may need to be twice this length to achieve equivalent thermal performance.

The advantages of horizontal GCHPs are that (1) they are typically less expensive than vertical GCHPs because relatively low-cost installation equipment is widely available, (2) many residential applications have adequate ground area, and (3) trained equipment operators are more widely available. Disadvantages include, in addition to a larger ground area requirement, greater adverse variations in performance because (1) ground temperatures and thermal properties fluctuate with season, rainfall, and burial depth, (2) slightly higher pumping-energy requirements, and (3) lower system efficiencies. OSU (1988a, 1988b) and Svec (1990) cover the design and installation of horizontal GCHPs.

Groundwater Heat Pump Systems

The second subset of GSHPs is groundwater heat pumps (Figure 13). Until the recent development of GCHPs, they were the most widely used type of GSHP. In the commercial sector, GWHPs can be an attractive alternative because large quantities of water can be delivered from and returned to relatively inexpensive wells that require very little ground area. Whereas the cost per unit capacity of the ground heat exchanger is relatively constant for GCHPs, the cost per unit capacity of a well water system is much lower for a large GWHP system. A single pair of high-volume wells can serve an entire building. Properly designed groundwater loops with well-developed water wells require no more maintenance than conventional air and water central HVAC. When the groundwater is injected back into the aquifer by a second well, net water use is zero.

One widely used design places a central water-to-water heat exchanger between the groundwater and a closed water loop which is connected to water-to-air heat pumps located in the building. A second possibility is to circulate groundwater through a heat recovery chiller (isolated with a heat exchanger), and to heat and cool the building with a distributed hydronic loop.

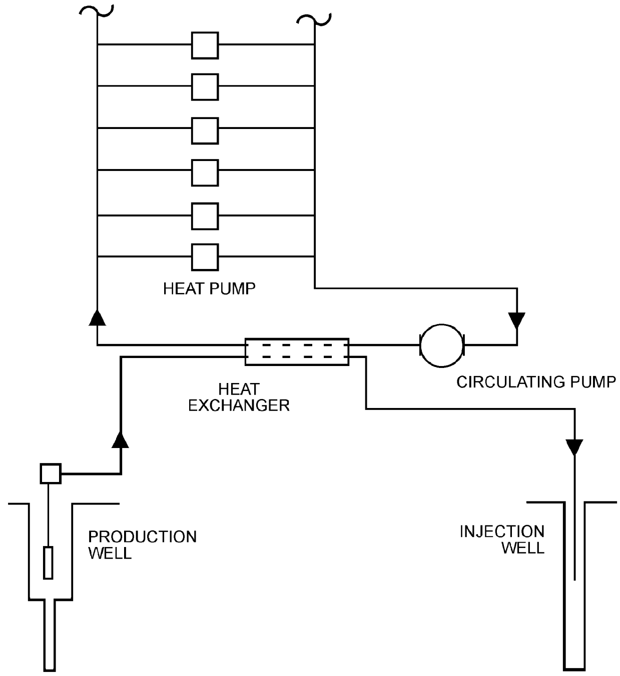

Fig. 13 Unitary Groundwater Heat Pump System

Both types and other variations may be suited for direct preconditioning in much of the United States. Groundwater below 60°F can be circulated directly through hydronic coils in series or in parallel with heat pumps. The cool groundwater can displace a large amount of energy that would otherwise have to be generated by mechanical refrigeration.

The advantages of GWHPs under suitable conditions are (1) they cost less than GCHP equipment, (2) the space required for the water well is very compact, (3) water well contractors are widely available, and (4) the technology has been used for decades in some of the largest commercial systems.

Disadvantages are that (1) local environmental regulations may be restrictive, (2) water availability may be limited, (3) fouling precautions may be necessary if the wells are not properly developed or water quality is poor, and (4) pumping energy may be high if the system is poorly designed or draws from a deep aquifer.

Surface Water Heat Pump Systems

Surface water heat pumps have been included as a subset of GSHPs because of the similarities in applications and installation methods. SWHPs can be either closed-loop systems similar to GCHPs or open-loop systems similar to GWHPs. However, the thermal characteristics of surface water bodies are quite different than those of the ground or groundwater. Some unique applications are possible, though special precautions may be warranted.

Closed-loop SWHPs (Figure 14) consist of water-to-air or water-to-water heat pumps connected to a piping network placed in a lake, river, or other open body of water. A pump circulates water or a water-antifreeze solution through the heat pump water-to-refrigerant heat exchanger and the submerged piping loop, which transfers heat to or from the body of water. The recommended piping material is thermally fused HDPE tubing with ultraviolet (UV) radiation protection.

The advantages of closed-loop SWHPs are (1) relatively low cost (compared to GCHPs) due to reduced excavation costs, (2) low pumping-energy requirements, (3) low maintenance requirements, and (4) low operating cost. Disadvantages are (1) the possibility of coil damage in public lakes and (2) wide variation in water temperature with outdoor conditions if lakes are small and/or shallow. Such variation in water temperature would cause undesirable variations in efficiency and capacity, though not as severe as with air-source heat pumps.

Open-loop SWHPs can use surface water bodies the way cooling towers are used, but without the need for fan energy or frequent maintenance. In warm climates, lakes can also serve as heat sources during the winter heating mode, but in colder climates where water temperatures drop below 45°F, closed-loop systems are the only viable option for heating.

Lake water can be pumped directly to water-to-air or water-to-water heat pumps or through an intermediate heat exchanger that is connected to the units with a closed piping loop. Direct systems tend to be smaller, having only a few heat pumps. In deep lakes (40 ft or more), there is often enough thermal stratification throughout the year that direct cooling or precooling is possible. Water can be pumped from the bottom of deep lakes through a coil in the return air duct. Total cooling is a possibility if water is 50°F or below. Precooling is possible with warmer water, which can then be circulated through the heat pump units.

Site Characterization

Site characteristics influence the GSHP system most suitable for a particular location. Site characterization is the evaluation of a site's geology and hydrogeology with respect to its effect on GSHP system design. Important issues include presence or absence of water, depth to water, water (or soil/rock) temperature, depth to rock, rock type, and the nature and thickness of unconsolidated materials overlying the rock. Information about the nature of water resources at the site helps to determine whether an open-loop system may be possible. Depth to water affects pumping energy for an open-loop system and possibly the type of rig used for drilling closed-loop boreholes. Groundwater temperature in most locations is the same as the undisturbed ground temperature. These temperatures are key inputs to the design of GSHP systems. The types of soil and rock allow a preliminary evaluation of the range of thermal conductivity/diffusivity that might be expected. The thickness and nature of the unconsolidated (soil, gravel, sand, clay, etc.) materials overlying the rock can influence whether casing will be required in the upper portion of boreholes for closed-loop systems, a factor which increases drilling cost.

After the GSHP system type has been decided, specific details about the subsurface materials' (rock/soil) thermal conductivity and diffusivity, water well static and pumping levels, drawdown, etc., are necessary to design the system. The methods for securing these more detailed data are discussed in other parts of this chapter.

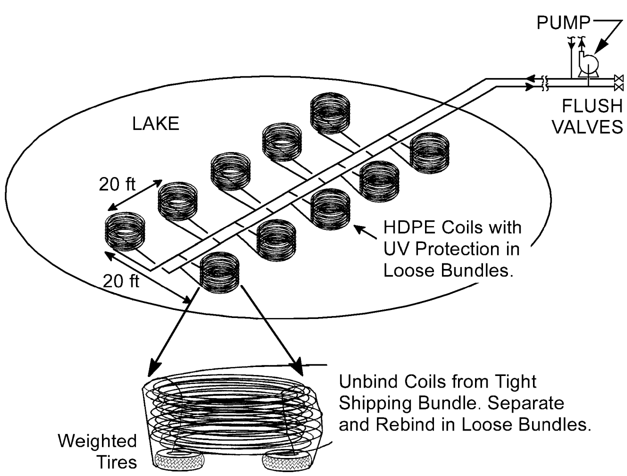

Fig. 14 Lake Loop Piping

There are many sources for gathering site characterization information, such as geologic and hydrologic maps, state geology and water regulatory agencies, the U.S. Geologic Survey (USGS 1995), and any information that may be available from geotechnical studies of the site. Among the best sources of information are water well completion reports for nearby water wells. These reports are filed by the driller upon completion of a water well and provide a great deal of information of interest for both open- and closed-loop designs. The most thorough versions of well completion reports (level of detail varies by state) will cover all of the issues of interest listed at the beginning of this section. Information about access to and interpretation of these reports and other sources of information for site characterization is included in Sachs (2002) and Rafferty (2000c).

Once the type of system has been selected, more site-specific tests (ground thermal properties test for GCHP or well flow test for GWHP) can be used to determine the parameters necessary for system design.

Commissioning GSHP Systems

The design phase of GSHP commissioning requires a thorough site survey and characterization, accurate load modeling, and ensuring that the design chosen (and its documentation) will meet the design intent.

The construction phase is dominated by observation of installation and verification of prefunctional checks and tests. It also involves planning, training development, and other activities to help future building operators understand the HVAC system.

The acceptance phase starts with functional tests and verification of all test results. It continues with full documentation: completing the commission report to include records of design changes and all as-built plans and documents, and completing the operations and maintenance manual and system manual. Finally, after system testing and balancing is complete, the owner's operating staff are trained. The acceptance phase ends when "substantial completion" is reached. The warranty period begins from this date.

Table 4 provides information on tasks and participants involved in the GSHP commissioning process. Additional details on this topic, along with preventive maintenance and troubleshooting information, are included in Caneta (2001).

GROUND-COUPLED HEAT PUMPS

Vertical Design

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. Heat is added in a water loop at a constant rate and data are collected as shown in Figure 15. 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 listed in Kavanaugh (2000, 2001) as follows:

- Thermal property tests should be performed for 36 to 48 h.
- The heat rate should be 15 to 25 W per foot of bore, which are the expected peak loads on the U tubes for an actual heat pump system.
- The 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) vs. average loop temperature.

Table 4 Example of GSHP Commissioning Process for Mechanical Design

System	Function	Performed By	Witnessed By
Heat pump piping	Pressure test, clean, and fill	Contractor	A/E
Ground source piping	Pressure test, clean, fill, and purge air	Contractor Contractor	A/E
Pumps	Inspect, test, and start-up	Contractor	—
Heat recovery unit	Inspect, test, and start-up; provide clean set of filters, staff instruction	Manufacturer Contractor Manufacturer	CA — CA/owner
Heat pump units	Inspect, test, and start-up; provide clean filters, staff instruction	Manufacturer Contractor Manufacturer	— — CA/owner
Chemical treatment	Flushing and cleaning, chemical treatment, staff instruction	Contractor Contractor/ manufacturer Manufacturer	A/E and CA — CA/owner
Balancing	Balancing, spot checking, follow-up site visits	TAB contractor TAB contractor TAB contractor	— A/E and CA CA
Controls	Installation/commissioning, staff instruction, performance testing, seasonal testing	Contractor CA CA CA	— CA/owner — —

Source: Caneta (2001).
A/E = Architect/engineer
CA = Commissioning authority
TAB = Testing, adjusting, and balancing

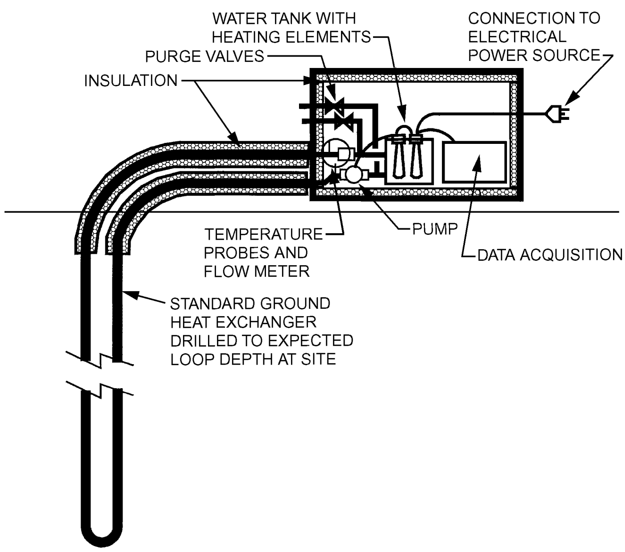

Fig. 15 Thermal Properties Test Apparatus

- The accuracy of the temperature measurement and recording devices should be ±0.5°F.
- The 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 recommended for low-conductivity soils (k < 1.0 Btu/h·ft·°F) after the ground loop 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 direct insertion of a probe inside a liquid-filled ground heat exchanger at three locations, representing the average, or by the measurement of temperature as the liquid exits the loop during the period immediately following start-up.
- Data collection should be at least once every 10 minutes.
- 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, the loop temperature should be allowed to return to within 0.5°F of the pretest initial ground temperature. This typically corresponds to a 10 to 12 day delay in mid- to high-conductivity formations and a 14 day delay in low-conductivity formations if a complete 48 h test has been conducted. Waiting periods can be proportionally reduced if test terminations occurred after shorter periods.

The ground loop design method uses a limited amount of information from commercial systems. A major missing component is long-term, field-monitored data. These data are needed to further validate the design method so that the effects of water movement and long-term heat storage are more fully addressed. The conservative designer can assume no benefit from water movement; designers who assume maximum benefit must ignore annual imbalances in heat rejection and absorption.

One design method is based on the solution of the equation for heat transfer from a cylinder buried in the earth. This equation was developed and evaluated by Carslaw and Jaeger (1947) and was suggested by Ingersoll and Zobel (1954) as an appropriate method of sizing ground heat exchangers. Kavanaugh (1985) adjusted the method to account for the U-bend arrangement and hourly heat rate variations. Alternative design methods are described by Eskilson (1987), Morrison (1997), Spitler et al. (2000), and Spitler (2000).

The method of Ingersoll and Zobel (1954) can be used to handle these shorter term variations. It uses the following steady-state heat transfer equation:

$$q = \frac{L(t_g - t_w)}{R} \tag{1}$$

where

q = heat transfer rate, Btu/h
L = required bore length, ft
t_g = ground temperature, °F
t_w = liquid temperature, °F
R = effective thermal resistance of the ground, h·ft·°F/Btu

The equation is rearranged to solve for the required bore length L. The steady-state equation is modified to represent the variable heat rate of a ground heat exchanger by using a series of constant heat rate "pulses." The thermal resistance of the ground per unit length is calculated as a function of time corresponding to the time span over which a particular heat pulse occurs. A term is also included to account for the thermal resistance of the pipe wall and interfaces between the pipe and fluid and the pipe and the ground. The resulting equation takes the following form for cooling:

$$L_c = \frac{q_a R_{ga} + (q_{lc} - 3.41\,W_c)(R_b + \text{PLF}_m R_{gm} + R_{gd} F_{sc})}{t_g - \dfrac{t_{wi} + t_{wo}}{2} - t_p} \tag{2}$$

The required length for heating is

$$L_h = \frac{q_a R_{ga} + (q_{lh} - 3.41\,W_h)(R_b + \text{PLF}_m R_{gm} + R_{gd} F_{sc})}{t_g - \dfrac{t_{wi} + t_{wo}}{2} - t_p} \tag{3}$$

Table 5 Summary of Potential Completion Methods for Different Geological Regime Types

Geological Regime Type	Grout 0.4 < k ≤ 0.8 Btu/h·ft·°F	Grout 0.8 < k ≤ 1.2 Btu/h·ft·°F	Grout k > 1.2 Btu/h·ft·°F	Backfill with Cutting	Two-Fill with Cuttings Below Aquifers	Two-Fill with Other* Below Aquifers
Clay or low-permeability rock,						
no aquifer	—	Yes	Yes	—	Yes	Yes
single-aquifer	—	Yes	Yes	—	—	Yes
multiple-aquifer	Yes	Yes	Yes	Yes	Yes	Yes
Permeable rock,						
no shallow aquifers	—	Yes	Yes	Yes	Yes	Yes
single-aquifer	—	Yes	Yes	Yes	Yes	Yes
multiple-aquifers	—	Yes	Yes	Yes	—	—
Karst terrains with secondary permeability	—	Yes	Yes	Yes	—	—
Fractured terrains with secondary permeability	—	Yes	Yes	Yes	Yes	Yes

*Use of a backfill material that has a thermal conductivity of $k \geq 1.4$ Btu/h·ft·°F
Yes = Recommended potentially viable backfill methods

The terms used in the Equations (2) and (3) are

F_{sc} = short circuit heat loss factor
L_c = required bore length for cooling, ft
L_h = required bore length for heating, ft
PLF_m = part load factor during design month
q_a = net annual average heat transfer to the ground, Btu/h
q_{lc} = building design cooling block load, Btu/h
q_{lh} = building design heating block load, Btu/h
R_{ga} = effective thermal resistance of ground (annual pulse), h·ft·°F/Btu
R_{gd} = effective thermal resistance of ground (daily pulse), h·ft·°F/Btu
R_{gm} = effective thermal resistance of ground—monthly pulse, h·ft·°F/Btu
R_b = thermal resistance of pipe, h·ft·°F/Btu
t_g = undisturbed ground temperature, °F
t_p = temperature penalty for interference of adjacent bores, °F
t_{wi} = liquid temperature at heat pump inlet, °F
t_{wo} = liquid temperature at heat pump outlet, °F
W_c = power input at design cooling load, W
W_h = power input at design heating load, W

Note: Heat transfer rate, building loads, and temperature penalties are positive for heating and negative for cooling.

Equations (2) and (3) consider three different pulses of heat to account for long-term heat imbalances (q_a), average monthly heat rates during the design month, and maximum heat rates for a short-term period during a design day. This period could be as short as 1 h, but a 4 h block is recommended.

The required bore is the larger of the two lengths L_c and L_h found from Equations (2) and (3). If L_c is larger than L_h, an oversized coil could be beneficial during the heating season. A second option is to install the smaller heating length along with a cooling tower to compensate for the undersized coil. If L_h is larger, the designer should install this length, and during the cooling mode the efficiency benefits of an oversized ground coil could be used to compensate for the higher first cost.

Selection of the fill material for the borehole is a function of thermal, regulatory, and economic considerations. Historically, a relatively low-thermal-conductivity bentonite grout commonly used in the water well industry and, in some cases, drill cuttings have been used as fill. More recently, thermally enhanced materials have been developed. Nutter et al. (2001) contains a detailed evaluation of potential fills and grouts for vertical boreholes. Table 5 summarizes potential completion methods for various geological conditions. The term "two-fill" refers to the practice of placing a low-permeability material in the upper portion of the hole and/or in intervals where it is required to separate individual aquifers, and a more thermally advantageous material in the remaining intervals.

The thermal resistance of the ground is calculated from ground properties, pipe dimensions, and operating periods of the representative heat rate pulses. Table 6 lists typical thermal properties for soils and fills for the annular region of the bore holes. Table 7 gives equivalent thermal resistance of the vertical high-density polyethylene (HDPE) U-tubes for two bore hole diameters (d_b).

Table 6 Thermal Properties of Selected Soils, Rocks, and Bore Grouts/Fills

	Dry Density, lb/ft^3	Conductivity, Btu/h·ft·°F	Diffusivity, ft^2/day
Soils			
Heavy clay (15% water)	120	0.8 to 1.1	0.45 to 0.65
Heavy clay (5% water)	120	0.6 to 0.8	0.5 to 0.65
Light clay (15% water)	80	0.4 to 0.6	0.35 to 0.5
Light clay (5% water)	80	0.3 to 0.5	0.35 to 0.6
Heavy sand (15% water)	120	1.6 to 2.2	0.9 to 1.2
Heavy sand (5% water)	120	1.2 to 1.9	1.0 to 1.5
Light sand (15% water)	80	0.6 to 1.2	0.5 to 1.0
Light sand (5% water)	80	0.5 to 1.1	0.6 to 1.3
Rocks			
Granite	165	1.3 to 2.1	0.9 to 1.4
Limestone	150 to 175	1.4 to 2.2	0.9 to 1.4
Sandstone		1.2 to 2.0	0.7 to 1.2
Wet shale	160 to 170	0.8 to 1.4	0.7 to 0.9
Dry shale		0.6 to 1.2	0.6 to 0.8
Grouts/Backfills			
Bentonite (20 to 30% solids)		0.42 to 0.43	
Neat cement (not recommended)		0.40 to 0.45	
20% Bentonite/80% SiO_2 sand		0.85 to 0.95	
15% Bentonite/85% SiO_2 sand		1.00 to 1.10	
10% Bentonite/90% SiO_2 sand		1.20 to 1.40	
30% concrete/70% SiO_2 sand, s. plasticizer		1.20 to 1.40	

Source: Kavanaugh and Rafferty (1997).

Table 7 Thermal Resistance of Bores (R_b) for High-Density Polyethylene U-Tube Vertical Ground Heat Exchangers

U-tube Diameter, in.	Bore Fill Conductivity,* h·ft·°F/Btu — 4 in. Diameter Bore 0.5	4 in. 1.0	4 in. 1.5	6 in. Diameter Bore 0.5	6 in. 1.0	6 in. 1.5
3/4	0.19	0.09	0.06	0.23	0.11	0.08
1	0.17	0.08	0.06	0.20	0.10	0.07
1-1/4	0.15	0.08	0.05	0.18	0.09	0.06

*Based on DR 11, HDPE tubing with turbulent flow

Corrections for Other Tubes and Flows

DR 9 Tubing	Re = 4000	Re = 1500
+0.02 h·ft·°F/Btu	+0.008 h·ft·°F/Btu	+0.025 h·ft·°F/Btu

Source: Kavanaugh (2001) and Remund and Paul (2000).

The most difficult parameters to evaluate in Equations (2) and (3) are the equivalent thermal resistances of the ground. The solutions of Carslaw and Jaeger (1947) require that the time of operation, the outside pipe diameter, and the thermal diffusivity of the ground be related in the dimensionless Fourier Number (Fo):

$$\mathrm{Fo} = \frac{4\alpha_g \tau}{d_b^2} \tag{4}$$

where

α_g = thermal diffusivity of the ground
τ = time of operation
d = outside pipe diameter

The method may be modified to permit calculation of equivalent thermal resistances for varying heat pulses. A system can be modeled by three heat pulses, a 10 year (3650 day) pulse of q_a, a 1 month (30 day) pulse of q_m, and a 6 h (0.25 day) pulse of q_d. Three times are defined as

$$\tau_1 = 3650 \text{ days}$$
$$\tau_2 = 3650 + 30 = 3680 \text{ days}$$
$$\tau_f = 3650 + 30 + 0.25 = 3680.25 \text{ days}$$

The Fourier number is then computed with the following values:

$$\mathrm{Fo}_f = 4\alpha\tau_f / d_b^2$$
$$\mathrm{Fo}_1 = 4\alpha(\tau_f - \tau_1)/d_b^2$$
$$\mathrm{Fo}_2 = 4\alpha(\tau_f - \tau_2)/d_b^2$$

An intermediate step in the computation of the thermal resistance of the ground using the methods of Ingersoll and Zobel (1954) is the determination of a G-factor, which is then determined from Figure 16 for each Fourier value.

$$R_{gA} = (G_f - G_1)/k_g \tag{5a}$$

$$R_{gB} = (G_1 - G_2)/k_g \tag{5b}$$

$$R_{gC} = G_2/k_g \tag{5c}$$

Ranges of the ground thermal conductivity k_g are given in Table 6. State geological surveys are a good source of soil and rock data. However, geotechnical site surveys are highly recommended to determine load soil and rock types and drilling conditions.

Performance degrades somewhat due to short-circuiting heat losses between the upward- and downward-flowing legs of a conventional U-bend loop. This degradation can be accounted for by introducing the short-circuit heat loss factor [F_{sc} in Equations (2) and (3)] in the table below. Normally U tubes are piped in parallel to the supply and return headers. Occasionally, when bore depths are shallow, two or three loops can be piped in series. In these cases, short-circuit heat loss is reduced; thus, the values for F_{sc} are smaller than for a single bore piped in series.

	F_{sc}	
Bores per Loop	**2 gpm/ton**	**3 gpm/ton**
1	1.06	1.04
2	1.03	1.02
3	1.02	1.01

Temperature. The remaining terms in Equations (2) and (3) are temperatures. The local deep ground temperature t_g can best be obtained from local water well logs and geological surveys. A second, less accurate source is a temperature contour map, similar to Figure 17, prepared by state geological surveys. A third source, which can yield ground temperatures within 4°F, is a map with contours, such as Figure 18. Comparison of Figures 17 and 18 indicates

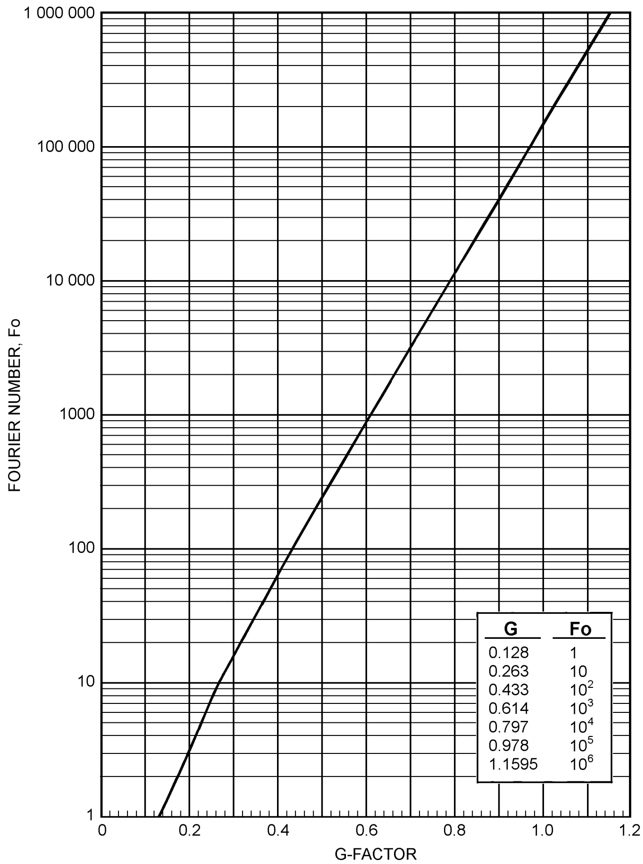

Fig. 16 Fourier/G-Factor Graph for Ground Thermal Resistance
(Kavanaugh and Rafferty 1997)

the complex variations that would not be accounted for without detailed contour maps.

Selecting the temperature t_{wi} of the water entering the unit is a critical choice in the design process. Choosing a value close to the ground temperature results in higher system efficiency, but the required ground coil length will be very long and thus unreasonably expensive. Choosing a value far from t_g allows the selection of a small, inexpensive ground coil, but the system's heat pumps will have both greatly reduced capacity during heating and high demand when cooling. Selecting t_{wi} to be 20 to 30°F higher than t_g in cooling and 10 to 20°F lower than t_g in heating is a good compromise between first cost and efficiency in many regions of the United States.

A final temperature to consider is the temperature penalty t_p resulting from thermal interferences from adjacent bores. The designer must select a reasonable separation distance to minimize required land area without causing large increases in the required bore length (L_c, L_h). Table 8 presents the temperature penalty for a 10 by 10 vertical grid of bores for various operating conditions after 10 years of operation. Correction factors are included to find the permanent temperature change in four other grid patterns. Note the higher the number of internal bores, the larger the correction factor.

The table includes the length of bore per ton of peak block load to which the temperature change corresponds. Smaller bore lengths per ton of peak block load result in larger temperature changes; the relationship between bore length and temperature change is inverse and linear.

The values in this table represent worst-case scenarios and the temperature change will usually be mitigated by groundwater recharge (vertical flow), groundwater movement (horizontal flow), and evaporation (and condensation) of water in the soil.

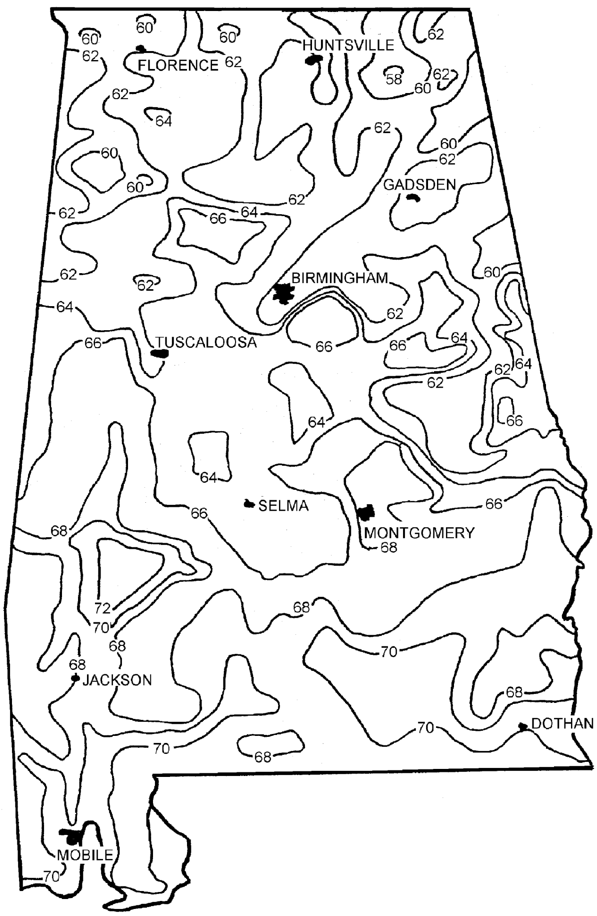

Fig. 17 Water and Ground Temperatures (°F) in Alabama at 50 to 150 ft Depth
(Chandler 1987)

Table 8 Long-Term Change in Ground Field Temperature for 10 by 10 Vertical Grid with 100 Ton Block Load

Equivalent Full Load Hours Heating/Cooling	Bore Separation, ft	Temperature Penalty, °F	Base Bore Length, ft/ton (refrigeration)
1000/500	15	Negligible	180
1000/1000	15	4.7	225
	20	2.4	206
500/1000	15	7.6	260
	20	3.9	228
	15	12.8	345
500/1500	20	6.7	254
	25	3.5	224
	15	Not advisable	
0/2000	20	10.4	316
	25	5.5	252
Correction Factors for Other Grid Patterns			
1 × 10 grid	2 × 10 grid	5 × 5 grid	20 × 20 grid
$C_f = 0.36$	$C_f = 0.45$	$C_f = 0.75$	$C_f = 1.14$

Source: Kavanaugh and Rafferty (1997)

Groundwater movement strongly affects the long-term temperature change in a densely packed ground loop field (Chiasson et al. 2000). Because the effect has not been thoroughly studied, the design engineer must establish a range of design lengths between one based on minimal groundwater movement, as in very tight clay soils with poor percolation rates, and a second based on the higher rates characteristic of porous aquifers.

The long-term temperature change table and a commonly used software for GCHP system design both involve the use of equivalent full-load hour (EFLH) calculations. To the extent that annual loads are proportional to peak loads, the equivalent full-load hours method provides a simple estimate of annual loads from peak loads. The EFLHs in Table 9 provide a quick means to estimate annual loads needed to size ground heat exchangers at the initial feasibility study phase of a project. Because EFLHs vary with both changes in annual loads and changes in peak loads, not all building parameters effects are included in EFLHs. For instance, the building operating hours will change annual loads by increasing the amount of time that internal gains are at elevated levels, but they do not change the peak load. Occupancy hours can add load without increasing the installed capacity, thereby changing the EFLHs. Furthermore, changes in other parameters, such as internal gains, will not necessarily scale with the system capacity in the same proportion as the annual load, again leading to changing EFLHs. Potential users of EFLHs must understand these sources of variability to use them effectively (Carlson 2001).

Horizontal Design

The buried pipe of a closed-loop GSHP may theoretically produce a change in temperature in the ground up to 16 ft away. For all practical purposes, however, the ground temperature is essentially unchanged beyond about 3 ft from the pipe loop. For that reason, the pipe can be buried relatively near the ground surface and still benefit from the moderating temperatures that the earth provides. Because the ground temperature may fluctuate as much as ±10°F at a depth of 6 ft, an antifreeze solution must be used in most heating dominated regions. The critical design aspect of horizontal applications is to have enough buried pipe loop within the available land area to serve the equipment. The design guidelines for residential horizontal loop installations can be found in OSU (1988).

A horizontal loop design has several advantages over a vertical loop design for a closed-loop ground source system:

- Installation of the ground loop is usually less expensive than for vertical well designs because the capital cost of a backhoe or trencher is only a fraction of the cost of most drilling rigs.
- Most ground-source contractors must have a backhoe for construction of the header pits and trenches to the building, so they can perform the entire job without the need to schedule a special contractor.
- Large drilling rigs may not be able to get to all locations because of their size and weight.
- There is usually no potential for aquifer contamination because of the shallow depth of the trench.
- There is minimal residual temperature effect from unbalanced annual loads on the ground loop because the heat transfer to or from the ground loop is small compared to the normal heat transfer occurring at the ground surface.

Some limitations on selecting a horizontal loop design include the following:

- The minimum land area needed for most nonspiral horizontal loop designs for an average house is about 0.5 acre. Horizontal systems are not feasible for most urban houses, which are commonly built on smaller lots.
- The larger length of pipe buried relatively near the surface is more susceptible to being cut during excavations for other utilities.
- Soil moisture content must be properly accounted for in computing the required ground loop length, especially in sandy soils or on hilltops that may dry out in summer.
- Rocks and other obstructions near the surface may make excavation with a backhoe or trencher impractical.

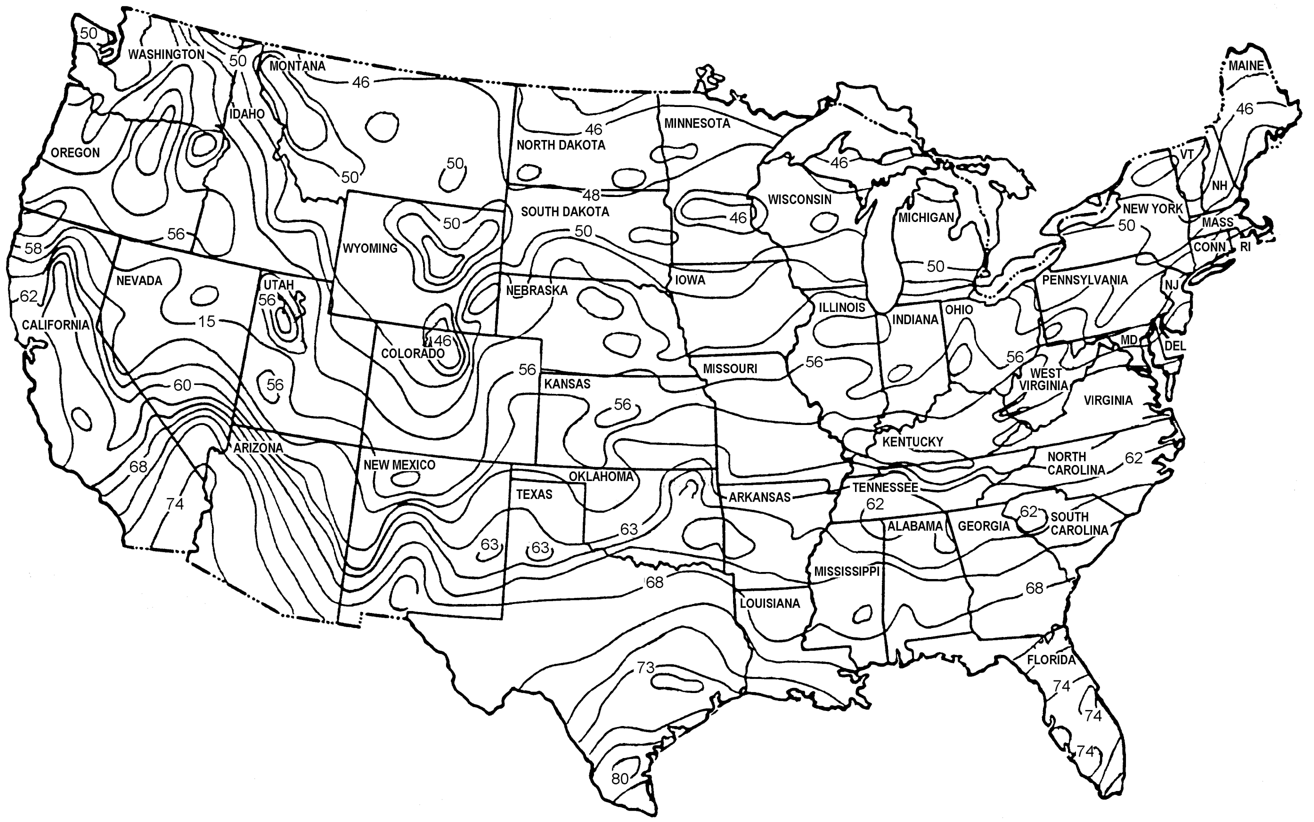

Fig. 18 Approximate Groundwater Temperatures (°F) in the Continental United States

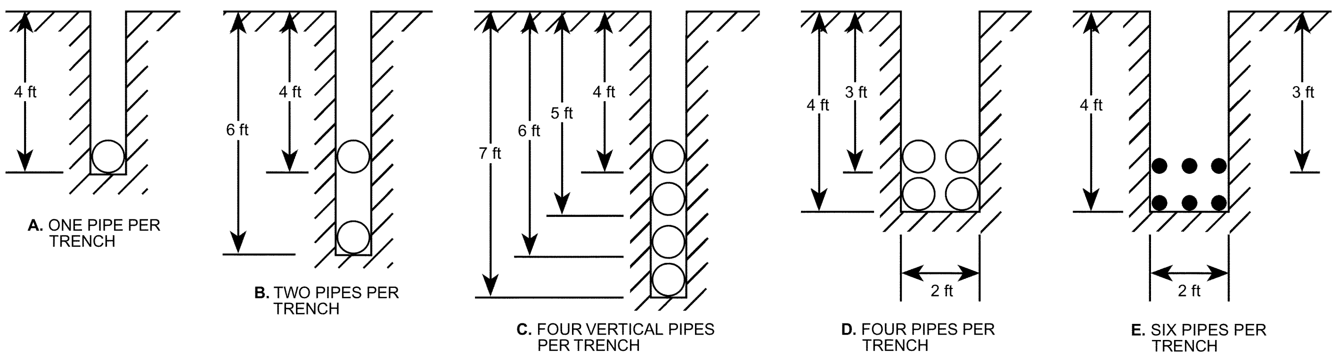

Fig. 19 Horizontal Ground Loop Configurations

Multiple pipes are often placed in a single trench to reduce the land area needed for horizontal loop applications. Some common multiple pipe arrangements are shown in Figure 19. When pipes are placed at two depths, the bottom row is placed first, and then the trench is partially backfilled before the upper row is put in place. Rarely are more than two layers of pipe used in a single trench because of the extra time needed for the partial backfilling. Higher pipe densities in the trench provide diminishing returns because thermal interference between multiple pipes reduces the heat transfer effectiveness of each pipe. The most common multiple-pipe applications are the two-pipe arrangement used with chain trenchers and the four- or six-pipe arrangements placed in trenches made with a wide backhoe bucket.

An overlapping spiral configuration, shown in Figure 20, has also been used with some success. However, it requires special

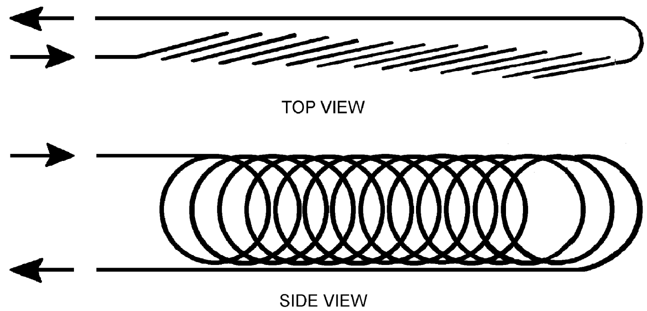

Fig. 20 General Layout of Spiral Earth Coil

Table 9 Equivalent Full-Load Hours (EFLH) for Typical Occupancy with Constant-Temperature Set Points

	EFLH Occupancy							
	School		Office		Retail		Hospital	
Location	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling
Atlanta, GA	290-200	690-830	690-480	1080-1360	600-380	1380-1860	430-160	2010-2850
Baltimore, MD	460-320	500-610	890-720	690-1080	770-570	880-1480	590-300	1340-2340
Bismarck, ND	500-460	150-250	990-950	250-540	900-810	340-780	730-530	540-1290
Boston, MA	520-450	300-510	1000-960	450-970	870-760	610-1380	680-420	1020-2330
Charleston, WV	440-310	430-570	840-770	620-1140	730-620	820-1600	550-320	1260-2560
Charlotte, NC	320-200	650-730	780-530	1060-1340	670-420	1350-1830	490-180	1990-2820
Chicago, IL	470-390	280-410	920-820	420-780	810-670	550-1090	640-400	870-1780
Dallas, TX	200-120	830-890	520-340	1350-1580	440-280	1660-2090	310-100	2320-3100
Detroit, MI	480-400	230-360	1020-970	390-820	900-790	530-1170	710-460	870-1950
Fairbanks, AK	630-560	26-54	1170-1050	64-200	1090-930	110-320	930-690	210-600
Great Falls, MT	430-360	130-220	890-820	210-490	800-680	290-710	640-420	500-1210
Hilo, HI	1-0	1360-1390	23-13	2440-2580	14-8	2990-3370	0-0	4060-4910
Houston, TX	130-90	940-1000	350-250	1550-1770	300-190	1870-2290	200-70	2540-3320
Indianapolis, IN	480-400	380-560	920-840	560-1000	820-690	730-1410	640-390	1120-2250
Los Angeles, CA	160-80	780-910	580-370	1280-1670	440-250	1740-2350	180-20	2740-3770
Louisville, KY	430-290	550-670	830-710	770-1250	720-570	1000-1720	550-300	1480-2690
Madison, WI	470-390	210-310	900-840	320-640	800-700	420-900	640-440	680-1490
Memphis, TN	240-170	700-830	600-420	1090-1350	510-330	1350-1780	370-140	1910-2680
Miami, FL	12-6	1260-1300	46-34	1980-2150	37-25	2350-2740	12-1	3110-3890
Minneapolis, MN	500-420	200-300	950-860	320-610	860-720	430-870	700-470	680-1420
Montgomery, AL	180-120	840-910	470-330	1260-1510	400-250	1550-1990	260-90	2170-2950
Nashville, TN	320-250	570-740	680-590	830-1280	590-470	1030-1710	450-240	1490-2620
New Orleans, LA	110-67	920-990	320-230	1500-1720	260-160	1820-2240	160-46	2500-3280
New York, NY	440-350	360-550	870-790	540-1040	760-630	720-1480	590-330	1160-2440
Omaha, NE	400-330	310-440	800-720	480-820	720-600	610-1130	570-360	920-1780
Phoenix, AZ	110-65	950-1020	290-210	1340-1610	250-170	1630-2090	140-34	2220-3040
Pittsburgh, PA	500-470	300-530	950-910	440-920	840-750	600-1310	650-420	960-2160
Portland, ME	480-400	190-300	980-880	310-630	870-710	410-900	690-420	700-1520
Richmond, VA	410-270	630-730	820-660	880-1310	710-520	1110-1770	530-250	1650-2760
Sacramento, CA	360-220	680-850	990-640	1080-1430	830-480	1460-2020	540-120	2250-3180
Salt Lake City, UT	540-520	410-710	1060-1040	510-1090	930-830	660-1520	720-440	1060-2470
Seattle, WA	650-460	260-460	1370-1270	440-1200	1170-960	710-1860	850-360	1340-3270
St. Louis, MO	400-280	460-550	800-710	680-1100	700-570	850-1500	550-320	1260-2330
Tampa, FL	58-35	1050-1110	190-140	1800-2000	160-100	2170-2580	90-22	2910-3710
Tulsa, OK	300-240	580-770	620-560	830-1300	540-450	1030-1730	410-220	1470-2630

Notes: 1. The ranges in values are from internal gains at 0.6 and 2.5 W/ft^2.
2. Operating with large temperature setbacks during unoccupied periods (effectively turning off the system) reduces heating EFLHs by 20% and cooling EFLHs by 5%.

Equations relating EFLH to Heating and Cooling Degree Days permitting the calculation of EFLH for locations other than those appearing in Table 9 can be found in Carlson (2001).

attention during the backfilling process to ensure that soil fills all the pockets formed by the overlapping pipe. Large quantities of water must be added to compact the soil around the overlapping pipes. The backfilling must be performed in stages to guarantee complete filling around the pipes and good soil contact. The high pipe density (up to 10 ft of pipe per linear foot of trench) may cause problems in prolonged extreme weather conditions, either from soil drying during cooling or from freezing during heating. This spiral design has been used in vertical trenches cut with a chain trencher as well as in laying the coil flat on the bottom of a large pit excavated with a bulldozer. Installations using the horizontal spiral coil on the bottom of a pit have generally performed better than those with spiral coils that were stood upright in a vertical trench.

The extra time needed to backfill and the extra pipe length required make spiral configurations nearly as expensive to install as straight pipe configurations. However, the reduced land area needed for the more compact design may permit their use on smaller residential lots that would be too small for conventional horizontal pipe ground loop designs. The spiral pipe configuration laid flat in a horizontal pit arrangement is used commonly in the northern Midwest part of the United States, where sandy soil causes vertical trenches to collapse. A large open pit is excavated by a bulldozer, and then the overlapping pipes laid flat on the bottom of the pit. The bulldozer is also used to cover the pipe, being careful to not run over them with the bulldozer tread.

Although most horizontal closed-loop systems are installed with either a chain trencher or a backhoe, horizontal boring machines are also now available for this application. Developed for buried utility applications such as electric or potable water service, these devices simply bore through the ground parallel to the ground surface. A detector at the surface can show the exact point where the boring head is located underground so that the boring process does not penetrate other known utilities or cross over into a neighbor's lot.

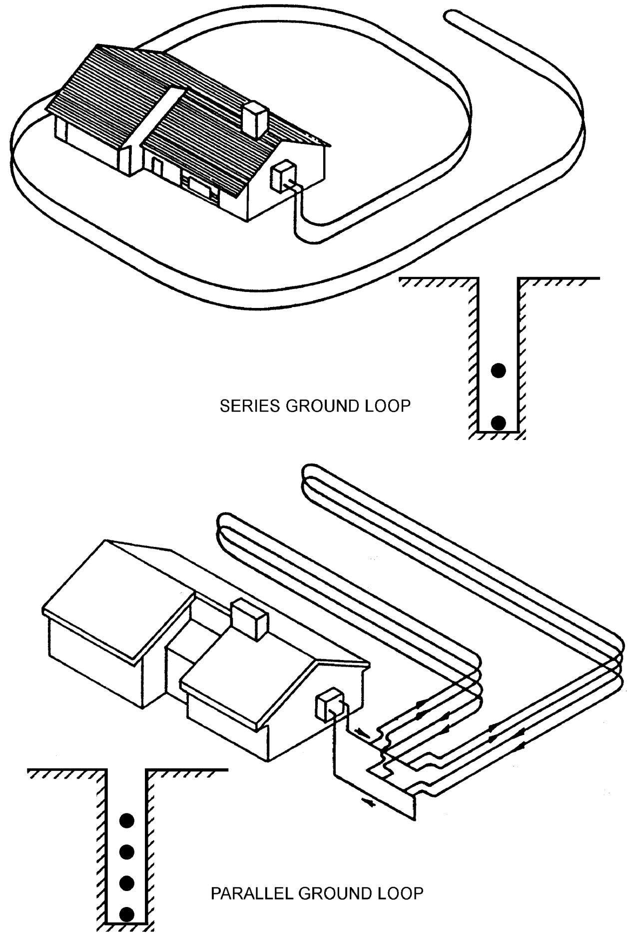

Fig. 21 Parallel and Series Ground Loop Configurations

Most horizontal loop installations place the pipe loops in a parallel rather than a single (series) loop to reduce pumping power (Figure 21). Parallel loops may require slightly more pipe, but may use smaller pipe and thus have smaller internal volumes requiring less antifreeze (if needed). Also, the smaller pipe is typically much less expensive for a given length, so total pipe cost should be less for parallel loops. An added benefit is that parallel loops can be flushed out with a smaller purge pump than would be required for a larger single-pipe loop. A disadvantage of parallel loops is the potential for unequal flow in the loops and thus nonuniform heat exchange efficiency.

The time required to install a horizontal loop is not much different from that for a vertical system. For the arrangements described above, a two-person crew can typically install the ground loop for an average house in a single day.

Soil characteristics are an important concern for any ground loop design. With horizontal loops, the soil type can be more easily determined because the excavated soil can be inspected and tested. EPRI (1989) compiled a list of criteria and simple test procedures that can be used to classify soil and rock adequately enough for horizontal ground loop design.

Although soil type and moisture content are important considerations in sizing the ground loop, some design guidelines have been developed based on extensive analysis of monitored systems in mostly southern climates (Kavanaugh and Calvert 1995). Table 10 gives recommended trench lengths for the various types of commonly used excavation methods. Heating-mode run times approaching 100% on a daily basis would be the norm at heating design conditions in heating-dominated climates. In contrast, daily run times of no more than 50% would be encountered at design cooling conditions in cooling-dominated climates. The combination of long run times and the formation of ice around the pipes will make the performance of horizontal systems dependent on both the loop field design and how the system is matched to the building load. Though many thousands of these systems have been installed in heating climates, no comparable analysis has been performed to determine proper design guidelines. The loop length data in Table 10 for soil temperatures below 56°F are based on nominal heat pump capacity and the use of supplemental resistance heat at design conditions. If installing such a system for the first time, contact several experienced contractors in the area to determine successful design lengths for the local climate and soil types.

Additional considerations for horizontal loop systems in colder climates arise from the potential for ice formation around the pipe loop. The loop should not pass within 2 ft of any buried water line (potable, sewer, or rainwater). If such proximity cannot be avoided, the GCHP loop can be insulated in that area. Horizontal loops should not be placed closer than 6 ft from a basement or crawl space wall when buried parallel to the wall. Heaving from ice formation could cause structural damage if placed in close proximity to the wall.

Leaks in the heat-fused plastic pipe are rare when attention is paid to pipe cleanliness and proper fusion techniques. Should a leak occur, it is usually best to try to isolate the leaking parallel loop and abandon it in place. The effort required to find the source of the leak usually far outweighs the cost of replacing the defective loop. Because the loss of as little as 0.25 gal of water from the system will cause the system to lose pressure and shut down, leaks cannot be located by looking for wet soil, as is commonly done with water lines.

Although leaks should be rare with properly thermally fused pipe, a number of states have adopted restrictions against the use of certain types of antifreeze mixtures in GCHP systems; check local water-quality regulations before selecting a mixture. Methanol has been used extensively due to its low cost and good physical properties when cold. A comprehensive study by Heinonen et al. (1996) showed that propylene glycol is a good alternative when issues of flammability or environmental safety are important considerations. A more thorough discussion of antifreeze solutions is given in the Antifreeze Requirements section of this chapter.

Fluid Flow and Loop Circuiting

Residential systems, like commercial applications, are sometimes characterized by excessive pumping power. This trend may be a result of undersized piping, excessive amounts of viscous antifreeze solutions, or conservative pump sizing. Because a 15 EER, 3 ton heat pump will require a total power (compressor and fan) of 2400 W, the addition of a second 1/6 hp pump (which draws 245 W) will reduce system efficiency by 10%. Table 11 is provided as a guideline to ensure adequate liquid flow rate with the least possible number of pumps. The table is to be used in conjunction with Table 10 and applies to loops with 0 to 15% propylene glycol solutions (by volume). This solution has the reputation of being the most difficult of the commonly used solutions to pump when cold. However, it is no more difficult to pump than ethyl alcohol and pumping penalties can be mitigated by adding only the required amount of antifreeze. Shorter loops may require higher levels of antifreeze solutions. See the antifreeze section at the end of this chapter for more details regarding antifreeze recommendations. Any exposed piping above the frost line must be insulated with closed-cell insulation with ultraviolet (UV) protection (paint or wrap).

GROUNDWATER HEAT PUMPS

A groundwater heat pump system (GWHP) removes groundwater from a well and delivers it to a heat pump (or an intermediate heat exchanger) to serve as a heat source or sink. Both unitary or central

Table 10 Recommended Lengths of Trench or Bore per Ton for GCHPs

Coil Type[a]		Pitch[b] Feet of Pipe per Feet Trench/Bore	Ground Temperature, °F 44 to 47	48 to 51	52 to 55	56 to 59	60 to 63	64 to 67	68 to 70
Horizontal	10-Pitch Spiral	10	125	120	115	120	125	150	180
	6-Pipe/6-Pitch Spiral	6	180	160	150	160	180	200	230
	4-Pipe/4-Pitch Spiral	4	190	180	170	180	190	220	260
	2-Pipe	2	300	280	250	280	300	340	400
Vertical U-tube	3/4 in. Pipe	2	180	170	155	170	180	200	230
	1 in. Pipe	2	170	160	150	160	170	190	215
	1 1/4 in. Pipe	2	160	150	145	150	160	175	200

Source: Kavanaugh and Calvert (1995).
[a]Lengths based on DR11 high-density polyethylene (HDPE) pipe. See Figures 19 to 21 for details.
[b]Multiply length of trench by pitch to find required length of pipe.

Note: Based on k = 0.6 Btu/h·ft·°F for horizontal loops and k = 1.2 Btu/h·ft·°F for vertical loops. Figures for soil temperatures < 56°F based on modeling using nominal heat pump capacity and the assumption of auxiliary heat at design conditions.

Multiply Table 10 Values by Bold Values Below to Correct for Other Values of Ground Conductivity

	Ground Thermal Conductivity in Btu/h·ft·°F 0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Horizontal loop	**1.22**	**1.0**	**0.89**	**0.82**	—	—	—	—	—
Vertical loop*	—	—	**1.23**	**1.10**	**1.0**	**0.93**	**0.87**	**0.83**	**0.79**

*Vertical loop values based on an annular fill with k = 0.85 Btu/h·ft·°F. Multiply lengths by 1.2 for $k_{annulus}$ = 0.4 Btu/h·ft·°F and 0.95 for $k_{annulus}$ = 1.1 Btu/h·ft·°F

Table 11 Recommended GCHP Piping Arrangements and Pumps

		Nominal Heat Pump Capacity, tons 2	3	4	5	6
		Required Flow Rate, gpm				
		5 to 6	**7 1/2 to 9**	**10 to 12**	**12 to 15**	**15 to 18**
Coil Type*		**Number of Parallel Loops**				
Spiral (10 pt.)		3 to 4	4 to 6	6 to 9	8 to 10	8 to 10
	6-Pipe	3 to 4	4 to 6	6 to 9	8 to 10	8 to 10
	4-Pipe	2 to 3	4 to 6	5 to 8	6 to 9	6 to 10
	2-Pipe	2 to 4	3 to 5	4 to 6	5 to 8	6 to 10
Vertical	3/4 in. pipe	2 to 3	3 to 5	4 to 6	5 to 8	6 to 10
	1 in. pipe	2 to 3	2 to 4	3 to 5	4 to 6	4 to 6
	1 1/4 in. pipe	1 to 2	1 to 2	2 to 3	2 to 3	2 to 4
Trench Length		**Header Diameter (PE Pipe), in.**				
Less than 100 ft		1 1/4	1 1/4	1 1/2	1 1/2 to 2	1 1/2 to 2
100 to 200 ft		1 1/4	1 1/2	1 1/2	2	2
		Size (No.) of Pumps Required				
		1/12 hp (1)	1/6 hp (1)	1/12 hp (2)	1/6 hp (2)	1/6 hp (2)

Source: Kavanaugh and Calvert (1995).
*Based on DR11 HDPE pipe.

plant designs are used. In the unitary type, a large number of small water-to-air heat pumps are distributed throughout the building. The central plant design uses one or a small number of large-capacity chillers supplying hot and chilled water to a two- or four-pipe distribution system.

Direct systems (in which the groundwater is pumped directly to the heat pump without an intermediate heat exchanger) are not recommended except on the very smallest installations. Although some systems of this design have been successful, others have had serious difficulty even with groundwater of apparently benign chemistry. As a result, prudent design for commercial/industrial-scale projects isolates the groundwater from the building system with a heat exchanger. The increased capital cost arising from the installation of the heat exchanger amounts to a small percentage of the total cost. In view of the greatly reduced maintenance requirements of these systems, the increased capital cost is quickly recovered.

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

Design Strategy

An open-loop system design must balance well pumping power with heat pump performance. As the groundwater flow is increased through a system, more favorable average temperatures are produced for the heat pumps. Higher flow rates, to a point, result in increasing system EER or COP as the increases in well pump power are outweighed by the decrease in heat pump power requirements (due to 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 the design of open-loop systems is identifying the point of maximum system performance with respect to the heat pump and the 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 system—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 flows) and heat pump performance versus entering water temperatures at different flow rates. The well information is generally derived from the well pump test results. Heat pump performance data are available from the manufacturer.

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 22 provides curves for two different groundwater temperatures (70 and 50°F) and two well pump heads (100 and 300 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.

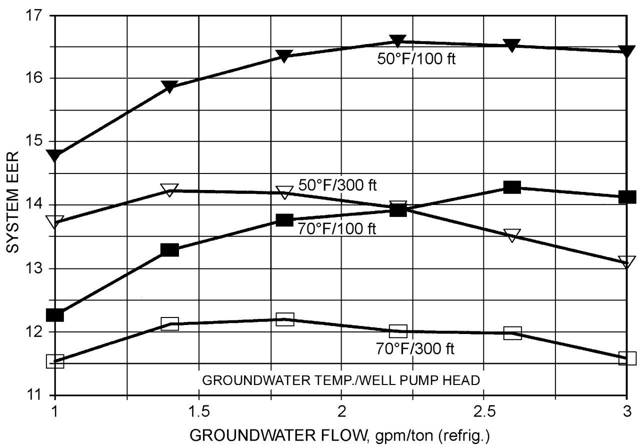

Fig. 22 Optimum Groundwater Flow for Maximum EER
(Kavanaugh and Rafferty 1997)

Table 12 provides design data for an example system.

Groundwater Quality

The importance of groundwater quality depends on the system design. Systems using isolation heat exchangers commonly encounter no water quality issues (other than iron bacteria) that would prevent the application of a GWHP system operating under reasonable maintenance levels.

For systems that use groundwater directly in the heat pump units (e.g., standing column systems and small residential GWHP systems), several issues are of concern. The primary water quality problem in the United States is scaling, usually of calcium carbonate (lime). Because this type of scaling is partially temperature driven, the temperature of surfaces that the ground water contacts will determine the extent to which scaling will occur. In these systems, peak temperatures in the refrigerant-to-water exchanger in the cooling mode are likely to be in excess of 160°F. For the same system using an isolation plate heat exchanger, the ground water will be unlikely to encounter temperatures in excess of 90°F. The use of the plate heat exchanger reduces the propensity for scaling and limits any scale that does occur to a single heat exchanger. Rafferty (2000a) provides information on water scaling potential on a state-by-state basis.

Although cupronickel, originally developed for seawater applications, is an excellent material in that role, it provides few benefits for most groundwater applications. It has been shown to perform more poorly than pure copper with hydrogen-sulfide-bearing waters.

Excessive iron, particularly ferrous iron, in the water can result in coating of heat transfer surfaces if the water is exposed to air (allowing the iron to oxidize to the ferric state, a form with much lower solubility in water). Removing this iron from the plates of a single heat exchanger is much less labor-intensive than removing it from tens or hundreds of individual heat pump heat exchangers.

Particulate matter (e.g., sand) in the ground water stream, although not a problem in the mechanical system, can effectively plug injection wells. Sand production should be addressed in the construction of the production well (screen/gravel pack). If it must be dealt with on the surface, a screen or strainer is much preferable to a centrifugal separator. The strainer does not suffer from ineffectiveness at start-up and shutdown as does the centrifugal separator (Kavanaugh and Rafferty 1997).

Well Pumps

Submersible pumps have not performed well in higher-temperature, direct-use projects. However, the submersible pump is a cost-effective option with normal groundwater temperatures, as encountered in heat pump applications. The low temperature eliminates the need to specify an industrial design for the motor/

Table 12 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.

protector, thereby greatly reducing the first cost relative to direct-use. Caution should still be exercised for wells that are expected to produce moderate amounts of sand. The high speed (3500 rpm) of most submersible pumps makes them susceptible to erosion damage.

Small groundwater systems have frequently been identified with excessive well pump energy consumption. The reasons for excessive pump energy consumption (high water flow rate, coupling to the domestic pressure tank, and low efficiency of small submersible pumps) are generally not present in large, commercial groundwater systems. In large systems, the groundwater flow per unit capacity is frequently less than half that of residential systems. The pressure at the wellhead is not the 30 to 50 psi that is typical of domestic systems, but is rather a function only of the pressure losses through the groundwater loop. Finally, large lineshaft well pumps are characterized by efficiencies of up to 83% compared to the 35 to 40% range for small submersible pumps.

In the design of a GWHP system, the method of control of the well pump determines the extent to which the optimum relationship between well pump power and heat pump power is preserved at off-peak conditions. There are several ways the pump can be controlled. Multiple pumps can be staged to meet system loads, either with multiple wells or with multiple pumps installed in a single well. A dual set-point control similar to that used in boiler/ tower systems energizes the well pump above a given temperature in the cooling mode and below a given temperature in the heating mode. Between those temperatures the building loop "floats" without the addition of groundwater. To control well pump cycling, it is necessary to establish a temperature range (difference between pump-on and pump-off temperatures) over which the pump operates in both the heating and cooling modes. The size of this range is primarily a function of the building loop water volume in terms of gallons per peak per ton of peak block system load (Rafferty 2000b). Table 13 summarizes these data. In the example in Table 12, the optimum system building loop return temperature (at peak system EER) is 80.6°F. If this system had a water volume of 8 gal/ton, from Table 13 a range of 8°F in the cooling mode would be required. This range would result in a well pump start temperature of 80.6 + (8/2) = 84.6°F and a well pump stop temperature of 80.6 – (8/2) = 76.6°F. A similar calculation can be made for the heating mode. It is apparent from Table 13 that, for systems with very low thermal mass, the dual set-point method of control becomes impractical due to the very large temperature range required. For these applications, an alternative method of control (variable speed, staging, etc.) is required.

Heat Exchangers

Design of a plate-and-frame heat exchanger is largely a trade-off between pressure drop, which influences pumping (operating cost), and overall heat transfer coefficient, which influences surface area (capital cost). In general, exchangers in GWHP systems can be economically selected for approach temperatures (between loop return and groundwater leaving temperatures) as low as 3°F. Most selections involve an approach of between 3 and 7°F and a pressure drop of less than 10 psi on the building loop side. Excessive fouling factors (>0.0002 $h \cdot ft^2 \cdot °F/Btu$) should not be specified when selecting plate heat exchangers, which can be easily disassembled and cleaned.

Heat exchanger cost may be reduced for groundwater applications by using Type 304 stainless steel plates rather than the Type 316 or titanium plates common in direct-use projects. The low temperature and generally low chloride content of heat pump fluids frequently make the less expensive Type 304 material acceptable.

Central Plant Systems

Central plant systems, in which a conventional or heat recovery central chiller is connected to a four-pipe system, are the oldest type of open-loop design, having first been installed in the late 1940s. Because of the cost and energy requirements of the central plant design, these systems typically do not result in the same level of energy efficiency as unitary systems.

For central plant groundwater systems, two heat exchangers are normally used, one in the chilled water loop and one in the condenser water loop (Figure 23). The evaporator-loop exchanger

Table 13 Controller Range Values for Dual Set-Point Well Pump Control*

	Building Loop Thermal Mass in Gallons per Ton of Peak Block Cooling Load						
	2	4	6	8	10	12	14
Cooling Range, °F	31	16	11	8	6	5	4
Heating Range, °F	18	9	6	4	3	3	3

*Table values for pumps > 5 hp. For pumps < 5 hp, three-phase range values may be reduced by 50%.

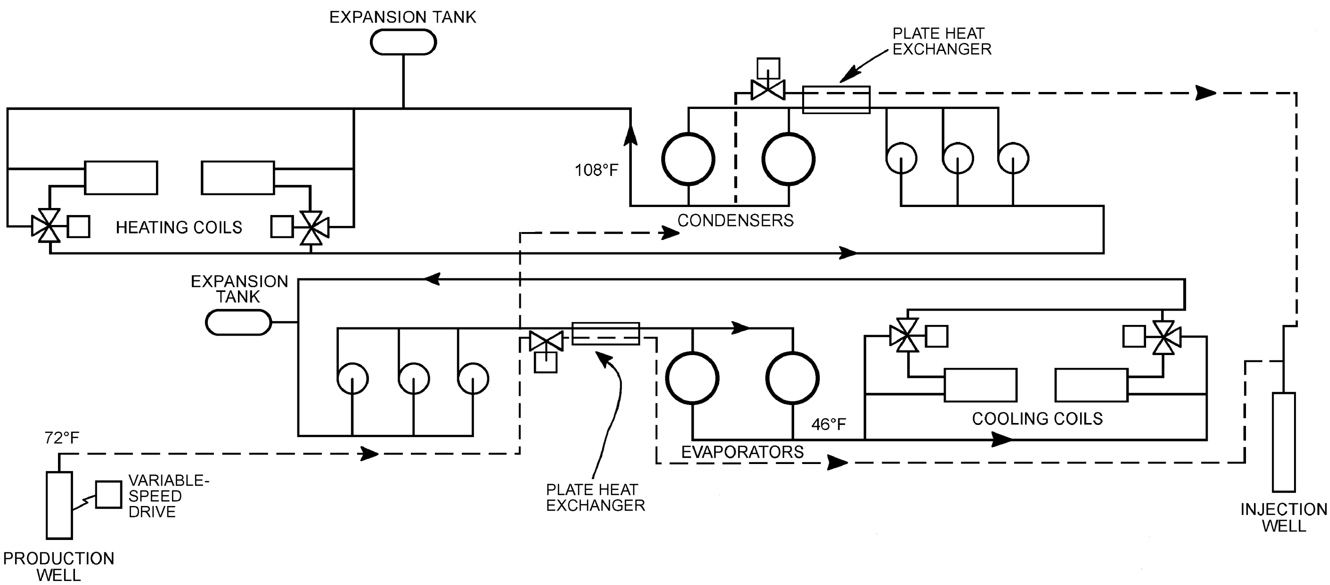

Fig. 23 Central Plant Groundwater System

provides a heat source for heating-dominated operation and the condenser-loop exchanger provides a heat sink for cooling-dominated operation.

Sizing of the **condenser-loop exchanger** is based on providing sufficient capacity to reject the condenser load in the absence of any building heating requirement.

Sizing of the **chilled-water-loop exchanger** must consider two loads. The primary criterion is the load required during heating-dominant operation. The exchanger must transfer sufficient heat (when combined with compressor heat) from the groundwater to the chilled-water loop to meet the space heating requirement of the building. Depending on the relative groundwater and chilled-water temperatures and on the design temperature rise, the exchangers may also provide some free cooling during cooling-dominant operation. If the groundwater temperature is lower than the temperature of the chilled water returning to the exchanger, some chilled-water load can be met by the exchanger. This mode will most likely be available in regions with groundwater temperatures below 60°F.

Central plant chiller controls must also allow for the unique operation with a groundwater source. Controls can be similar to those on a heat-recovery chiller with a tower, with one important difference. 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, or
- Chiller capacity is controlled by the heating-water (condenser) loop temperature, and the groundwater flow through the chilled-water exchanger is controlled by the 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.

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. A variety of water circulation designs are possible and several of the more common are presented.

In a **closed-loop system**, a water-to-air heat pump is linked to a submerged coil. Heat is exchanged to (cooling mode) or from (heating mode) the lake by the fluid (usually a water-antifreeze mixture) circulating inside the coil. 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. The pump can be located either slightly above or submerged below the lake water level. For heat pump operation in the heating mode, this type is restricted to warmer climates. Entering lake water temperature must remain above 42°F to prevent freezing.

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 the heating mode. Precooling or supplemental total cooling are also permitted when water temperature is between 50 and 60°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 temperature is greater than the water temperature), 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 the 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 temperature is lower than the air temperature. 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. The conduction gain from the ground is even less than convection gain (Pezent and Kavanaugh 1990).

Cooling of lakes is accomplished primarily by evaporative heat transfer at the surface. Convective cooling or heating in warmer months will contribute only a small percentage of the total because of the relatively small temperature difference between the air and the lake surface temperature. Back radiation typically occurs at night when the sky is clear, and can account for significant amount of cooling. The relatively warm water surface will radiate heat to the cooler sky. For example, on a clear night, a cooling rate of up to 50 Btu/h·ft^2 is possible from a lake 25°F warmer than the sky. The last major mode of heat transfer, conduction to the ground, does not play a major role in lake cooling (Pezent and Kavanaugh 1990).

To put these heat transfer rates in perspective, consider a 1 acre (43,560 ft^2) lake that is used in connection with a 10 ton (120,000 Btu/h) heat pump. In cooling mode, the unit will reject approximately 150,000 Btu/h to the lake. This is 3.4 Btu/h·ft^2, or approximately 1% of the maximum heat gain from solar radiation in the summer. In the winter, a 10 ton heat pump would absorb only about 90,000 Btu/h, or 2.1 Btu/h·ft^2, from the lake.

Thermal Patterns in Lakes

The maximum density of water occurs at 39.2°F, not at the freezing point of 32°F. This phenomenon, in combination with the normal modes of heat transfer to and from lakes, produces temperature profiles advantageous to efficient heat pump operation. In the winter, the coldest water is at the surface. It tends to remain at the surface and freeze. The bottom of a deep lake stays 5 to 10°F warmer than the surface. This condition is referred to as winter stagnation. The warmer water is a better heat source than the colder water at the surface.

As spring approaches, surface water warms until the temperature approaches the maximum density point of 39.2°F. The winter stratification becomes unstable and circulation loops begin to develop from top to bottom. This condition of spring overturn (Peirce 1964) causes the lake temperature to become fairly uniform.

Later in the spring as the water temperatures rise above 45°F, the circulation loops are in the upper portion of the lake. This pattern continues throughout the summer. The upper portion of the lake remains relatively warm, with evaporation cooling the lake and solar radiation warming it. The lower portion (hypolimnion) of the lake remains cold because most radiation is absorbed in the upper zone. Circulation loops do not penetrate to the lower zone, and conduction to the ground is quite small. The result is that in deeper lakes with small or medium inflows, the upper zone is 70 to 90°F, the lower zone is 40 to 55°F, and the intermediate zone (thermocline) has a sharp change in temperature within a small change in depth. This condition is referred to as summer stagnation.

As fall begins, the water surface begins to cool by radiation and evaporation. With the approach of winter, the upper portion begins to cool towards the freezing point and the lower levels approach

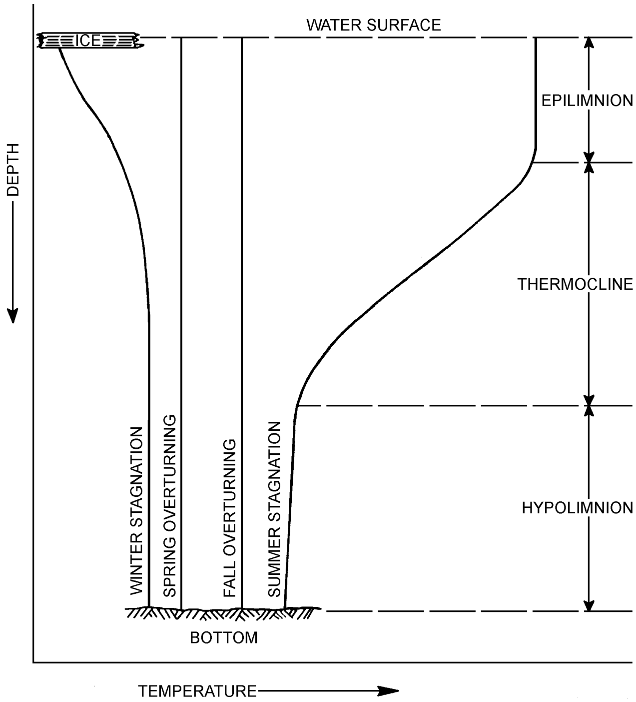

Fig. 24 Idealized Diagram of Annual Cycle of Thermal Stratification in Lakes

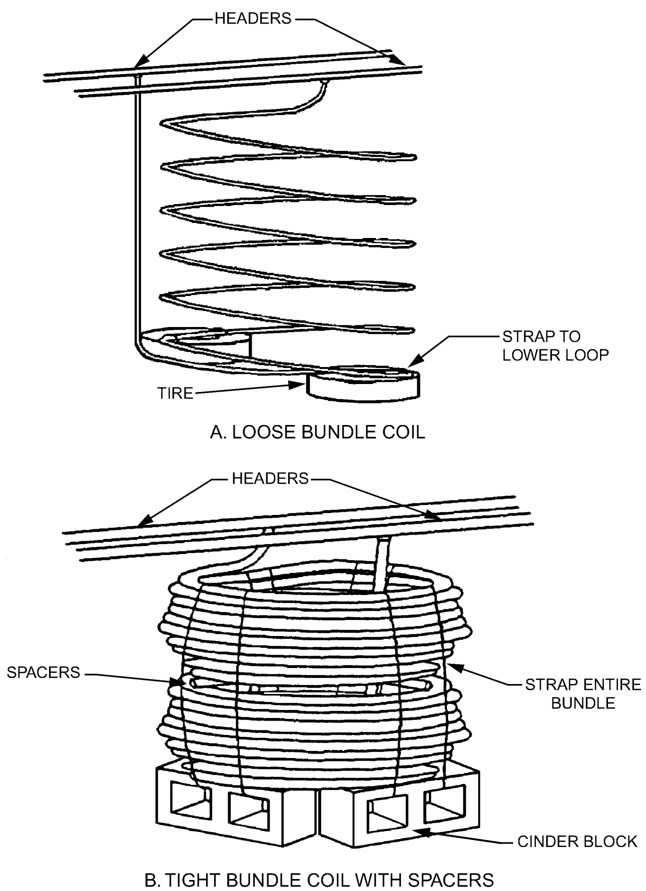

Fig. 25 Closed-Loop Lake Coil in Bundles
(Kavanaugh 1991)

the maximum density temperature of 39.2°F. An ideal temperature-versus-depth chart is shown in Figure 24 for each of the four seasons (Peirce 1964).

Many lakes do exhibit near-ideal temperature profiles. However, a variety of circumstances can disrupt the profile. These characteristics include (1) high inflow/outflow rates, (2) insufficient depth for stratification, (3) level fluctuation, (4) wind, and (5) lack of enough cold weather to establish sufficient amounts of cold water necessary for summer stratification. Therefore, a thermal survey of the lake should be conducted or existing surveys of similar lakes in similar geographic locations should be consulted.

Closed-Loop Lake Water Heat Pump

The closed-loop lake water heat pump shown in Figure 25 has several advantages over the open-loop. One advantage is the reduced fouling resulting from the circulation of clean water (or water-antifreeze solution) through the heat pump. A second advantage is the reduced pumping-power requirement. This results from the absence of an elevation head from the lake surface to the heat pumps. A third advantage of a closed-loop is that it is the only type recommended if a lake temperature below 40°F is possible. The outlet temperature of the fluid will be about 6°F below that of the inlet at a flow of 3 gpm per ton. Frosting will occur on the heat exchanger surfaces when the bulk water temperature is in the 34 to 38°F range.

A closed-loop system has several disadvantages. Performance of the heat pump drops slightly because the circulation fluid temperature drops 4 to 12°F below the lake temperature. A second disadvantage is the possibility of damage to coils located in public lakes. Thermally fused polyethylene loops are much more resistant to damage than copper, glued plastic (PVC), or tubing with band-clamped joints. The third possible disadvantage is fouling on the outside of the lake coil, particularly in murky lakes or where coils are located on or near the lake bottom.

Polyethylene (PE 3408) is recommended for all intake piping. All connections must be either thermally socket fused or butt fused. These plastic pipes should also have protection from UV radiation, especially when near the surface. Polyvinyl chloride (PVC) pipe and plastic pipe with band-clamped joints is not recommended.

The piping networks of closed-loop systems resemble those used in ground-coupled heat pump systems. Both a large-diameter header between the heat pump and lake coil and several parallel loops of piping in the lake are required. The loops are spread out to limit thermal interference, hot spots, and cold pockets. Although this layout is preferred in terms of performance, installation is more time consuming. Many contractors simply unbind plastic pipe coils and submerge them in a loose bundle. Some compensation for thermal interference is obtained by making the bundled coils longer than the spread coils. A diagram of this type of installation is shown in Figure 25.

Copper coils have also been used successfully. Copper tubes have a very high thermal conductivity, so coils only one-fourth to one-third the length of plastic coils are required. However, copper pipe does not have the durability of PE 3408 or polybutylene, and if the possibility of fouling exists, coils must be significantly longer.

Antifreeze Requirements

Closed-loop horizontal and surface water heat exchanger systems will often require an antifreeze be added to the circulating water in locations with significant heating seasons. Antifreeze may not be needed in a comparable vertical borehole heat exchanger because the deep ground temperature will be essentially constant. At a depth of 6 ft, a typical value for horizontal heat exchangers, the ground temperature varies by approximately ±10°F. Even if the

Table 14 Suitability of Selected GCHP Antifreeze Solutions

Category	Methanol	Ethanol	Propylene Glycol	Potassium Acetate	CMA	Urea
Life cycle cost	***	***	**[1]	**[1]	**[1]	***
Corrosion	**[2]	**[3]	***	**	**[4]	*[5]
Leakage	***	**[6]	**[6]	*[7]	*[8]	*[9]
Health risk	*[10,11]	**[10,12]	***[10]	***[10]	***[10]	***[10]
Fire risk	*[13]	*[13]	***[14]	***	***	***
Environment risk	**[15]	**[15]	***	**[15]	**[15]	***
Future-use risk	*[16]	**[17]	***	**[18]	**[19]	**[19]

Key: * Potential problems, caution in use required
** Minor potential for problems
*** Little or no potential for problems

Category	Notes
Life cycle cost	1. Higher-than-average installation and energy costs.
Corrosion	2. High black iron and cast iron corrosion rates. 3. High black iron and cast iron, copper and copper alloy corrosion rates. 4. Medium black iron, copper and copper alloy corrosion rates. 5. Medium black iron, high cast iron, and extremely high copper and copper alloy corrosion rates.
Leakage	6. Minor leakage observed. 7. Moderate leakage observed. Extensive leakage reported in installed systems. 8. Moderate leakage observed. 9. Massive leakage observed.
Health risk	10. Protective measures required with use. See Material Safety Data Sheet (MSDS). 11. Prolonged exposure can cause headaches, nausea, vomiting, dizziness, blindness, liver damage, and death. Use of proper equipment and procedures reduces risk significantly. 12. Confirmed human carcinogen.
Fire Risk	13. Pure fluid only. Little risk when diluted with water in antifreeze. 14. Very minor potential for pure fluid fire at elevated temperatures.
Environment risk	15. Water pollution.
Future-use risk	16. Toxicity and fire concerns. Prohibited in some locations. 17. Toxicity, fire, and environmental concerns. 18. Potential leakage concerns. 19. Not currently used as GSHP antifreeze solution. May be difficult to obtain approval for use.

Source: Heinonen and Tapscott (1996)

mean ground temperature were 60°F in late winter, the ground temperature at a 6 ft depth would drop to 50°F. The heat extraction process would lower the temperature even further around the heat exchanger pipes, probably by an additional 10°F or more. Even with good heat transfer to the circulating water, the entering water temperature (leaving the ground heat exchanger) would be around 40°F. Lakes that freeze at the surface in the winter approach 39°F at the bottom, yielding nearly the same margin of safety against freezing of the circulating fluid. An additional 10°F temperature difference is usually needed in the heat pump's refrigerant-to-water heat exchanger to transfer the heat to the refrigerant. Having a refrigerant-to-water coil surface temperature below the freezing point of water risks the possibility of growing a layer of ice on the water side of the heat exchanger. In the best case, icing of the coil would restrict and may eventually block the flow of water and cause a shutdown. In the worst case, the ice could burst the tubing in the coil and require a major service expense.

Several factors must be considered when selecting an antifreeze for a ground loop heat exchanger. The most important considerations are (1) impact on system life cycle cost, (2) corrosivity, (3) leakage, (4) health risks, (5) fire risks, (6) environmental risks from spills or disposal, and (7) risk of future use (the antifreeze will be acceptable over the life of the system). A study by Heinonen and Tapscott (1996) of six antifreezes against these seven criteria is summarized in Table 14. No single material satisfies all criteria. Methanol and ethanol have good viscosity characteristics at low temperatures, yielding lower-than-average pumping power requirements. However, they both pose a significant fire hazard when in concentrated forms. Methanol is also toxic, eliminating it from consideration in areas that require nontoxic antifreeze to be used. Propylene glycol had no major concerns, with only leakage and pumping-power requirements prompting minor concerns. Potassium acetate, calcium magnesium acetate (CMA), and urea have favorable environmental and safety performance, but they are all subject to significant leakage problems, which has limited their use in the past.

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