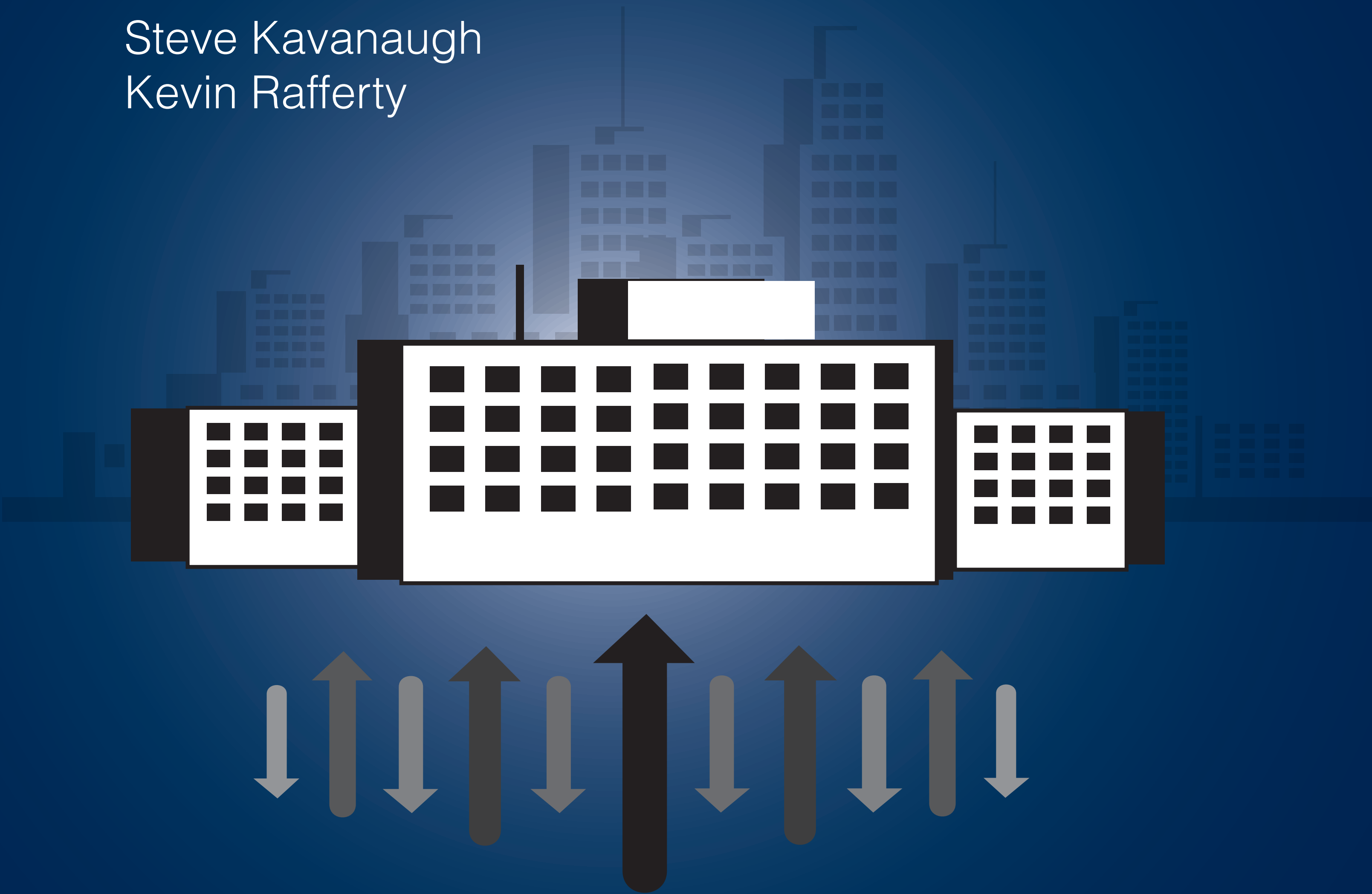
RP-1674

Geothermal Heating and Cooling

Design of Ground-Source Heat Pump Systems

Steve Kavanaugh
Kevin Rafferty



A Complete Guide to Design of Ground-Coupled, Groundwater, and Surface-Water Systems for Commercial and Institutional Buildings

ASHRAE

Geothermal Heating and Cooling

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This book is dedicated to our friend Ralph Cadwallader, a tall Texan whose company installed hundreds of miles of vertical ground loops and countless water wells. He was one of the early pioneers of high-production closed-loop ground-source heat pump installations for commercial and institutional buildings. Ralph also contributed immeasurably to the industry through his participation in such organizations as the National Ground Water Association (past president), the Geothermal Heat Pump Consortium, and the International Ground Source Heat Pump Association. May he rest in peace!

Steve Kavanaugh

Dr. Steve Kavanaugh, Fellow ASHRAE, Fellow ASME, served as a professor of mechanical engineering at the University of Alabama from 1984 to 2007 and is now Professor Emeritus. He was the owner of Energy Information Services from 1993 to 2012 and currently maintains the website www.geokiss.com, a resource of HVAC and GSHP information and design tools.

Kavanaugh is the author of the ASHRAE publication *HVAC Simplified* (2006) as well as numerous other articles, and he has presented more than 140 GSHP and HVAC seminars to more than 4500 attendees on the topics of ground-source heat pumps, energy efficiency, and HVAC. These include ASHRAE professional development seminars (PDSs), short courses, and several local chapter-sponsored sessions. In 2001, he was the recipient of ASHRAE's Crosby Field Award for the highest-rated paper presented at an ASHRAE Technical Session, Symposium, or Poster Session for the year.

Kavanaugh is the Handbook Subcommittee chair of ASHRAE Technical Committee (TC) 6.8, Geothermal Energy, and has served as chair of both TC 6.8 and the now merged TC 9.4, Applied Heat Pumps and Heat Recovery. He was also an ASHRAE Scholarship Trustee in 2013–14. He served as the chair of the Board of Directors of Habitat for Humanity of Tuscaloosa from 2001–2003 and 2010–2011, and he was the construction supervisor for five homes of Habitat for Humanity of Tuscaloosa.

He has lived in a home heated and cooled by a GSHP for 30 years.

Kevin Rafferty

Kevin Rafferty, PE, is a consulting engineer and former Associate Director of the Oregon Institute of Technology Geo-Heat Center. He is the coauthor of the original GSHP book and served as co-editor of the ASHRAE special publication *Commercial Ground Source Heat Pump Systems* (1992–1995). He is also the principal author of *Geothermal Direct Use Engineering and Design Guidebook* (1998, Oregon Institute of Technology).

Rafferty has served as Handbook subcommittee chair of TC 6.8 for 16 years and as TC 6.8 chair. He was co-presenter of both the ASHRAE short course and the professional development seminar covering GSHP systems.

He has served as chair of the National Ground Water Association Geothermal Interest Group and has presented seminars on GSHPs for such clients as utilities, universities, professional associations, the U.S. Army Corps of Engineers, Geothermal Resources Council, and ASHRAE.

He has been involved the HVAC industry since 1972, rising from service technician through engineering and research roles to retirement in 2012.

Contents

This book is accompanied by Microsoft® Excel® macro-enabled spreadsheets that can be used for a variety of GSHP calculations and can be found at www.ashrae.org/GSHP.

Preface

Geothermal Heating and Cooling is a complete revision of the 1997 ASHRAE publication *Ground Source Heat Pumps: Design of Geothermal Systems for Commercial and Institutional Buildings*. The primary audience includes HVAC design engineers, design-build contractors, GSHP subcontractors, and energy/construction managers of building owners. A unique feature of interest for building owners and architects is that the book provides characteristics of quality engineering firms and information that should be provided by design firms competing for GSHP projects.

This new work takes advantage of the many lessons learned since the time of the original publication, when GSHPs were primarily residential applications. Many improvements have evolved, and performance data, both positive and negative, is available to guide the development of best practices. Information was gathered from ASHRAE and GSHP-industry research and development projects, measured data from long-term installations, and optimized installation practices used by high-production GSHP contractors. As part of the revision, new research was conducted in critical areas not adequately addressed in previous projects.

Seven of the original eight chapters and appendices were completely rewritten and include coverage of closed-loop ground (ground-coupled), groundwater, and surface-water systems, as well as GSHP equipment and piping. Additional information on site characterization has been added, including a new hydrogeological chapter. The final chapter was replaced and contains results of recent field studies, energy and demand characteristics, and updated information to optimize GSHP system cost.

Substantial effort was taken to develop tables, graphs, and equations in both Inch-Pound (I-P) and International System (SI) units, though there are a few instances where content is supplied in I-P units only. Appendix A provides a screenshot of UnitsConverter.xlsx that is useful for manual conversion of units from I-P to SI and vice versa, and Appendix B offers a list of references to publications and standards with information on procedures and specifications that are specific to the GSHP industry.

In addition, this book is accompanied by Microsoft® Excel® macro-enabled spreadsheets, which can be found at www.ashrae.org/GSHP. The spreadsheet tools include *UnitsConverter.xlsx*, *HVACSystemEff.xlsx*, *BoreResistance.xlsm*, *E-PipeAlator14.xlsm*, *WAHPCorrector14.xlsm*, *GroundTemp&Resist.xlsm*, *Heat Exchanger Temperature Prediction*, *HeadLossTableIP.xlsm*, and *HeadLossTableSI.xlsm*. These files can be used for a variety of GSHP calculations. If the files or information at the link are not accessible, please contact the publisher.

Acknowledgments

From Steve Kavanaugh

Gratitude is extended to the members of the Project Monitoring Subcommittee who reviewed this text and provided many very useful suggestions for improvement. The reviewers included Bill Murphy (PMS Chair), Jeremy Fauber, Steve Hamstra, Gary Phetteplace and Lisa Meline. Kirk Mescher, Roxanne Scott, Dan Pettway, and Lisa Meline provided the advocacy and support to ensure the project was undertaken.

I feel especially fortunate to have had Dr. Jerald Parker as my advisor at Oklahoma State University. He is a model educator not only in terms of technical knowledge but also in his lifelong joyful commitment to students. I have tried to treat my students as well as he treated me. Thus, a great deal of the information contained in this book resulted from the hard work of many students at the University of Alabama (see listing that follows). In addition to coauthor Kevin Rafferty, this work has also benefitted from association with many colleagues, especially Joey Parker, Allan Skouby, Chuck Remund, Daniel Morris, Barry Johnson, Mike Green, David Dinse, Lonnie Ball, Charles Davis, Charles Smith, Harold Olsen, and, of course my dad, Joe Kavanaugh, who started my interest in GSHPs by installing one in our home in 1959.

From Kevin Rafferty

I'm especially indebted to Steve Kavanaugh for inviting me to join him in the original edition of this book in 1994. In any writing project, and particularly one encompassing as broad a scope as this, the authors, and hence the content, are influenced by a great many individuals. Though only two names appear on the cover, the following have contributed directly or indirectly to its production. Thanks to Earl Baumgartner and Joe Panczak for giving me a start in the HVAC business over 40 years ago. To Gene Culver, Associate Director (retired), OIT Geo-Heat Center, for sharing his geothermal expertise over the past 35 years and for his careful review of Chapters 7 and 8; Darryl Anderson of Anderson Engineering, Lakeview, OR, for his review of Chapters 7 and 8 and sharing his extensive collection of drilling photos; Quinn Dellinger of Cal State Sacramento for the review of Chapters 7 and 8; John Harms of Anderson Engineering for assistance with figures; the hundreds of GSHP seminar attendees from across the United States and Canada whose questions, comments, and arguments have molded the format and content of the information included here. Thanks also to Mike Schnieders of Water Systems Engineering, Ottawa, KS, for permission to reprint his water analysis report (Appendix N).

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Symbols, Acronyms, and Abbreviations

α	thermal diffusivity
AHU	air-handling unit
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
ANSI	American National Standards Institute
AWWA	American Water Works Association
BAS	building automation system
BEP	best efficiency point
bhp	brake horsepower
Btu/h	British thermal units per hour (heat rate unit)
c_p	specific heat
C_v	flow coefficient (flow in gpm that results in Δp = 1.0 psi)
CF (C_f)	correction factor
cfm	cubic feet per minute, ft^3/m
CTS	copper tube size
COP	coefficient of performance, W/W
CO_2	carbon dioxide
Δ	delta (difference)
db	dry bulb (temperature)
DD	drawdown
DOAS	dedicated outdoor air system
DR	dimension ratio (outside diameter/wall thickness)
DX	direct expansion (of refrigerant)
e	roughness (pipe wall)
EAT	entering air temperature
EATDB	entering air dry-bulb temperature
EATWB	entering air wet-bulb temperature
ECM	electronically commutated motor
EER	energy efficiency ratio (for cooling), Btu/Wh or kBtu/kWh
EFLH	equivalent full-load hours
EIA	Energy Information Administration (U. S. Department of Energy)
ELT	entering liquid temperature (used instead of entering water temperature, EWT, when fluid is not pure water)
EPA	U.S. Environmental Protection Agency
ERU	energy recovery unit (sensible and latent heat)

ESP	external static pressure
EWT	entering water temperature
g	acceleration of gravity
g_c	constant to relate mass, length, force, and time [= 32.2 lb_m·ft/lb_f ·s^2 (I-P), = 1.0 (SI)]
GCHP	ground-coupled heat pump (also called closed-loop ground-source heat pump, GSHP)
GLHP	ground-loop heat pump (also called ground-coupled heat pump, GCHP)
gpm	gallons per minute
GSHP	ground-source heat pump
GWHP	groundwater heat pump (also called open-loop ground-source heat pump, GSHP)
η	efficiency
HC	heating capacity
HDPE	high-density polyethylene (piping material)
hp	horsepower (unit of power, = 0.746 kW)
HVAC	heating, ventilating, and air-conditioning
Hz	frequency unit (cycles/second)
ID (d_i)	inside diameter
IPS	iron pipe size
ISO	International Organization for Standardization
IWL	injection water level
k	thermal conductivity
kW	kilowatt (unit of power or heat rate)
kWh	kilowatt-hour (unit of electrical energy)
kW/ton	kilowatt per ton, electrical demand per unit cooling capacity, kW_{refrig}/ kW_{elect}
LEED®	Leadership in Energy and Environmental Design®
LLT	leaving liquid temperature (used instead of leaving water temperature, LWT, when fluid is not pure water)
LMTD	log mean temperature difference, °F (°C)
L/min	litres per minute
L/s	litres per second
LSI	Langlier saturation index
LWT	leaving water temperature
kBtu/h	British thermal units per hour × 1000 (heat rate unit)
NBR	nitrile butadiene rubber
NGWA	National Ground Water Association
NPSH	net positive suction head
NWWA	National Water Well Association
OD (d_o)	outside diameter
Pa	pascal (pressure)
PE	polyethylene
PEX	cross-linked polyethylene (tubing)
PLF	part-load factor
ppm	parts per million
psi	pounds per square inch (unit of pressure)
PVC	polyvinyl chloride (piping material)
PWL	pumping water level
q	heat rate, Btu/h or kW

Q	volumetric flow rate
ρ	density
R	thermal resistance
Re	Reynolds number (= $\rho DV/\mu$)
RSI	Ryznar stability index
rpm	revolutions per minute
Sch	Schedule (pipe dimension)
SEER	seasonal energy efficiency ratio (for cooling), Btu/Wh or kBtu/kWh
SC	sensible cooling capacity (thermal) or specific capacity (of water well flow rate)
SDR	standard dimension ratio (outside diameter/wall thickness)
SWHP	surface-water heat pump
SWHE	surface-water heat exchanger
SWL	static water level
τ	time
t	temperature, °F (°C)
TC	total cooling (capacity) or thermal conductivity
ton	cooling capacity (12,000 Btu/h, rate required to freeze 2000 pounds of water in 24 hours)
UFAD	underfloor air distribution
USGS	U.S. Geological Survey
VAV	variable air volume
VFD	variable-frequency drive (also called variable-speed drive, VSD)
VSD	variable-speed drive (also called variable-frequency drive, VFD)
wb	wet bulb (temperature)
WLHP	water-loop heat pump (a.k.a water-source heat pump, WSHP)
WSHP	water-source heat pump (a.k.a water-to-air heat pump; water-to-water heat pump; water-loop heat pump, WLHP)
X	dimensionless number for line heat source equation $\{= r/[2(\alpha\tau)^{0.5}]\}$

1 Introduction to Ground-Source Heat Pumps

1.1 OVERVIEW, NOMENCLATURE, AND GSHP TYPES

Ground-source heat pump (GSHP) is an all-inclusive term for a variety of systems that use the ground, groundwater, or surface water as a heat source and sink. GSHPs are subdivided by the type of exterior heat exchange system. This includes ground-coupled heat pumps (GCHPs) that are closed-loop piping systems buried in the ground, groundwater heat pumps (GWHPs) that are open-loop piping systems with water wells, and surface-water heat pumps (SWHPs) that are closed-loop piping coils or open-loop systems connected to lakes, streams, or other reservoirs. Heat pumps are located in the buildings and cool by removing indoor heat and rejecting it to the exterior GSHP loop. In heating, the process is reversed as heat is removed from the outdoor loop by the heat pumps and is delivered to the building. Many parallel terms exist for GSHPs, such as *geothermal heat pumps* (GHPs), *earth energy systems*, and *GeoExchange®* systems that are used to meet a variety of marketing or institutional needs. However, ASHRAE (2011) has established a standard nomenclature to which this book attempts to conform.

GSHPs initially were more widely applied to residential buildings but are now increasingly being utilized in the commercial and institutional sectors. The economics of GSHPs can be very attractive in larger buildings because elaborate equipment and controls are not required to provide comfort and high efficiency. When simple design approaches are followed, the added cost of ground heat exchangers can be offset to a large extent. Simple designs also have the advantage of reducing maintenance requirements, which can be very attractive to building owners with minimal maintenance resources (e.g., schools). However, simply attaching a ground heat exchanger, groundwater loop, or surface-water coils to conventional water-cooled HVAC systems (e.g., chilled-water variable-air-volume systems) usually results in higher installation costs, poor efficiency, and added maintenance requirements. Typical installation recommendations, design guides, and conventional approaches must be amended in order to take full advantage of these systems. This book provides engineers with GSHP design methods that deal with larger multiple-zone buildings with diverse loads and occupancy patterns. Other sources (Remund 2011; Kavanaugh 1991) provide detailed treatment of the design and installation of residential and light commercial GSHPs.

GSHPs are rarely effective in cooling-only or heating-only applications. Thus, heat pumps of some type are connected to the exterior ground, groundwater, or surface-water loops to provide cooling and heating inside the building. The most widely used unit is a water-to-air heat pump as shown in Figure 1.1. Water or water-antifreeze solution circulates through a liquid-to-refrigerant heat exchanger. Air to be heated or cooled is circulated through a conventional finned-tube air-to-refrigerant heat exchanger and air distribution system. In applications where the heat pumps are located near an area where a water heating load is present (i.e., a kitchen), optional heat recovery heat exchangers can be included. Packaged heat pumps in the range of 0.5 to 50 tons (2 to 175 kW) are available. Note that small and mid-size units typically have higher efficiencies because of the lower fan power requirements compared to larger units that often have fans with much higher total static pressure in order to provide circulation through more extensive air distribution networks.

Water-to-water heat pumps as shown in Figure 1.1 are also commonly used and can be especially effective when the building water-loop temperatures are not extreme. Thus, in-floor heating systems that might only require maximum temperatures near 100°F (38°C) and chilled-beam applications with temperatures near 55°F (13°C) tend to have higher efficiencies. Good efficiencies can also be attained using low-static-pressure fan-coil units (FCUs) and water-to-water heat pumps with supply water-heating temperatures below 115°F (46°C). However, large central air-handing units (AHUs) with high total-static-pressure fans and/or systems that require higher heating-mode supply temperatures (>120°F [49°C]) are not recommended if system efficiency and low operating costs are primary goals.

A third type of GCHP is the direct-expansion (DX) GCHP, which uses a buried copper piping network as one of the heat pump coils through which refrigerant is circulated. These systems normally incorporate a forced-air distribution system, although hydronic systems can also be used. Systems using water-to-air and water-to-water heat pumps are often referred to as *GCHPs with secondary solution loops* to distinguish them from DX GCHPs. This book concentrates on the design of secondary solution systems; DX GCHPs are not covered.

Chapter 2 of this book covers in more detail heat pump equipment, system efficiencies, and accompanying accessories.

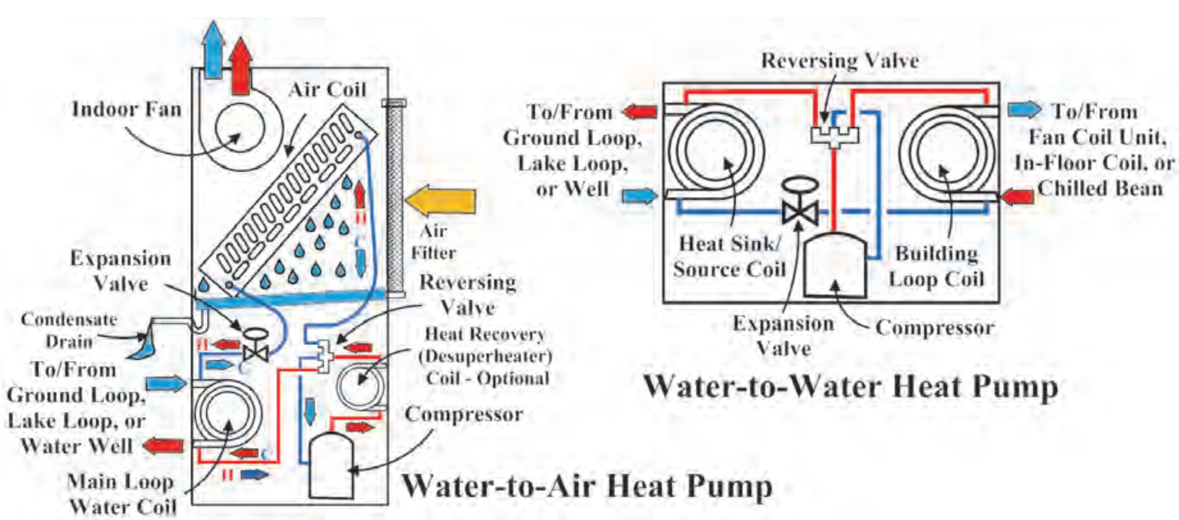

Figure 1.1 Primary GSHP Equipment Options

1.2 GROUND-COUPLED HEAT PUMPS

GCHPs are a subset of GSHPs and are often referred to as *closed-loop ground-source heat pumps*. A GCHP refers to a system that consists of a network of heat pumps that are linked to a closed ground heat exchanger buried in the soil. GCHPs are further subdivided according to ground heat exchanger design.

Vertical GCHPs are by far the most common type. The ground heat exchanger is usually constructed by placing two high-density polyethylene (HDPE) tubes in a vertical borehole as shown in Figure 1.2. The tubes are thermally fused at the bottom of the bore to a close return U-bend. Standard prefabricated vertical tube sizes range from 3/4 to 1 1/4 in. (25 to 40 mm) nominal diameter. Common bore depths range between 200 and 300 ft (60 and 90 m), but local drilling conditions may dictate they be shorter or, in many cases, over 400 ft (150 m) in depth. Deeper bores are not common and caution is required to offset deep-bore hydrostatic conditions and added pipe head losses even when the largest standard-sized U-tubes are applied (see Appendix C).

The advantages of vertical GCHPs are that they require relatively small plots of ground, are in contact with soil that varies very little in temperature and thermal properties, require the smallest amount of pipe and pumping energy, and can yield the most efficient GCHP system performance. The disadvantage is that they are typically higher in cost because of limited availability of appropriate equipment and installation personnel. In some cases, when the cooling requirements exceed the heating needs, installation cost can be reduced by installing a hybrid system with ground loop sized to meet the heating requirement in parallel with a fluid cooler or cooling tower. These systems require added maintenance, added controls, and following ASHRAE (2000) guidelines to minimize the risks associate with cooling towers. The system design of vertical GCHPs is the focus of Chapters 3 and 4 of this book.

Horizontal GCHPs can be divided into three subgroups: single pipe, multiple pipes, and coiled pipe that looks like a Slinky™ toy. Initial designs of single-pipe horizontal

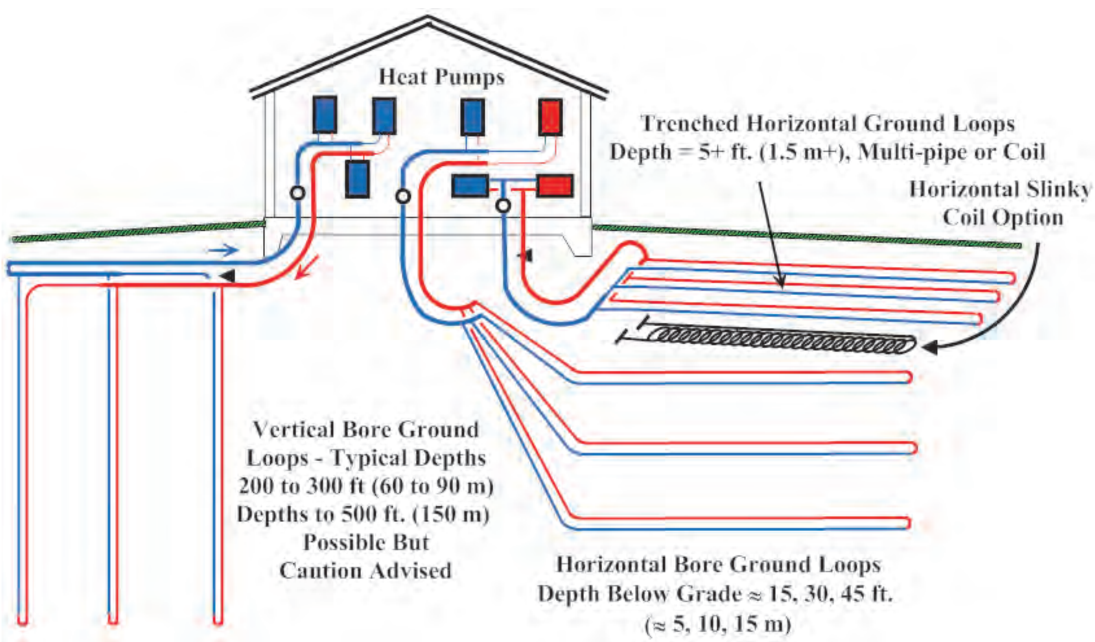

Figure 1.2 Closed-Loop Ground-Coupled Heat Pump with Three Ground-Loop Options

GCHPs had them placed in narrow trenches at least 5 ft (1.5 m) deep. These designs require the greatest amount of ground area. Multiple pipes (usually two or four) placed in a trench at a greater depth than the minimum (5 ft [1.5 m]) can reduce the amount of required ground area. Contractors have used either deep, narrow trenches (dug with a chain-type trencher) or wide trenches (dug with a backhoe) with pipes separated by 12 to 24 in. (30 to 60 cm). Although trench length can be reduced, total pipe length must be increased with multiple-pipe GCHPs in order to overcome thermal interference with adjacent pipes in the same trench. The slinky coil is reported to also reduce required ground area. These horizontal ground heat exchangers are constructed by stretching small-diameter HDPE 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.

Horizontally bored ground loops are a crossover between vertical and horizontal ground loops. Horizontal drilling machines can install heat exchangers deeper and use multilayer placement of U-tubes, which substantially reduces the required land area compared to shallow horizontal loops. As with vertical loops, the surrounding ground temperature and thermal properties vary little with season. Thus, horizontally bored ground loops are well suited to larger building applications. (See Appendix D for information on vertical-loop installation equipment and procedures.)

The advantages of horizontal GCHPs are that they are typically less expensive than vertical GCHPs in residential and small (< 20 ton [70 kW]) commercial building applications because appropriate installation equipment is often more widely available and many residential applications have adequate ground area. These GCHPs (except for deep horizontally bored loops) are less commonly used in commercial and institutional buildings because of the larger ground area required. Other disadvantages include greater adverse variations in performance because horizontal ground temperatures and thermal properties fluctuate with season, rainfall, and burial depth; slightly higher pumping energy requirements; and lower system efficiencies. Remund (2011) covers the design and installation of horizontal GCHPs in greater detail.

1.3 GROUNDWATER HEAT PUMPS

The second subset of GSHPs is groundwater heat pumps (GWHPs). Until the recent development of GCHPs, GWHPs were the most widely used type of GSHP. GCHP systems were developed in part in response to the widespread water quality problems experienced by residential GWHP systems in the 1960s and 1970s. In the commercial sector, plate heat exchangers are used to isolate the building loop from exposure to groundwater, eliminating water quality problems in the building. While the cost of the ground heat exchanger per ton of capacity is relatively constant for a GCHP, the cost of a well-water system (on a per-ton [per-kW] basis) is much lower for a large system (Rafferty 1995), as discussed in Chapter 8. A single high-volume well can serve an entire building. Properly designed GWHP systems require more maintenance than GCHP or closed-loop SWHP systems, but this cost is small in the context of the potential capital cost savings (see Chapter 8).

Various systems are possible. A widely used system places a central water-to-water heat exchanger between the groundwater and a closed water loop that is connected to water-to-air heat pumps located in the building (Figure 1.3). In smaller buildings (<20 tons [70 kW]), it is possible to circulate the groundwater directly through each heat pump at the risk of corrosion and fouling of heat exchangers and control valves that may result when untreated water is circulated through a distributed system. A third possibility is to circulate groundwater through a central chiller (or heat pump) and to heat and cool

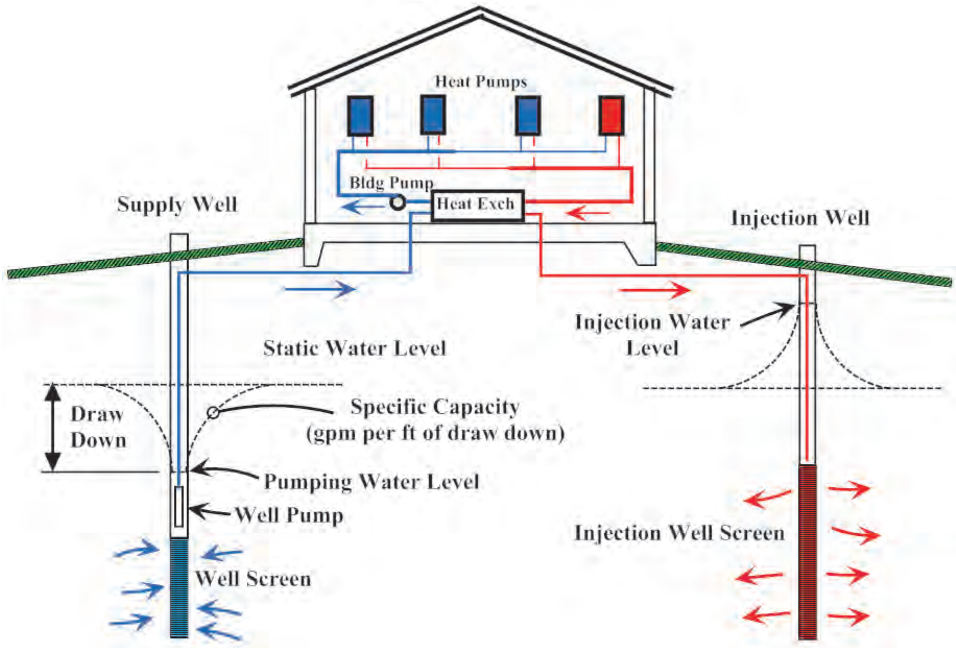

Figure 1.3 Open-Loop Groundwater Heat Pump with Isolation Heat Exchanger

the building with a conventional chilled- and hot-water distribution system, though central chiller systems tend not be as energy efficient as unitary designs.

All three types of systems (and other variations) lend themselves to the possibility of direct precooling or cooling in much of the United States. Low-temperature groundwater (<58°F [15°C]) can be circulated through hydronic coils in conjunction with heat pumps. This can displace a large amount of energy required for cooling, especially when precooling outdoor ventilation air. Direct cooling is possible with colder water found in the northern portion of the US.

The advantages of GWHPs are that they are lower in cost compared to GCHP systems, the water well is very compact, water well contractors are widely available, and the technology has been used for decades. Disadvantages are that local environmental regulations may preclude use or injection of groundwater, water availability may be limited, fouling precautions may be necessary if the well is not properly developed or water quality is poor, and pumping energy may be excessive if the pump is oversized or poorly controlled.

1.4 SURFACE-WATER HEAT PUMPS

Surface-water heat pumps (SWHPs) 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, thermal characteristics of surface water bodies are quite different from those of the ground. Some unique applications are possible and special precautions are warranted.

Closed-loop SWHPs consist of water-to-air or water-to-water heat pumps located in a building and connected to a piping network placed in a lake, river, or other open body of water (Figure 1.4). A pump circulates a water-antifreeze solution through the heat pump's water-to-refrigerant coils and the submerged piping loop that transfers heat to or from the

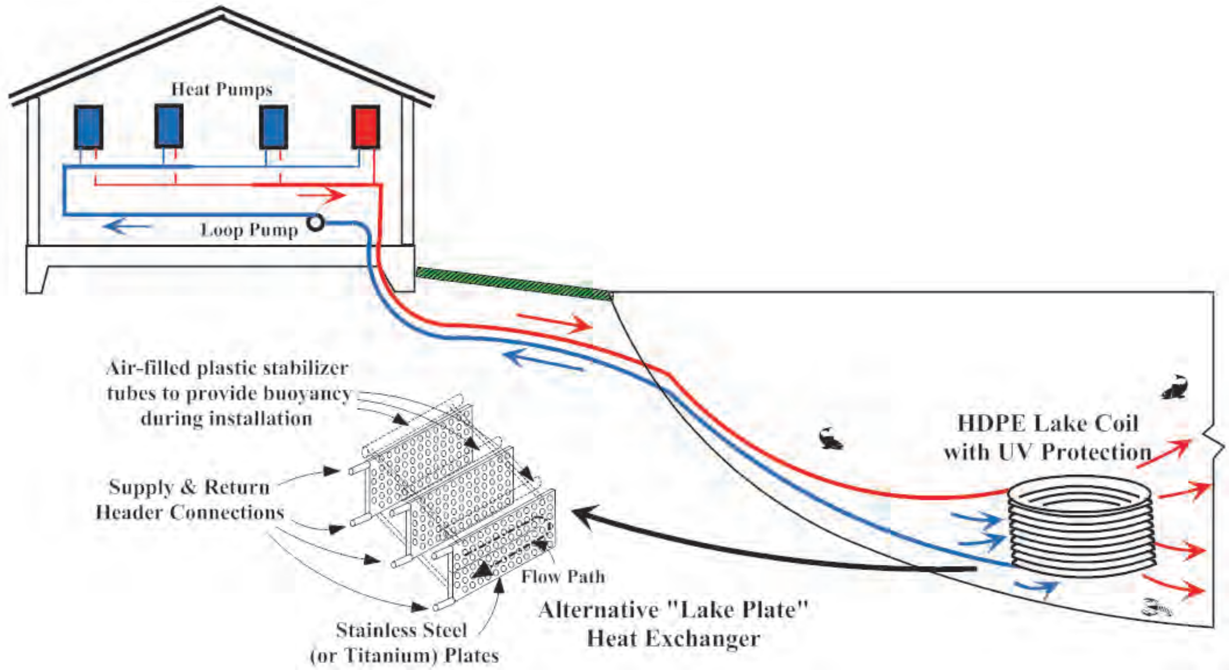

Figure 1.4 Closed-Loop Surface-Water Heat Pump with Two Lake Coil Options

lake. The recommended piping material is thermally fused HDPE with some type of ultraviolet radiation protection. Copper and other types of plastic tubing have also been used, but polyvinyl chloride (PVC) should be avoided. Many installations have used 3/4 in. or 1 in. (25 or 32 mm) HDPE tubing for the primary heat exchanger coils. Larger-diameter, thicker-wall tubing is recommended for areas in which damage from boats is a possibility. Coils are normally arranged in multiple parallel piping patterns to minimize pressure losses. Plate heat exchangers as shown in Figure 1.4 are also available with stainless steel or titanium materials. The main header pipes connecting the primary heat exchanger coils are sized to minimize losses, and they are normally of larger diameter than the individual coil tubing. Additional ASHRAE research is in progress to develop design tools for SWHPs systems (ASHRAE 2009), but results are not yet available.

The advantages of closed-loop SWHPs are relatively low cost (compared to GCHPs), low pumping energy requirements, high reliability, low maintenance requirements, and low operating costs. Disadvantages are the possibility of coil damage in public lakes and wide temperature variations with outdoor conditions if lakes are small and/or shallow. This would result in some undesirable variations in efficiency and capacity, but they would not be as severe as with air-source heat pumps.

Open-loop SWHPs can use surface water bodies in a manner similar to cooling towers, without the need for fan energy or frequent maintenance. In warm climates, lakes can also serve as heat sources during the winter heating mode. However, closed-loop systems are the only viable option for heating in moderate and colder climates.

Surface 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, with only a few heat pumps. In deep lakes (≥40 ft [≥12 m]), thermal stratification often exists throughout the year to the extent that direct cooling or precooling is possible. Water can be pumped from the bottom of deep lakes through heat exchangers in the return air duct. Total cooling is a possibility if water is

50°F (10°C) or less. Precooling is possible with slightly warmer water that can then be circulated through the heat pump units. Section 5.8 in Chapter 5 provides recommendations for direct cooling and precooling system design.

Water pump options fall into three categories: above surface, vertical pumps with submerged impellers and above-surface motors, and submersible. Above-surface pumps must have low net positive suction head (NPSH) requirements, and precautions must be taken to ensure water remains in the pump during off cycles. Vertical pumps with submerged impellers connected to above-surface motors are often an alternative if precautions are taken for lake level fluctuations. Submersible pumps can serve as a flexible alternative. Low-head single-stage types can be used if the building is located near the lake. Multistage units can provide water for greater elevations and distances. Filtration of coarse particles and objects can be accomplished on the suction side of any of the above pumps. This is often sufficient if heat exchangers are equipped to be periodically flushed. A thorough feasibility study for a large central New York chilled-water system presents detailed design, environmental, and economic information on existing direct cooling systems (SUNY 2011). Although somewhat dated, the information by Kavanaugh (1991) provides some additional details regarding residential SWHP systems and design recommendations for direct cooling and precooling with surface water or groundwater.

1.5 EXTERIOR AND BUILDING LOOP PIPING OPTIONS

Conventional wisdom assumes the best practice for large piping loops is to incorporate a central loop with large variable-speed pumps and two-way control valves on the HVAC equipment. As discussed in the following sections, field studies have shown this assumption is often incorrect for closed-loop GCHP systems (Kavanaugh and Kavanaugh 2012). While this practice has some economic advantages in conventional chilled-water systems, GWHPs, and SWHPs, the economy of scale is not present to the same degree with GCHPs, especially in large-footprint one- and two-story buildings. Although building diversity often results in reduced length for central ground loops, the total cost of the system (especially in large-footprint buildings) will be greater because of the added cost of extensive runs of large-diameter interior piping. Multiple interior loops also afford the possibility of using HDPE and fiber-core polypropylene, thus eliminating the need for corrosion inhibitors. This could be an important factor in locations where certain chemicals are prohibited from being circulated in deep underground piping that is in contact with sensitive aquifers. Engineers should carefully consider other options, some of which are shown in Figure 1.5. Figures 1.6 to 1.11 demonstrate other common options, which are discussed in greater detail with additional variations in later chapters.

1.6 FIELD STUDY RESULTS

Results of a field study of long-term performance of 40 commercial and institutional buildings with GCHP systems have appeared in a series of seven articles in *ASHRAE Journal*. Energy performance in terms of ENERGY STAR® rating (EPA 2012) was categorized by the loop types shown in Figures 1.6, 1.7, 1.8, and 1.9 (Kavanaugh and Kavanaugh 2012). An explanation of the ENERGY STAR rating method and additional details of the long-term GSHP performance monitoring project appear in Chapter 9. Additional buildings were monitored to supplement background information for this book. Appendix E presents results for one of the monitored buildings.

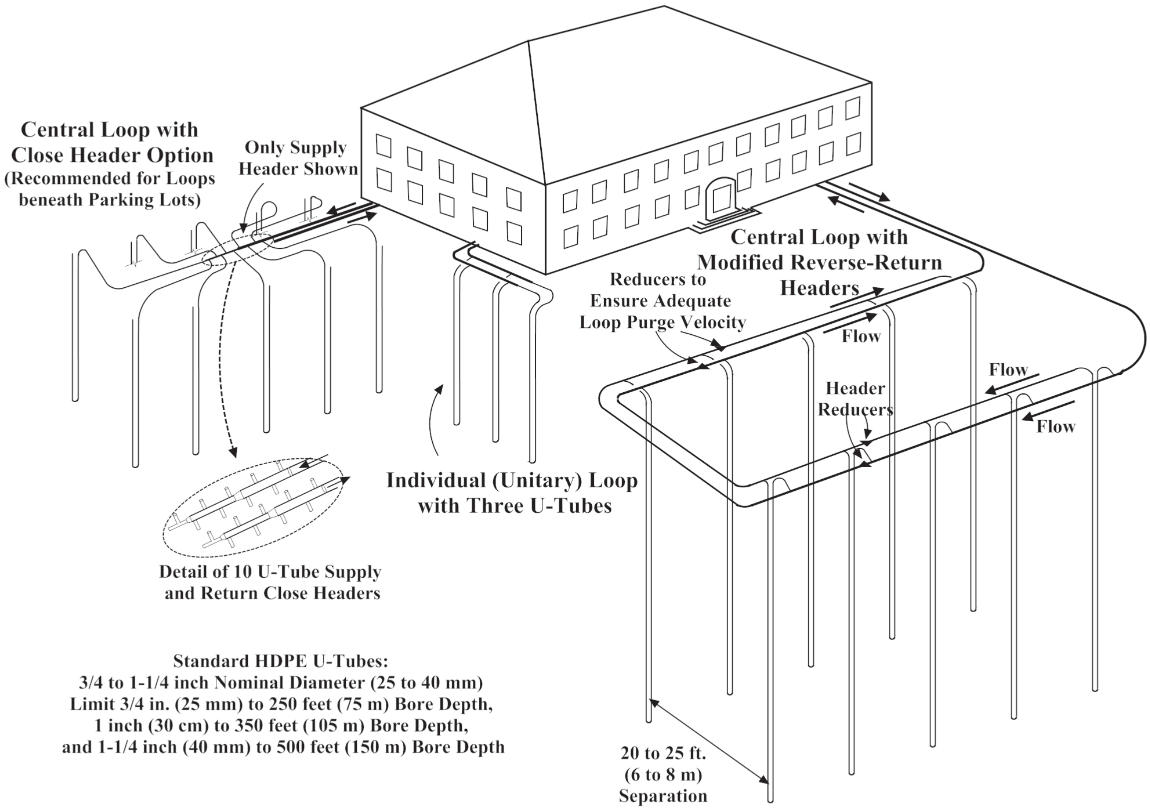

Figure 1.5 Three Options for Closed-Loop Heat Pump Vertical Ground-Loop Circuits

Four of the monitored buildings in the field study have unitary loop systems as shown in Figure 1.6. Each unit is connected to an individual ground loop consisting of two, three, or four vertical U-tubes. Water-loop circulation is provided by small on-off pumps. Larger, less frequently occupied spaces such as cafeterias and gyms are conditioned by air-cooled equipment. All four buildings are schools (two elementary, one middle, and one high school) located in a hot climate and were built between 1996 and 2001. The classrooms, offices, and libraries are heated and cooled by water-to-air heat pumps. ENERGY STAR ratings ranged from 93 to 100 with an average of 97. (An ENERGY STAR rating of 97 indicates the building uses less source energy than 97% of buildings of this type when corrections for climate, occupancy, schedule, and internal loads are applied. EPA [2012] provides details.)

Six of the monitored buildings in the study are served by multiple water-to-air heat pumps connected to a one-pipe building loop as shown in Figure 1.7. When a unit is activated, liquid is removed from the loop by a low-head circulator pump on each unit and discharged a short distance downstream. Main pumps, controlled by loop temperature, provide continuous circulation to ensure no recirculation occurs. As shown in Figure 1.7, the ground loop is a conventional two-pipe reverse-return network. All six sites are schools (five elementary and one middle school) located in Illinois. One school was built in 1938 and the others were built in the 1950s. The buildings were retrofitted with the GSHPs between 2006 and 2008. Each school is heated and cooled by water-to-air heat pumps connected to the central one-pipe loop. ENERGY STAR ratings ranged from 82 (1938 school) to 99 with an average of 94. When the older building is not considered the average rating of the five 1950 vintage schools was 96.

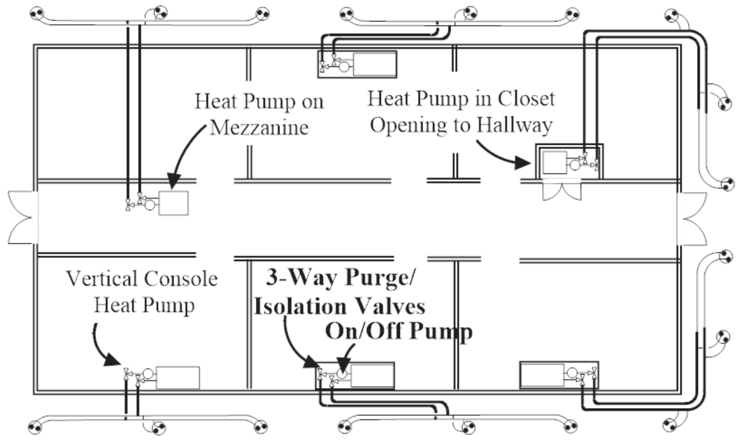

Figure 1.6 Unitary-Loop GCHP with Each Heat Pump Connected to Individual Loops

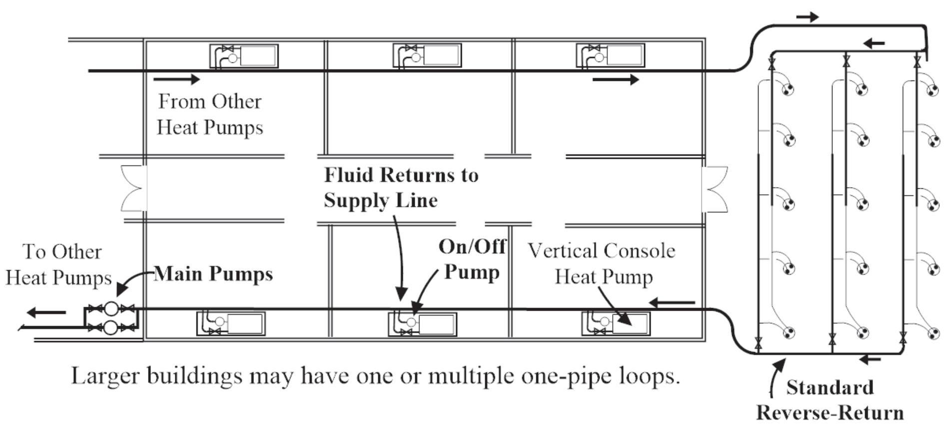

Figure 1.7 One-Pipe Loop GCHP with Reverse-Return Header Ground Loop

Five of the monitored buildings had common-loop systems as shown in Figure 1.8. Multiple water-to-air heat pumps are connected to a common two-pipe loop. Each unit has its own on-off circulator pump that circulates water through the entire common building and ground loop. Check valves are installed on the pump discharge to prevent reverse circulation from other units when the pump and heat pump are not operating. Four of the buildings have multiple common loops (thus the alternative term *subcentral* for *common*) with 2 to 15 heat pumps on each loop. One building has a single common loop for the entire building with flow provided by small circulator pumps on each heat pump. Four of the sites are schools (three elementary and one middle school) and one is an office. Four buildings are located in Alabama and one elementary school is in Kentucky. The Kentucky school was built in 2007 and the Alabama office was built in 1993. The Alabama middle school was built in 1929 and the elementary schools in the 1950s. Portions of all three schools were retrofitted with the GSHPs in 2002. ENERGY STAR ratings ranged from 97 for the Kentucky school down to 21 for the Alabama office. The low score for the office resulted from the use of multiple large pumps that operated continuously. Only 29% of the middle school was conditioned with a GCHP, and it received an ENERGY STAR rating of 56. The Alabama elementary schools had ENERGY STAR ratings of 82 and 85 with 45% and 69% of the floor areas being conditioned with GCHPs.

Eighteen of the monitored buildings are served by multiple water-to-air heat pumps connected to a central building loop as shown in Figure 1.9. Two of buildings are served by the setup of a central chiller connected to a central ground loop with some portions being served by water-to-air heat pumps. Fourteen of the buildings have variable-speed pumps controlled primarily by differential pressure on the building supply and return headers. Four systems have constant-speed continuously operating pumps. Fourteen of the sites are schools (seven elementary, three middle, and four high schools), four are offices, one is a hotel, and one is an active senior living facility. The sites are located in Florida, Georgia, Mississippi, Tennessee, and Kentucky. At one site a fluid cooler was installed after the first year of operation due to high loop temperatures. Two additional sites (in the same school district) were equipped with coolers at installation, but because

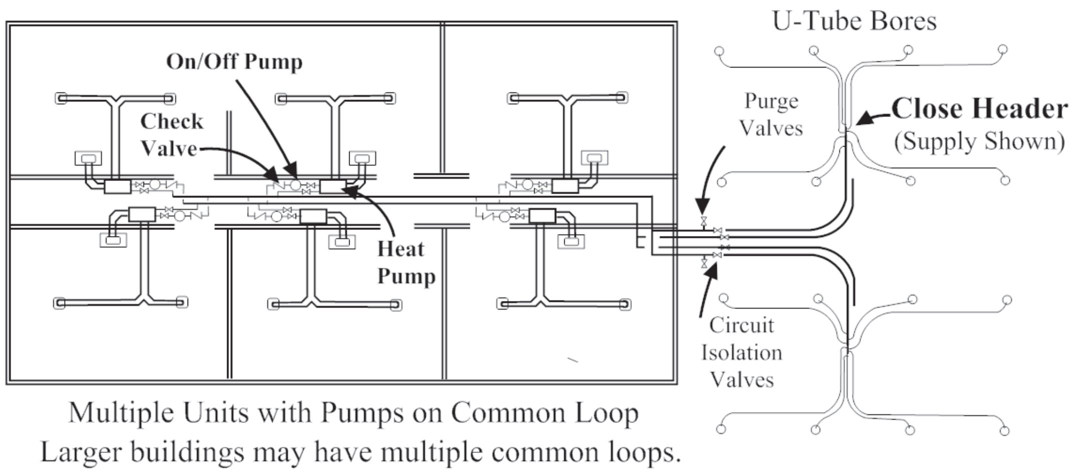

Figure 1.8 Common (Subcentral) Loop GCHP with Close Header Ground Loop

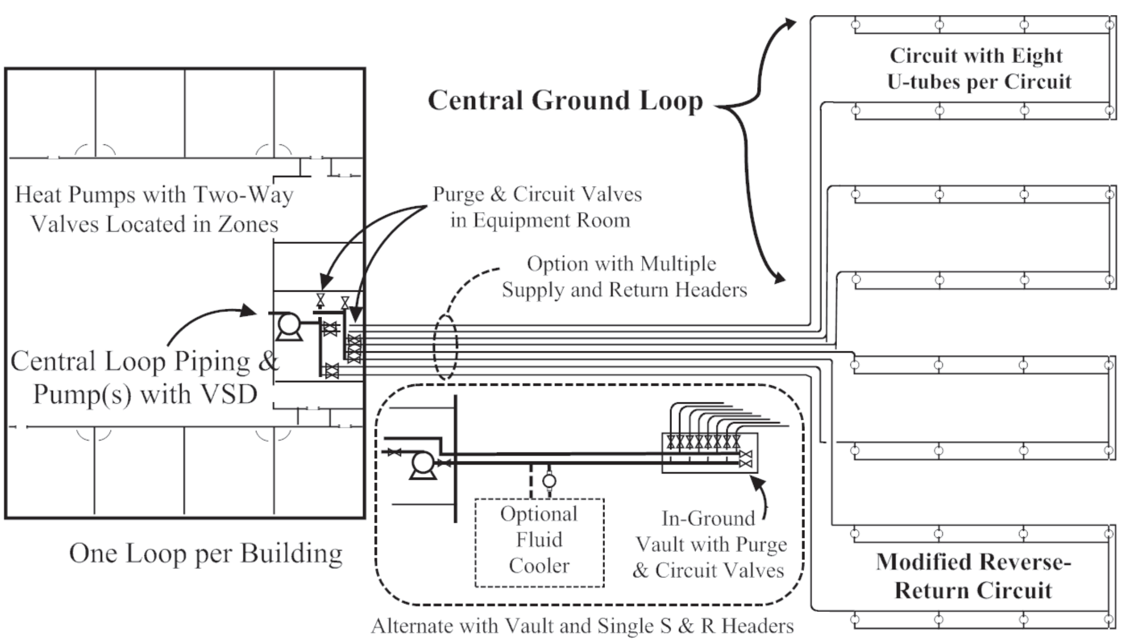

Figure 1.9 Central Loop GCHP with Modified Reverse-Return Header Ground Loop

the ground loops were 50% larger than those of the first school, the coolers did not need to operate. Five of the GCHPs were retrofits and the remaining systems were installed when the buildings were constructed. Dates of GCHP installations range from 1988 to 2008. ENERGY STAR ratings ranged from 1 (hotel) to 93 (retrofit school). If the rating of 1 were not considered, the average ENERGY STAR rating would be 60. The systems with variable-speed drive pumps had an average rating of 57, the constant-speed pump systems had an average of 72, and the systems with chillers had an average rating of 21. The hybrid (fluid cooler equipped) system with the smaller loop had an ENERGY STAR rating of 79, while the systems with larger loops and unused fluid coolers had ratings of 93 and 87.

None of the monitored buildings were GWHP systems as shown in Figure 1.10 or SWHP systems as shown in Figure 1.11.

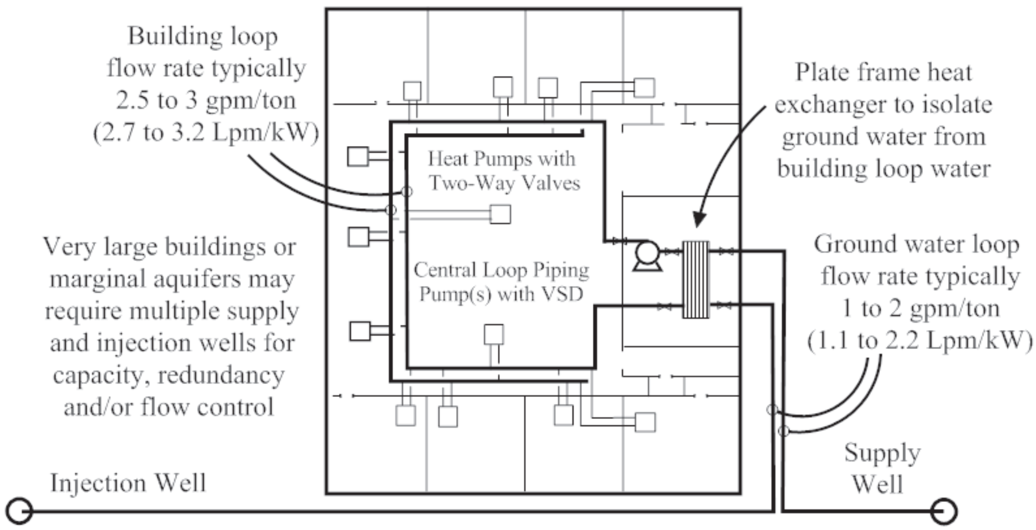

Figure 1.10 Central-Loop GWHP with Plate-Frame Isolation Heat Exchanger

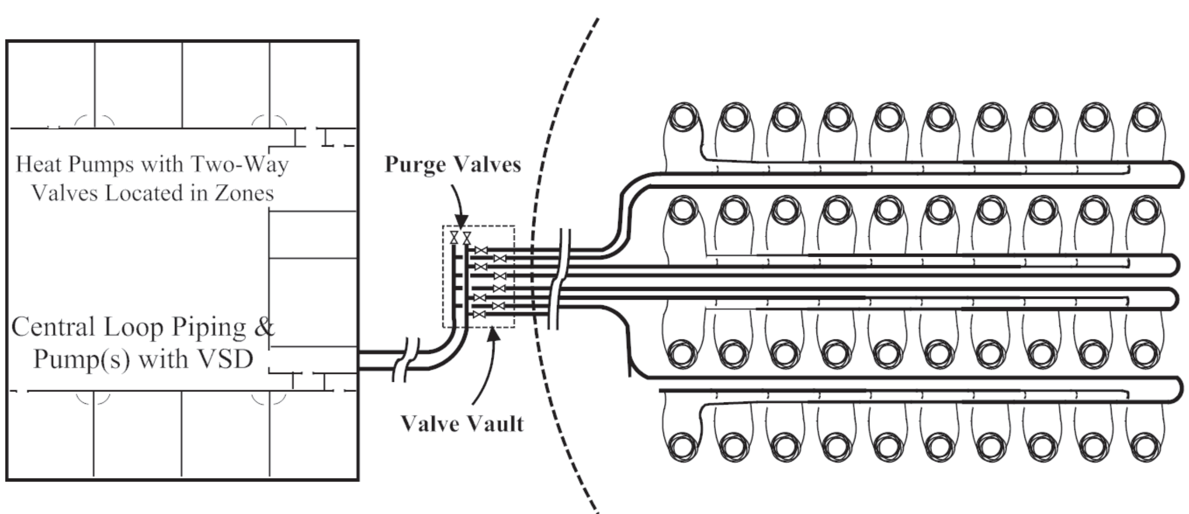

Figure 1.11 Central-Loop SWHP with Reverse-Return Header Lake Coils

1.7 PRELIMINARY ASSESSMENT, DESIGN STEPS, AND DELIVERABLES

During the preliminary stages of any GSHP project, three considerations must be evaluated to determine what type of system (ground-coupled, groundwater, or surface water) is optimal for the building and the site:

- Hydrogeological characteristics and land availability of the site
- Local, state, and federal regulations and cost of permitting
- Building cooling/heating requirements and layout, which dictate the most appropriate HVAC system that is affordable and maintainable by the owner

The characteristics of the site should be considered before the type of GSHP is chosen. A great amount of state and U.S geological survey information is well documented to assist in determining drilling and formation conditions. A book is available from ASHRAE (Sachs 2002) that helps HVAC engineers familiarize themselves with hydrogeological concepts. Local, state, and federal regulations vary significantly and must be identified. A comprehensive GSHP regulation study was conducted in the 1990s (Den Braven and Jensen 1996; Den Braven 1998), but it has not been updated recently. Highly regulated locations may have permitting fees that can be a considerable percentage of total ground heat exchanger costs. Equally important, a preliminary evaluation of the *system* efficiency and equipment costs for the HVAC system is critical to the success of a project, as the HVAC cost has been found to be approximately three-fourths of the total GSHP system cost (Kavanaugh et al. 2012).

GCHPs seem to be the most common GSHP type in both commercial and residential buildings. The lack of exposure of the “outdoor” unit, which eliminates weather-related and environmental damage, theft, and maintenance requirements, is an especially attractive characteristic to building owners with limited operation resources (schools, small building owners, etc.). However, the land area requirement can eliminate GCHPs from consideration, especially in urban, high-density applications. Consider that a single vertical bore can typically support one to two cooling tons (3.5 to 7 kW), which requires approximately 400 ft^2 (40 m^2) of land area. In buildings where the cooling load is much greater than the heating requirement, the required land area can be reduced significantly with hybrid GCHPs. Also, designers are attempting to drill to greater depths to reduce the required land area. Caution is advised with deeper drilling because pump requirements will likely be greater, bore separation should be increased to reduce the possibility of cross-drilling during installation, and the potential for pipe failure for depths beyond 500 ft (150 m) is not yet well established (see Appendix C). Additional details of GCHP site selection can be found in Sections 3.5 and 3.6 of Chapter 3.

The presence of a nearby reservoir or the site requirement of a water retention pond would sway the decision toward using a SWHP. SWHPs tend to be less expensive than GCHPs and can be more efficient in cooling if the summer water temperatures are lower than ground temperatures, as may be the case in deep reservoirs or large open bodies of water. Reservoir size and depth requirements are discussed in Section 5.10 and temperature profiles are found in Section 5.3.

The availability of plentiful groundwater would sway the choice toward a GWHP. This is especially true for larger buildings and where the groundwater is shallow, because the economics of GWHPs compared to GCHPs and SWHPs improves with larger building size and shallow water wells. The required separation distance between the supply and the injection well in some cases may impact the site requirement. These issues are addressed in Section 7.5. General groundwater availability information can be obtained from state and federal geological surveys, but the level of detail needed for system design typically requires a well flow test, as discussed in Chapter 7.

Too often designers attempt to attach traditional HVAC systems to groundwater or surface-water heat exchangers. In some cases two different design teams are separated at the building wall, one responsible for the HVAC and the other responsible for the outdoor heat exchanger. These decisions almost always drive down system efficiency and elevate system installation costs.

Section 2.4 outlines the recommended procedure for evaluating GSHP system efficiency that considers the input of all primary HVAC components, including heat pumps or chillers, supply fans, terminal fans, return fans, indoor pumps, outdoor pumps, and fluid cooler/cooling tower fans (for hybrid systems). This procedure is critical but it is rarely performed unless there is a complaint of high energy use by the owner. Section 9.2 provides such an analysis for a LEED Platinum building with an underperforming GSHP system. Section 9.4 provides a recommended procedure for estimating the cost of the (inside-the-building) HVAC system. Performing this procedure before the final design is initiated may prevent time-consuming, painful, and ill-advised redesign to bring the GSHP system cost to within an allowable budget.

The recommended design steps for GCHP systems provided below are an update of previous versions provided in an *ASHRAE Transactions* paper (Kavanaugh 2008) and the Geothermal Energy chapter of *ASHRAE Handbook—HVAC Applications* (2011). While several of the steps are also common to GWHPs and SWHPs, steps in which the procedures are different are subdivided into three substeps, one for each type of system.

1. Calculate peak zone cooling and heating loads and estimate off-peak loads.
2. Provide suggestions to reduce building envelope, lighting, and ancillary loads with estimates of reduction in HVAC and ground-loop costs.
3. Estimate the annual heat rejection into and absorption from the loop field to account for potential ground, groundwater, or reservoir-water temperature change.
4. Select the preliminary loop operating temperatures and flow rate to begin optimization of first cost and efficiency (selecting temperatures near the normal source temperature will result in high efficiencies but larger and more costly ground loops).
5. Correct heat pump performance at rated conditions to actual design conditions (Chapter 2). *Note that some designers prefer to reverse the order of Steps 5 and 6.*
6. Select heat pumps to meet cooling and heating loads and locate units to minimize duct cost, fan power, and noise.
7. Arrange heat pumps into ground-loop circuits to minimize system cost, pump energy, and electrical demand (Chapters 4 and 6).
8. Conduct a site survey.
   a. For closed-loop GCHPs, conduct a thermal property test to determine ground thermal properties and drilling conditions (Chapter 3). For small projects a survey of geological reports can be used to conservatively estimate these values.
   b. For open-loop GWHPs, conduct a well flow test (Chapter 7).
   c. For closed-loop SWHPs, determine or conduct a survey of the surface-water reservoir depth and, if time permits, water temperature in late winter (February, early March) and late summer (late August, September). If temperature surveys are not possible, consult references (such as EIS 2014) for temperature profiles for lakes of similar dimensions and locality. Additional

information may be available in the final report of the SWHP heat pump investigation (ASHRAE 2009) when it becomes available.

9. Assess outdoor heat exchanger options.
    a. For closed-loop GCHPs, determine and evaluate possible loop field arrangements that are likely to be optimum for the building and site (bore depth, separation distance, completion methods, annulus grout/fill, and header arrangements). Include subheader circuits (typically 5 to 15 U-tubes on each) with isolation valves to permit air and debris flushing of sections of the loop field through a set of full-port purge valves.
    b. For open-loop GWHPs, site the production well(s) and injection well(s) to provide adequate separation and access to the wellhead for maintenance.
    c. For closed-loop SWHPs, estimate the number of coils or plates necessary and locate them in a deeper portion of the reservoir that is in reasonable proximity (i.e., the required pump power is less than 10% of total heat pump power).
10. Determine the optimum ground, groundwater, or surface-water heat exchanger dimensions with calculations provided in this book or by commercial software. Recognize one or more alternatives that provide equivalent performance and that may yield more competitive bids.
11. Evaluate alternative designs: loop field arrangements, operating temperatures, flow rates, heat exchanger dimensions and materials, grout/fill materials, etc.
12. Lay out interior piping and compute head loss through the critical path, and select pumps and control method.
13. Determine system efficiency and consider modifying the water distribution system if pump demand exceeds 10% of the system total demand, modify the air distribution system if fan demand exceeds 15% of the system total, select more efficient pumps, or redesign ground/groundwater/surface-water loop.

ASHRAE Handbook—HVAC Applications (2011) lists the minimum deliverables necessary to adequately specify a closed-loop GCHP installation; items are added here for GWHPs and SWHPs:

- Heat pump specifications at rated conditions.
- Pump specifications, expansion tank size, and air separator.
- Fluid specifications (system volume, inhibitors, antifreeze concentration if required, water quality, etc.).
- Design operating conditions (entering and leaving ground-loop temperatures, return-air temperatures [including wet bulb in cooling], airflow rates, and liquid flow rates.
- Pipe header details with ground-loop layout, including pipe diameters, spacing, and clearance from building and utilities.
- Specifications for outdoor heat exchanger.
    - For closed-loop GCHPs: bore depth, approximate bore diameter, bore separation, and grout/fill specifications (thermal conductivity, acceptable placement methods to eliminate any voids).
    - For open-loop GWHPs: well depth, casing material and diameter, well screen specifications, filters, injection-well specifications, and precautions to avoid air entrainment.
    - For closed-loop SWHPs: surface-water heat exchanger materials, length of tubing (or size of plates), number of loops, numbers of circuits, header size, and burial method.

- Piping material specifications and visual inspection and pressure testing requirements.
- Purge provisions and flow requirements to ensure removal of air and debris without reinjection of air when switching to adjacent subheader circuits.
- Instructions on connections to building loop(s) and coordination of building and ground-loop flushing.
- Sequence of operation for controls.

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2 Equipment for Ground-Source Applications

2.1 HEAT PUMP TYPES

The most common type of heat pump used with ground-source applications is the water-to-air unit as shown in Figure 2.1. The water-to-refrigerant coil is linked to the external (source) water loop and serves as the condenser in cooling and the evaporator in heating. The air-to-refrigerant coil is usually linked to a forced-air system. However, there is increasing use of water-to-water heat pumps (and dedicated cooling or heating units). Water-to-water units are used for hydronic floor heating, dedicated domestic water heating, outdoor air preconditioning, and hydronic heating and cooling.

Water-to-air cooling-only units have also been used in refrigeration applications, while heating-only units have been used to heat water. Caution is advised against cooling-only and heating-only GSHP systems in order to minimize the long-term heat imbalance within the ground, groundwater, or surface-water source. Thus, cooling-only or heating-only equipment should be integrated into systems that also have heat pumps that provide both heating and cooling to more closely balance the amount of heat delivered to or removed from the source. In some cases prudent combinations of heating-only and cooling only equipment can reduce the size of a shared ground loop. Examples are a convenience store with a car wash, as shown in Figure 2.2, or a food-service kitchen that has refrigeration equipment always adding heat to the ground loop and water heater units always removing heat. In the convenience store example, the heat rejection of the cooler and freezer is coupled to a loop that also has heat pump water heaters for the car wash. In a kitchen, the refrigeration equipment and cooling units could be connected to the same loop with heat pump water heaters for the dish washers.

Development of water-source heat pumps has been primarily directed toward satisfying the needs of the residential sector. Advances can be applied to the commercial sector with little or no modifications in units with capacities of less than 65,000 Btu/h (19 kW). Development of larger high-efficiency units has been slower, which means systems with multiple small heat pumps will typically consume less energy than those with fewer large units.

GSHP systems installed before 1980 often used heat pumps that were intended for water-loop heat pump applications in which a cooling tower is used to reject heat and a boiler is used to provide heat. System efficiencies suffered because this equipment was not optimized for heating with water below 60°F (16°C). Also, the cooling efficiency was