Commercial Ground-Source Heat Pump Systems

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Commercial Ground-Source Heat Pump Systems

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A Capital Cost Comparison of Commercial Ground-Source Heat Pump Systems

Kevin Rafferty, P.E.

ABSTRACT

Commercial ground-source heat pump systems have been installed in a variety of configurations. Among the most common are groundwater, vertical ground-coupled, and hybrid ground-coupled (with cooling tower). This paper reports on a comparison of the capital costs associated with the installation of these three designs. Based on the assumption of equal building loop costs, a comparison is made of those costs associated with the ground-source portion of the system. Sensitivity of cost to a variety of factors including well depth, system capacity, and soil (or groundwater temperature) is evaluated. Results indicate that shallow (200 ft [60 m]) groundwater systems are the least-cost alternative (ranging from 500 $/ton (142 $/kW) at 50 tons (176 kW) to less than 200 $/ton (47 $/kW) at 500 tons (1760 kW) for capacity range evaluated in this report. When deeper (600 ft to 800 ft [180 m to 240 m]) groundwater wells are required, hybrid and ground-coupled systems are less expensive at system sizes less than about 150 tons (528 kW). Above 150 tons, groundwater systems are the lowest-cost approach. When injection wells are omitted, groundwater systems are the lowest-cost alternative down to 100 tons (352 kW), even when requiring two 800 ft (240 m) production wells.

INTRODUCTION

Unitary ground-source heat pump systems for commercial buildings can be installed in a variety of configurations including groundwater, vertical ground-coupled, horizontal ground-coupled, hybrid ground-coupled, standing column, and lake water. The distinction between these designs resides almost entirely in the ground portion of the system. The building heat pump loop remains essentially constant. As a result, it is useful to evaluate the costs associated with different designs in order to identify the conditions under which each is most favorable. The results presented here summarize a study (Rafferty 1994) that evaluated the capital cost of the three currently most popular ground-source designs: groundwater, ground-coupled, and hybrid ground-coupled systems.

The oldest and, until recently, most widely used approach is the groundwater system (Hatten 1992). In this design (Figure 1), groundwater from a well or wells is delivered to a heat exchanger installed in the heat pump loop. After passing through the heat exchanger (where it absorbs heat from or delivers heat to the loop), the groundwater is disposed of on the surface or in an injection well. The use of an injection well is desirable in order to conserve the groundwater resource (ASHRAE 1995).

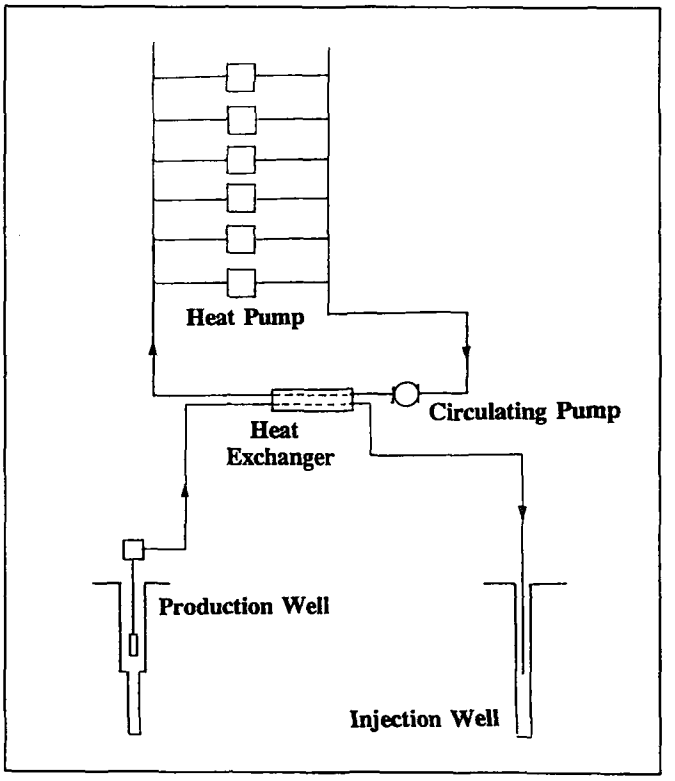


Figure 1: *Groundwater heat pump system.*

At the time this article was written, Kevin Rafferty was a research associate at the Geo-Heat Center at the Oregon Institute of Technology, Klamath Falls. Reprinted from *ASHRAE Transactions 1995*, Vol. 101, Part 2.

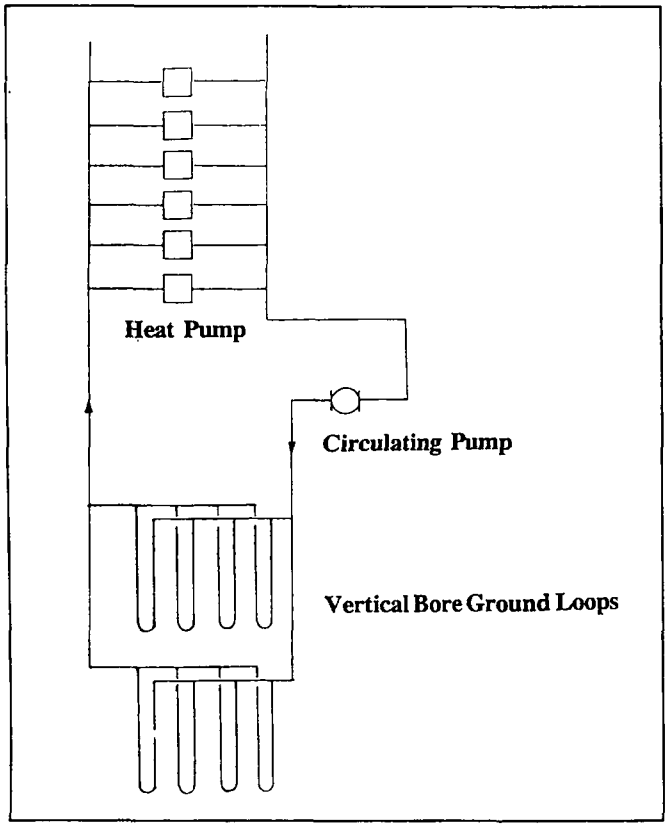


Figure 2: *Ground-coupled heat pump system.*

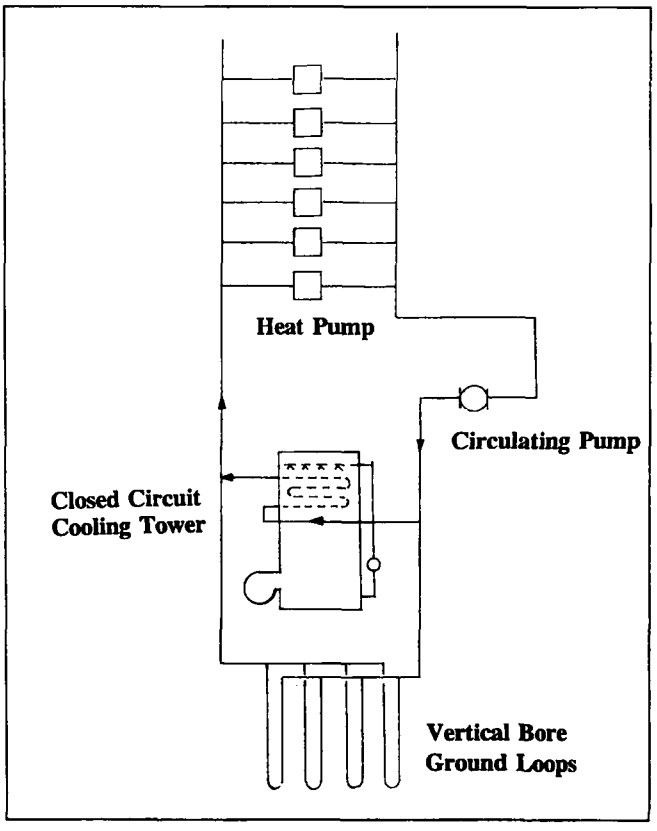


Figure 3: *Hybrid ground-coupled heat pump system.*

A second and increasingly popular design is the ground-coupled heat pump system. In this approach (Figure 2), a closed loop of buried piping is connected to the building loop. For most larger commercial applications, the buried piping is installed in a grid of vertical boreholes 100 ft to 300 ft (30 m to 90 m) deep. Heat pump loop water is circulated through the buried piping network, absorbing heat from or delivering heat to the soil. The quantity of buried piping varies with climate and building characteristics but is generally in the range of 150 ft to 250 ft (of borehole) per ton (13 m/kW to 22 m/kW) of system capacity. Borehole length requirements are almost always dictated by heat rejection (cooling mode) duty for commercial buildings.

A third design for ground-source systems in commercial buildings is the hybrid system. This approach (Figure 3) may also be considered a variation of the ground-coupled design. Due to the high cost associated with installing a ground loop to meet the peak cooling load, the hybrid system includes a cooling tower to reduce the length of ground loop required for cooling. The use of the tower allows the designer to size the ground loop for the heating load and to use it in combination with the tower to meet the peak cooling load. The tower preserves some of the energy efficiency of the system but reduces the capital cost associated with the ground loop installation.

The costs considered here are those associated with the heat source/heat sink or ground-source portion of the system. In order to standardize the heat rejection over the three designs, it was assumed that the heat pump loop would operate at a temperature range of 85°F (29°C) to the heat pumps and to 95°F (35°C) from the heat pumps under peak conditions for all three system types. The assumption of constant loop temperature conditions for all three permits an apples-to-apples comparison of the alternatives.

"Commercial building" is a term that covers a very broad spectrum of sizes from a few hundred square feet to several million square feet. The range selected for this work includes system sizes from 50 tons to 500 tons (175 kW to 1,760 kW). Using an average value of 300 ft^2 per ton (8 m^2/kW), this translates into a building area range of 15,000 ft^2 to 150,000 ft^2 (1,400 m^2 to 14,000 m^2). Buildings in this size range comprise the bulk of the commercial building stock in the United States (Korte 1994).

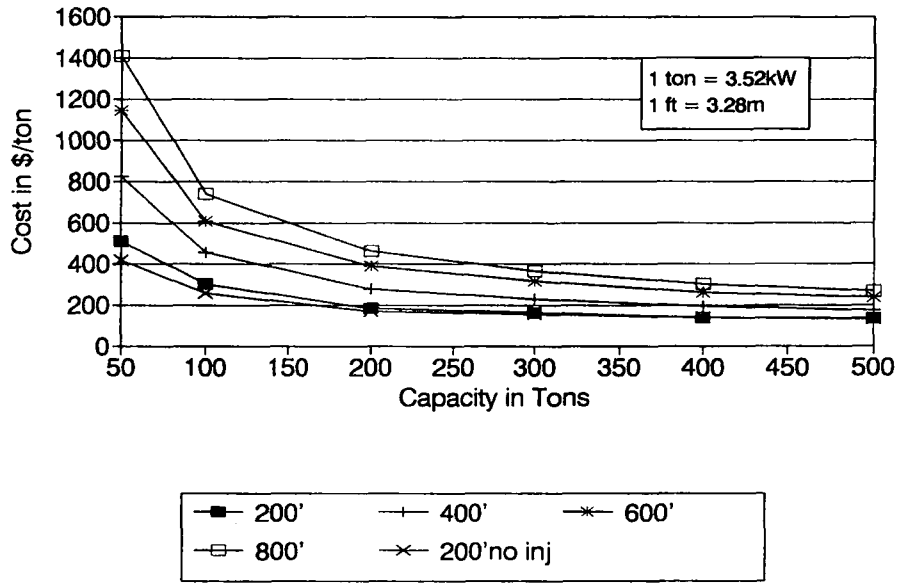


Figure 4: *Groundwater system cost (1 well — 60°F [15.5°C] water).*

It is common in the ground-source heat pump industry to refer to costs for the ground-source portion of the system on a cost per ton basis. In keeping with this practice, most cost data presented for this report are expressed in terms of cost per ton. It is important to note, however, that the cost per ton refers to the actual load imposed on the ground-source portion of the system. This is not the same as the installed capacity of the equipment. Due to load diversity, the peak load imposed on the heat rejection equipment is frequently less than the total installed capacity. The load used for cost calculations in this report is sometimes referred to as the peak block load.

GROUNDWATER SYSTEMS

Individual cost items evaluated for all groundwater uses include the following:

- Production well (or wells)
- Production well pump test
- Production well pump
- Well pump variable-speed drive
- Buried piping (wells to buildings)
- Heat exchanger
- Heat exchanger controls
- Injection well
- Injection well test
- 15% contingency factor

Production well costs were developed from a number of sources including a national survey by a leading industry publication (NTP 1992), a limited survey of western U.S. drilling costs (Culver 1991), and historical cost data (McCrea 1994). Figures used for this project were the average of those reported in the above-mentioned references. It is the author's experience that drilling costs can vary by a factor of two from the lowest to the highest.

Costs for equipment were based on vendor quotes, catalog data, and information from an industry design guide (Culver 1991). Installation costs were based on values from a standard construction estimating guide (Means 1993).

Costs were developed for three groundwater temperatures of 50°F, 60°F, and 70°F (10°C, 15.5°C, and 21.1°C), representing northern, central, and southern climates. For brevity, only the results for the 60°F (15.5°C) cases are presented in this summary.

Figure 4 presents the results for the 60°F (15.5°C) groundwater case assuming the use of a single production/ injection well pair to serve the system. The five curves shown indicate costs (in $/ton) for four different groundwater well depths: 200, 400, 600, and 800 ft (60, 122, 183, and 244 m) and 200 ft (122 m) without an injection well. In all but the last case, the values shown include costs for the production wells, well flow testing, production well pump, pump variable-speed drive, buried piping for transport of the groundwater to the building, heat exchanger to isolate the groundwater from the building loop, heat exchanger controls, injection well (same depth as production well), injection well flow testing, and a

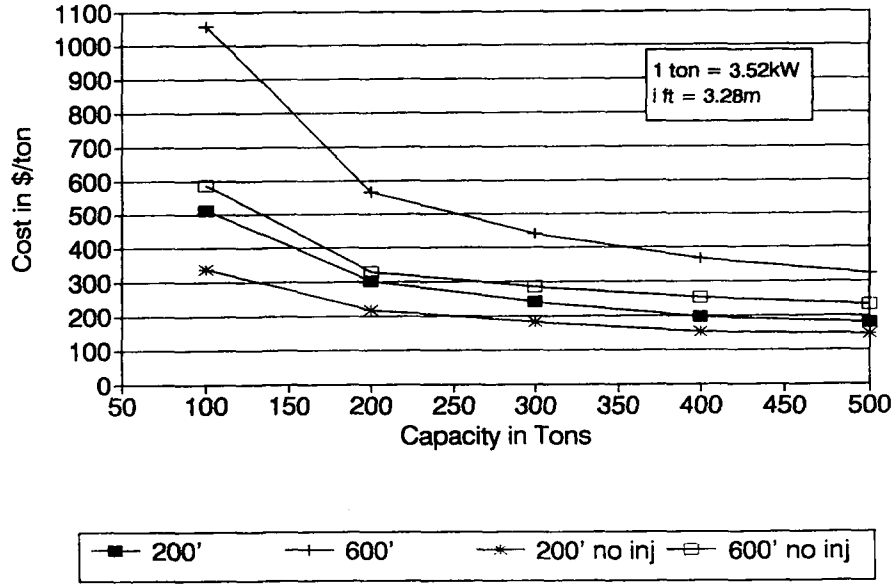


***Figure 5:** Groundwater system costs (2 wells — 60°F [15.5°C] water).*

15% contingency factor. As indicated, the depth requirement for the wells has a substantial impact on the installed cost. In addition, the unit cost for small systems of 50 tons to 100 tons (175 kW to 350 kW) is often higher by a factor of 3 compared to costs for larger systems of 300 tons to 500 tons (1060 kW to 1760 kW). Cost variation with groundwater temperature varies but is generally in the range of +20% (@ 70°F [21°C]) to -15% (@ 50°F [10°C]) for large systems relative to the 60°F (1.15°C) case. Cost variation for small systems is less than ±10% between 50°F (10°C) and 70°F (21°C).

In many cases, a single production/injection well pair may not be capable of producing (or injecting) the required system flow rate. To address this situation, costs were calculated for systems using two production wells and two injection wells. In addition to the wells, adjustments were also made in well pump, piping, and testing costs to accommodate the installation of the additional wells. Figure 5 presents these costs for 200 ft and 600 ft (60 m and 122 m) well depths and system sizes of 100 tons to 500 tons (350 kW to 1760 kW). In addition, costs are shown for systems that use two production wells but no injection wells at these two depths.

GROUND-COUPLED SYSTEMS

For ground-coupled systems, actual project costs rather than calculations were used. Costs for these systems are a function of two values—the number of feet of borehole necessary per ton of heat rejection and the cost per foot for completing the vertical bore and installing the piping. For purposes of this report, the values of 150 ft per ton (13 m/kW) for 50°F (10°C) soil, 200 ft per ton (17.3 m/kW) for 6O°F (15.5°C) soil, and 250 ft per ton (21.7 m/kW) for 70°F (21°C) soil have been used. To arrive at a cost per ton, a value of $5 per ft ($16.40 per m) of bore has been used. Although some recent projects have been the beneficiary of costs as low as $3.75 per ft ($12.30 per m) and one as low as $3 per ft ($9.84 per m), many areas of the country ate still reporting costs of as much as $15 per ft ($49.22 per m) (Braud 1992, 1994; Kavanaugh 1994; Lienau 1994; Huttrer 1994). A plot of these costs for the 60°F soil case appears in Figure 6.

HYBRID SYSTEMS

Hybrid systems include both a ground loop and a cooling tower. The ground loop is sized to meet the heating load and, along with the tower, is used to meet the cooling heat rejection load. As a result, hybrid system costs are a combination of ground loop costs and cooling tower costs. Using the $5 per ft ($16.90 per m) value for the hybrid ground loop portion and vendor quotes for the cooling tower, Figure 6 shows the cost per ton for the hybrid system based on a 60°F (15.5°C) soil temperature. Hybrid system costs were also developed for 50°F and 70°F (10°C and 21°C) soil. Costs for the 50°F (10°C) case are approximately 20% less than those shown for the 60°F (15.5°C) case. For 70°F (21°C) soil, the

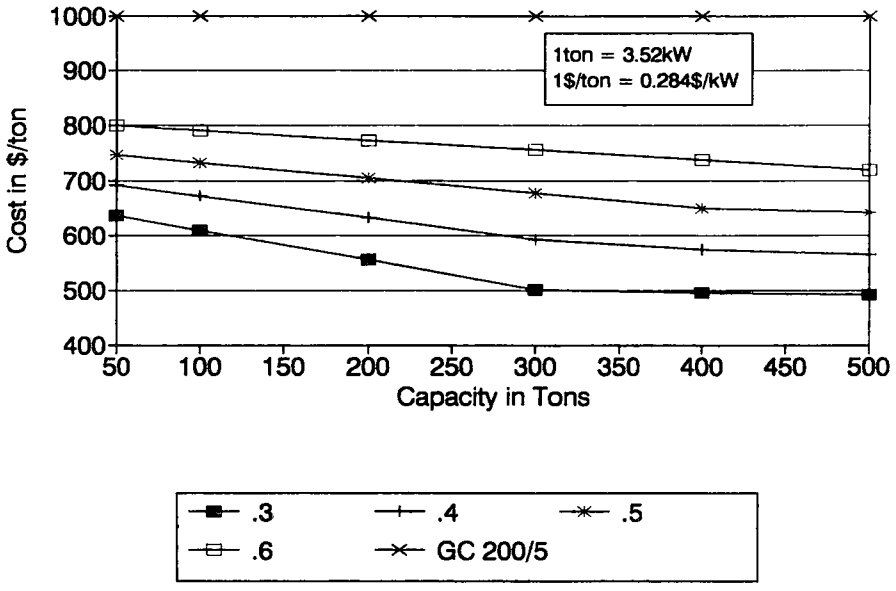


Figure 6: *Hybrid system cost (60°F [15.5°C] soil).*

cost results are 15% to 20% higher than the 60°F (15.5°C) values. Installation items included in the tower cost were piping, electrical connections for the fan and pump, and tower mounting pad.

The four curves shown for the hybrid system reflect costs for different ratios of heating loop length versus cooling loop length. As indicated, hybrid systems enjoy more favorable economics as the heating ground loop length decreases as a percentage of the cooling ground loop length requirement (low loop ratio values). This is because the cost per ton of the cooling tower is less than the cost per ton of the ground loop.

Generally, the hybrid system is attractive in situations where ground loop costs per ton are high, and where the heating loop length requirement is low relative to the cooling loop length requirement. Low loop length ratios would be characteristic of large buildings with high core to perimeter area ratios and buildings in warm climates.

RESULTS

Figure 7 presents a comparison of the three types of systems for 60°F (15.5°C) soil. The ground-coupled system cost line is based on $5 per ft ($16.40 per m) and 200 ft per ton (17.3 m/kW) ($1000 per ton [$283.72 per kW]). The two hybrid system curves are based on loop length ratios (heating length ÷ cooling length) of .30 and .40. These are the most favorable ratios for hybrid systems evaluated in this report. The upper two groundwater curves are based on 200 ft (60 m) wells and one production/injection well pair (lower curve) and two production/injection well pairs (upper curve). The bottom curve indicates costs for a system using a 200-ft (60-m) production well and no injection well. Again, these are the most favorable conditions calculated for groundwater systems in this report. It is clear that, based on these conditions, the groundwater system enjoys substantial capital cost advantage over the remaining two systems over the entire range of capacity covered in this report.

Figure 8 presents additional data for the 60°F (15.5°C) case. Again, the ground-coupled line is based on 200 ft per ton (17.3 m/kW) and $5 per ft ($16.40 per m). The two hybrid system curves are based on loop length ratios of.50 (lower) and .60 (upper). These are the least favorable conditions for the hybrid systems covered in this report. The two upper curves for the groundwater system are based on a single production/injection well pair at a depth of 800 ft (244 m) (lower curve) and two production/injection well pairs at a depth of 600 ft (183 m) (upper curve). The bottom curve is based on a system using two 800-ft (244-m) production wells and no injection wells. These are the least favorable conditions for the groundwater system covered in this report.

As indicated, at system capacities of 100 tons to 175 tons (350 kW to 616 kW) and below, the hybrid system has the capital cost advantage over groundwater and ground-coupled systems. Above this range, the groundwater system is the most attractive.

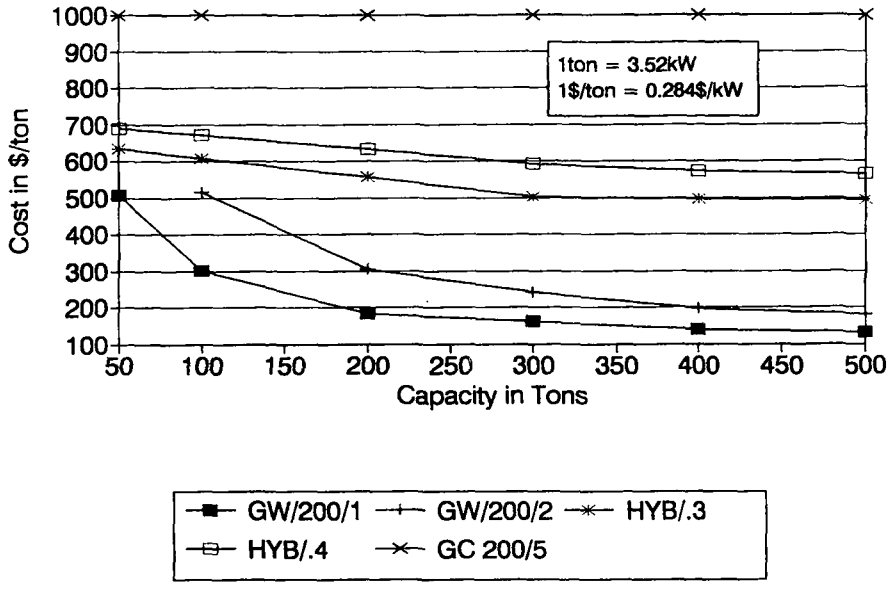


Figure 7: *Ground-source system costs (60°F [15.5°C] water or soil — low case).*

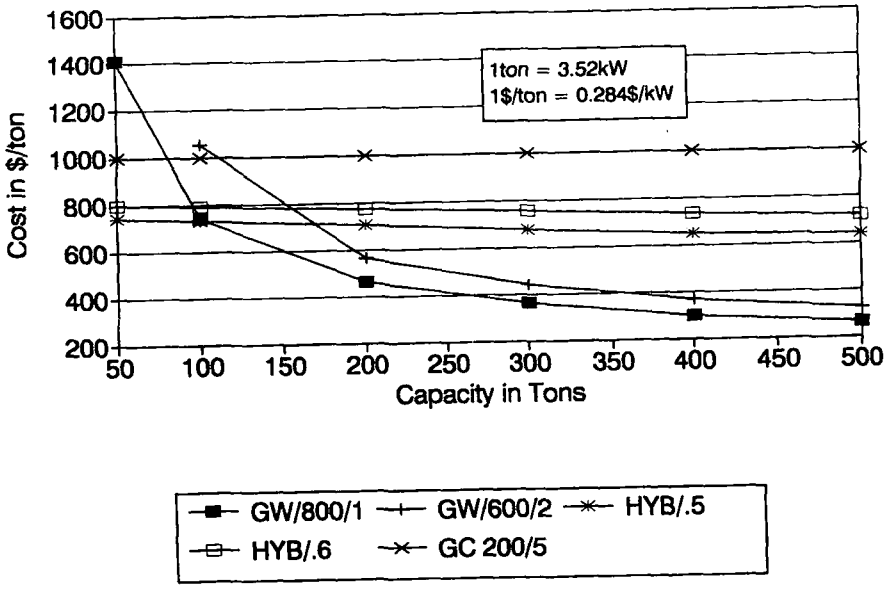


Figure 8: *Ground-source system costs (60°F [15.5°C] water or soil — high case).*

It is only under conditions of less than 100 tons with well depths of 800 ft that the groundwater system capital cost exceeds that of the ground-coupled system assuming injection is employed. If injection is not used even at 800-ft depth and two production wells per system, the groundwater approach is the least expensive at system sizes greater than 100 tons.

These data address only system capital cost. In the process of system selection, other issues should be considered as well. These would include hybrid system costs associated with cooling tower operation, such as pump and fan electrical consumption, water treatment, and makeup water, and for groundwater systems, additional pumping and regulatory requirements. As a result, system capital cost provides only a portion of the information required for informed decision making.

REFERENCES

ASHRAE. 1995. Chapter 29, Geothermal energy. *1995 ASHRAE Handbook — Applications.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Braud. H. 1992. Ground coupled/tower systems. Baton Rouge, Louisiana State University, Agriculture Center.

Braud, H. 1994. Personal communication. Consultant, Glasmer. LA.

Culver, G. 1991. Chapter 6, Drilling and well construction. *Geothermal Direct Use Engineering and Design Guidebook.* Klamath Falls: Geo-Heat Center, Oregon Institute of Technology.

Hatten, M. 1992. Groundwater heat pumping: Lessons learned in 43 years at one building. *ASHRAE Transactions* 98(1).

Huttrer. G. 1994. A vertical geothermal heat exchanger survey for Sandia National Laboratory. H AH-4148. Frisco, CO: Geothermal Management Company Inc.

Kavanaugh. S. 1994. Personal communication. Tuscaloosa: University of Alabama.

Korte, B. 1994. HVAC/R opportunities in existing buildings. *Heating, Piping and Air Conditioning* 66(9).

Lienau, PJ. 1994. Personal communication. Klamath Falls: Geo-Heat Center, Oregon Institute of Technology.

McCrea, K. 1994. Personal communication. Dublin, OH: National Ground Water Association.

Means, R.S. & Co. 1993. *Means mechanical cost data — 1993.* Keyston, MS: Robert Snow Means Co.

NTP. 1992. 1992 Water well industrial survey. *Groundwater Age Magazine* 26(12). Latham, NY: National Trade Publications.

Rafferty, K. 1994. A capital cost comparison of commercial ground-source heat pump systems. DOE Grant No. DE-FG07-90ID 13040. Klamath Falls: Geo-Heat Center, Oregon Institute of Technology.

A Comparison of Measured and Predicted Performance of a Ground-Source Heat Pump System in a Large Building

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ABSTRACT

A building energy analysis program and a separate spreadsheet implementation of a ground heat exchanger model have been used together to simulate the performance of a closed-loop ground-source heat pump (GSHP) system installed in a large secondary school. Predicted electrical energy use and demand and entering water temperatures to the heat pump system are compared to measured data from the same building. Predictions in both areas compare favorably to the measured data. As it was thought that the ground heat exchanger was oversized, additional runs were undertaken to assess the sensitivity of the entering water temperature to reductions in installed heat exchanger length from the original design. Under favorable conditions, with soils of fairly high permeability and sufficient groundwater movement through the borefield, considerable reductions in the installed heat exchanger length would be possible without significantly increasing the maximum entering water temperature in this cooling load dominated building.

INTRODUCTION

Ground-source heat pump systems are being specified in more and more commercial buildings in both the United States and Canada. A closed-loop, vertical ground heat exchanger coupled to a decentralized, water-loop heat pump system is the most popular design currently employed. Unlike the traditional water-loop heat pump, the ground-source heat exchanger system does not require a closed-circuit cooler and boiler. The conventional two-pipe circulation system is connected to supply and return headers in the mechanical room, which are, in turn, connected to the supply and return runouts from the vertical ground heat exchanger field. When the heat pumps in the building are in a net cooling mode, excess heat is rejected to the ground; in a net heating mode, heat is extracted from the ground. Some designs have a ground heat exchanger bypass, which permits internal heat recovery when the heat pump's heat rejection and extraction are approximately the same, i.e., the water-loop is in thermal balance.

One of the challenges facing designers of such buildings is to determine how much vertical heat exchanger to install to meet the heating and cooling loads on the water loop. Early designs used residential "rules of thumb," typically 150 ft to 200 ft (45 m to 60 m) of drilled borehole per installed ton (kW) of heat pump capacity. In a multizone building, not all zones experience peak loads at the time of the peak load on the building, often called the block load. To base the heat exchanger length on the installed capacity rather than on the block load often leads to oversizing. This technique was refined to base the length required on the diversified or block load of the building. Only recently have some designers used hourly energy analysis methods, which more accurately estimate loads year-round, and sophisticated heat exchanger computer models (Eskilson 1987) to more accurately predict the amount of vertical heat exchanger required.

This paper will present one attempt to simulate the performance of a ground-source heat pump system installed in a large secondary school and compare it with field-monitored data. An hour-by-hour energy analysis computer program was used to predict the loads on the water-loop or ground heat exchanger; then these loads were input to a ground heat exchanger system model implemented in a

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