DESIGN ISSUES IN THE COMMERCIAL APPLICATION OF GSHP SYSTEMS IN THE U.S.

Kevin Rafferty
Geo-Heat Center

ABSTRACT

Commercial ground-source heat pump (GSHP) systems can best be described as an emerging HVAC technology in the U.S. Verified, scientifically-based design tools have only recently become available. This paper discusses some of the key design issues in both ground-coupled and groundwater heat pump systems. Guidelines in the form of acceptable values are provided for pumping, flow rates, equipment performance and costs.

INTRODUCTION

Ground-source heat pump (GSHP) systems have been in service in commercial buildings in the U.S. for approximately 50 years. The earliest systems employed groundwater and central chillers, and many of these are still in service. Groundwater systems have remained consistently popular, and in the last 10 years have been joined by various closed-loop designs. Although started in the residential sector, closed loop systems are now emerging in the commercial building market. Due to the high cost of some conventional HVAC systems, GSHPs can often compete more effectively in first cost in commercial applications compared to residential applications. Coupled with the substantial energy savings available, the prospect for much wider use of the systems in commercial buildings is very positive. Currently, the two building categories in which GSHPs have made the greatest penetration are schools and office buildings. According to the Geothermal Heat Pump Consortium (GHPC, 1999), there are now over 600 schools in the U.S. with GSHP systems.

TERMINOLOGY

One of the most confusing issues for those unfamiliar with GSHP systems is terminology. Many terms are used to describe these systems and some are more effective than others. For purposes of this paper, the terms developed by the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE, 1999) will be used. As indicated in Figure 1, the general term for all systems is ground-source heat pumps (GSHP). Parallel terms to this, used for marketing purposes are GS systems, GeoExchange and Geothermal Heat Pumps (GHP). Subcategories under GSHP are ground-coupled (GCHP), groundwater (GWHP) and surface-water (SWHP) systems. In addition to those shown in the figure, other designs in occasional usage for commercial applications are standing-column and hybrid systems. Standing-column systems use a deep well, typically completed in a competent formation to supply well water to the heat pumps in the building. After passing through the heat pumps, approximately 90% of the water is returned to the bottom of the well. The remaining 10% of the water is disposed of on the surface. This assists in bringing "new" water into the well from the aquifer to stabilize temperature. A submersible well pump provides circulation for the system. Well depth requirements are typically in the range of 50 ft per ton. To date, this system has been most popular in the northeast portion of the U.S.

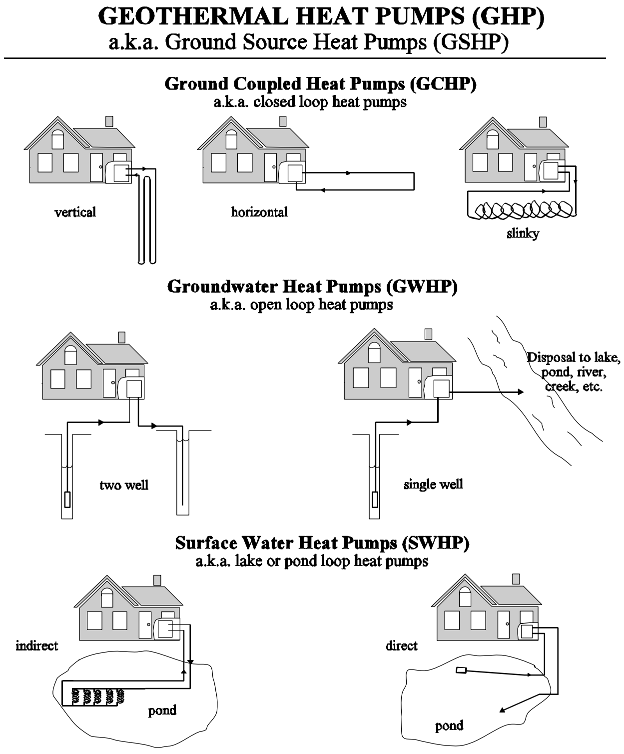

Figure 1.

The hybrid system is a variation on the closed-loop system. A smaller ground loop is installed to support only the heating requirement of the building. This downsized loop, in parallel with a cooling tower serves the heat rejection load of the system. The hybrid is a strategy to reduce system first costs in heavily cooling-dominated climates.

HEAT PUMP EQUIPMENT

Water-to-air unitary heat pumps in the 0.5 to 20 ton range are the type most often used in commercial GSHP systems. These units are of the "extended range" type, designed to operate with entering water temperatures in the 32 to 100°F range. Units are available in a wide variety of configurations including vertical, horizontal, counter-flow, split, rooftop and console; but, the vertical and horizontal designs are the most frequently employed. Although desuperheaters are available for commercial applications, they are not often used. Due to the size of the loads, dedicated water-to-water heat pumps are applied to commercial water heating applications.

In the past 10 years, unitary heat pumps have achieved substantial improvements in the areas of both performance and noise reduction. Approximately, a 40% increase in EER has been achieved in the units of 5 tons or less. Motivated by marketing issues in the residential sector, manufacturers have added more efficient fan motors, larger evaporator coils, more effective refrigerant-to-water heat exchangers and scroll compressors. In the >5 ton size range, somewhat smaller gains are evident for many manufacturers since improvements made in the residential-sized equipment have been less applied here. This is particularly true in units of >10 tons. Where cooling EERs in the mid-teens (ARI 330) are common for small units, larger equipment of >10 tons is often characterized by EERs of less than 10.

Paralleling the gains in energy efficiency are similar improvements in the operating noise characteristics of this equipment. In part, these issues are related. The use of scroll and rotary compressors in newer equipment has reduced the vibration associated with the compressor. The larger and slower turning fan wheels coupled with lower coil face velocities have reduced the air side noise as well. The result, from some manufacturers, is a substantially quieter unit compared to the older water-loop system equipment.

HEAT PUMP RATINGS

Water-to-air heat pumps are rated, at present, under one of three specifications. For units applied to the so-called water-loop heat pump systems (with a central boiler and cooling tower), the Air Conditioning & Refrigeration Institute (ARI) 320 rating applies. Cooling performance (EER) is reported at an entering water temperature of 85°F and heating at 70°F. This equipment is not intended for and should generally not be applied in GSHP systems.

The rating intended for GWHP systems is ARI 325. Under this rating EER and COP are both reported at entering water temperatures of 70°F and 50°F. A heavy pumping penalty (~250 w/ton) is applied in the rating calculations to reflect the well pump power requirements in a typical residential application. This level of pumping may not be appropriate for many commercial applications.

ARI 330 is the rating intended for GCHP systems. Heating performance is reported at an entering water temperature of 32°F and cooling at 77°F. A much smaller pumping penalty is included to reflect the power requirement of a small loop circulating pump.

None of these ratings are reflective of the performance that would occur in a large commercial application. They are useful primarily for the comparison of one manufacturer's equipment to another. Beyond this, the ratings described above are all single-point values and are not "seasonal" in nature as with fossil fuel equipment (AFUE) and air-source heat pumps (HSPF and SEER).

DESIGN CONSIDERATIONS FOR COMMERCIAL GCHP SYSTEMS

The successful application of commercial GSHP systems relies upon the careful consideration of three issues: heat pump selection, loop design and pumping.

As mentioned earlier, only extended range heat pumps should be specified for closed-loop systems. Units should be required to achieve a minimum ARI 330 rating of 13.0 (Kavanaugh and Rafferty, 1997) in high speed (if 2-speed units are used). To preserve maximum latitude for the owner, all units should be capable of operation under the control of nothing more than a heat pump thermostat. Consideration should be given to the use of several smaller tonnage units in place of a smaller number of large units due to the potential for greater performance in the smaller equipment. Beyond this, the use of smaller units can reduce ductwork costs and mechanical floor space requirements since units of 5 tons or less can often be installed in the ceiling space.

Loop design is a complex issue, but a few key points warrant special attention. Among these are building load, borehole spacing, borehole fill material, and site characterization. In commercial buildings, the loop length requirement is, even in moderately cold climates, driven by the cooling load. In making the loop length calculation, the peak block load rather than the installed capacity should always be used. Basing the calculation on the installed capacity results in longer length and higher first cost. Due to the relatively linear cost relationship in loop installation, over-sizing carries a much higher penalty than is the case with conventional equipment. The generally higher cooling loads in commercial buildings, tend to reject, on an annual basis, much more heat to the ground than they remove from it. When boreholes are located close to each other, there is interference between them such that heat transfer from one borehole is negatively influenced by adjacent boreholes. For a large number of boreholes arranged in a grid pattern, this can be a significant influence on the required loop length. For commercial systems in moderate-to-warm climates, a minimum borehole spacing of 20 ft is recommended (Kavanaugh and Rafferty, 1997) to lessen the impact of borehole interference.

The material used to fill the void between the U-tube and the borehole wall (called fill or backfill) exerts a heavy influence on the performance of vertical systems. Due to its location in the critical heat transfer region, the thermal conductivity impedes heat transfer and results in the need for longer ground loops. Unfortunately for many years, the industry recommended grouting the boreholes with a "high solids" bentonite grout. The thermal conductivity of the standard grouts available in the drilling industry is approximately 0.43 Btu/hr ft°F; whereas, most native soils are in the range of 0.6 to 1.2 Btu/hr ft°F and rocks 1.0 to 3.0 Btu/hr ft°F. It is apparent that the use of standard grout should be avoided. To address this situation, thermally enhanced grouts (bentonite with sand added) have been developed with a thermal conductivity of 0.85 Btu/hr ft°F, and both cement and bentonite-based grouts with conductivities up to 1.4 Btu/hr ft°F are under development (Allen, 1998).

An accurate design cannot be accomplished without adequate information about the soil and rock thermal properties at the site. As a result, for larger commercial systems, it is often worth considering a test bore and possibly an in-situ thermal properties test. The test bore is an opportunity to determine the nature of the materials in the subsurface. It not only permits a better estimate of the thermal properties, but also alerts the driller to the drilling conditions and provides an indication of the depth at which a transition occurs from soft to hard formations. In the largest projects, an in-situ test may be a useful investment. This is a test in which a single borehole is completed with a U-tube and backfilled at the site. A load is connected to the U-tube, and temperature and load data recorded for an interval of time (usually 12 to 48 hrs). Analysis of the data can yield accurate values for the thermal conductivity and thermal diffusivity of the subsurface materials.

Excessive pumping energy is one of the most common reasons for less than expected savings in commercial GSHP systems. In order to control pumping costs, it is necessary to adequately address flow, head and control. Loop flow rate in these systems should not exceed 2.5 to 3.0 gpm block load ton. Pump head in smaller systems consists of approximately 1/3 due to the heat pump unit, 1/3 for the ground loop and 1/3 for the building piping. Head loss in the heat pump units should be no greater than 12 ft for units <5 tons and 20 for larger units (Kavanaugh and Rafferty, 1997). Ground loop head loss is determined by the layout and size of the structure; but, piping should be designed for unit head losses no greater than 4.0 ft/100 ft of pipe as recommended by ASHRAE. Careful loop design should result in a peak pump power of 7 ½ hp/100 tons (Kavanaugh and Rafferty, 1997). Variable-speed control is recommended for larger systems to minimize pump power consumption. In smaller systems, a variety of strategies are available including grouping of similar zones into smaller loops, using individual pumps for each heat pump and interlocking pump operation to heat pump operation.

DESIGN CONSIDERATIONS FOR COMMERCIAL GWHP SYSTEMS

Key issues in the design and application of GWHP systems are isolation of the groundwater from the building mechanical system, optimization of the groundwater flow rate, avoidance of open tanks in the system, accurate specification of the water wells and accurate control of the well pump.

Water wells are the foundation of an open-loop system. Unfortunately, the design of the wells is often left to the contractor since HVAC design engineers are unfamiliar with water wells. This is not an advisable strategy. Wells, like any other part of the mechanical system, must be carefully designed and specified if they are to be successful. Guide specifications for water wells are available from a variety of sources (NGWA, 1981; Roscoe Moss Company, 1985; Rafferty, 1998) and should be incorporated into the construction documents to assure quality construction and materials are used, and that the well produces water of an adequately low sand content. For systems using an injection well, it is critical that the injected fluid be "sand free" (<1 ppm). Surface tanks are not an appropriate method for sand removal. Sand should be controlled by careful well construction (screens and/or gravel packs and development) as a primary strategy and surface strainers or separators as a secondary strategy. Open tanks, intended to settle sand, allow oxygen to enter the water and CO_2, if present, to escape. Both of these occurrences impact water chemistry and can accelerate corrosion and scaling.

Plate-and-frame heat exchangers are used in GWHP systems to isolate the building loop from the groundwater. It is often mistakenly believed that the object is to design the heat exchanger in such a way as to have the heat pump entering water temperature as close to the groundwater temperature as possible. In most cases, this is not an effective strategy since it causes the loop flow and groundwater flow to be equal. In most applications, maximum system performance occurs when the groundwater flow rate is in the range of 1.0 to 2.25 gpm/ton (depending upon well pump head) and building loop flow in the range of 2.5 to 3.0 gpm/ton. This results in the approach temperature on the heat exchanger occurring at the building loop entering/groundwater leaving side. Generally, an approach of 3 to 7°F is used (Kavanaugh and Rafferty, 1997). Maximum heat exchanger pressure drop should be less than 10 psi on the building loop side.

The groundwater flow as mentioned above should not be simply selected to match the building loop flow. It is determined from an analysis of the well pump power compared to the heat pump unit performance at various groundwater flows. As groundwater flow is increased, the heat pumps see more favorable entering water temperatures resulting in better performance, but the well pump power requirements increase at the same time. At some point, for every application, there is an optimum groundwater flow and this is the point for which the system is designed. Figure 2 demonstrates this strategy based on constant well pump head. In actual applications, pump head does not remain constant but varies with flow resulting in much steeper curves.

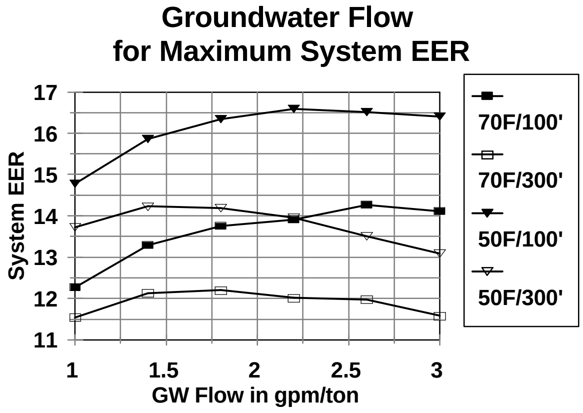

Figure 2.

Control of the well pump is a key aspect of the system design. There are a variety of control schemes, but two are fairly common: dual set point and variable speed. In the dual set point approach, the well pump is started above a loop temperature set point in the heating mode. The loop temperature is permitted to "float" in between the set points. System thermal mass is a key consideration in the dual set point approach. To avoid the short cycling on the well pump, the range around each set point (difference between cut in and cut out temps) must be sufficient to result in an acceptable pump cycle time. Table 1. Presents some guidelines on recommended controller ranges for the pump controller. Variable-speed control of the well pump is sometimes used for GWHP systems. In this case, the pump speed is varied in response to some temperature or load signal from the loop. It is critical that the pump and motor manufacturers are aware that their equipment will be installed in a variable-speed application.

Table 1. **Recommended Controller Range for Dual Set Point Operation**

	System Water Volume in gal/block ton						
Pump hp	6	8	10	12	14	16	18
<5	6	5	4	3	2		
7.5+	18	13	11	9	8	7	6

COSTS

There has been a great deal of concern over the capital costs for GSHP systems in the U.S. Many feel that this is a significant barrier to expanded use of the systems. While this is true in the residential arena, the economics of larger commercial applications are more positive. In general, GCHP systems can be installed for an increment of 0 to 20% more than conventional systems (exclusive of rooftop package equipment).

The type of GSHP systems has a substantial impact upon the capital cost as well. Figure 3 presents a comparison of the costs for the ground loop portion of the three most common GSHP systems (GCHP, GWHP and Hybrid). Several points are apparent from the plot. GWHP systems due to the much more pronounced economy of scale are significantly less cost for large system sizes. In fact, if shallow (<300 ft depth) wells can be completed, GWHP systems are 40 to 70% less cost than GCHPs. Even at well depths of 600 to 800 ft. GWHP systems are less cost than GCHP systems in the >150 ton range (Rafferty, 1995). Hybrid systems can also greatly reduce first cost in warm climates.

The extent to which capital cost can be reduced depends upon the relative heating and cooling loop length requirements. In cases where the heating loop length requirement is 50% of the cooling loop length, capital costs for the ground loop portion of the system can be reduced by 30 to 35%.

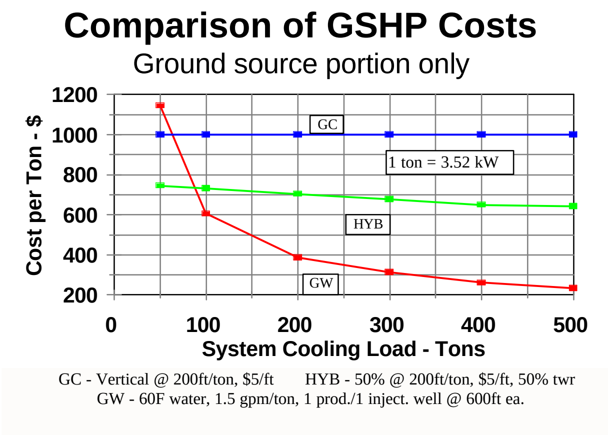

Figure 3.

GCHP systems are currently being installed in commercial buildings in the U.S. for $10 per square foot of floor space and less. In most cases, the ground loop constitutes approximately 25 to 35% o the total system costs. Figure 4 presents a summary of the relative costs for a small office building (Kavanaugh and Rafferty, 1997). It is apparent that there is much more potential for cost control on "inside the building" portions of the building than there is in the ground loop.

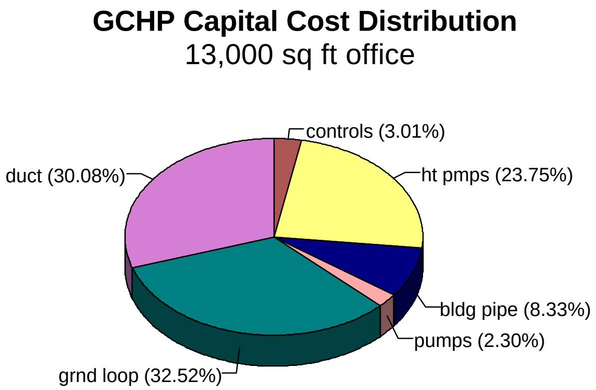

Figure 4.

CONCLUSION

Commercial application of GSHP technology remains in it's infancy in the U.S., but the potential is great. Some of the early commercial systems were designed using "rules of thumb" carried over from residential practices. Predictably, these systems encountered operational problems. The recent development of design tools for the engineer will assist in the design and installation of more cost effective, reliable and efficient systems in the future. Though it is likely that the use of ground-source systems in the residential sector will remain limited to the niche market, it now occupies in the high-end 3,000+ square foot market, the prospect for much greater penetration in the commercial building market is very bright.

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