Innovative Commercial "Ground Source" Heat Pump System Sources and Sinks: Engineering and Economics

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ABSTRACT

Geothermal heat pumps, which will be called "GX systems" in this paper, have been employed in specialty applications on both residential and commercial buildings for several decades. GX systems generally have very competitive life cycle costs, but somewhat higher initial costs. The incremental cost of the ground heat exchanger cost is close to the average cost per ton, so GX systems work best with very efficient building shells. Innovative methods can reduce the ground heat exchanger cost. These include better coupling of the heat exchange boreholes to the ground, hybrid systems that use low cost closed fluid coolers to supplement the ground heat exchanger where cooling loads dominate, open loop systems, and "opportunistic" systems that use sewage effluent or other non-standard sources for heat exchange. These approaches and their benefits are illustrated through five case studies.

Introduction

Geothermal heat pumps, which will be called "GX systems" in this paper[1], have been employed in specialty applications on both residential and commercial buildings for several decades. By using the more temperate earth as the source or sink for heat exchange rather than the air, these systems achieve significantly higher efficiencies than their air-source counterparts. Furthermore, unlike rooftop and split-system heat pumps, all controls, pumps, fans and compressors for a GX heat pump can be located indoors. This reduces maintenance, increases life and, in many applications, improves the esthetics of the building.

Although most GX systems are now installed on single-family houses (Skerl 1998), commercial applications such as schools are increasing more quickly. At least 400 schools are now GX-equipped. Penetration rates are beginning to increase in other applications where the ability to easily implement zone temperature control and/or individual metering is valued. These include hotels, dormitories, and multi-tenant office buildings.

In contrast with the central chillers, large fans, and VAV distribution of most conventional commercial buildings, most new GX systems use distributed (zone-by-zone) unitary heat pumps with

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[1] "Geothermal" is a misleading term-of-art, since few systems actually capture significant energy from radioactive decay of rock. The term GeoExchange^{SM} is an inclusive alternative that includes ground source, ground water, surface water, subpotable water, and related heat pump systems. We do not include distributed heat pump systems using a common loop whose temperature is controlled solely by a boiler and cooling tower. These systems, which lack an earth connection, generally use lower-efficiency ARI-320 equipment instead of the extended range ARI-325 (open loop) and ARI-330 equipment employed in GeoExchange systems.

capacities between ¾ ton (2.6 kW) and 5 tons (17.6 kW). Larger systems, such as the 4,700 ton (16.5 MW) Galt House East open-loop complex in Louisville, KY (GHPC & Galt 1997), and the 1,600 ton (5.6 MW) Stockton College, Pomona, NJ closed-loop system (Stiles et al. 1997) may use hundreds of heat pumps, restricted to a small number of models. A smaller number of systems use central-station equipment (GHPC & McMath 1997).

Almost all GX installations are either *open-loop* or *closed-loop* designs that use water as a secondary heat exchange fluid. In open-loop systems, ground water is pumped from a well, circulated through the heat pump, and then either returned to the same well or discharged to a separate well, stream or other sink. In closed-loop systems, either water or a water/antifreeze mixture is circulated between the heat pump and a heat exchanger buried in the ground. No water is either drawn or discharged to the environment[2]

The GX heat exchanger is a particularly fruitful area for innovation. Its cost is almost always a large fraction of the installed system cost, sometimes more than $2/ft^2 of conditioned space ($600 - $1300/ton, or $170 - $370/kW, of cooling equivalent). Furthermore, this cost increases almost linearly with capacity in most applications. This has two highly significant implications: (1) Design approaches that reduce the cost of the GX heat exchanger without compromising system performance can swing the economics of ownership in favor of the GX technology in many new markets. (2) GX is more synergistic with building energy efficiency improvements than almost any other heating, ventilating, and air-conditioning (HVAC) technology. Each ton of avoided load reduces cost the same $600 - $1300/ton.

Life cycle economics in commercial-scale buildings generally favor GX systems, although first costs may be higher. For example, for nine in-depth case studies, the average GX system used 14.4 equivalent kWh/ ft^2 –yr., against a calculated 22.7 for conventional systems. The return on investment for these nine systems averaged 19%, ranging from immediate (less cost than the alternative evaluated) to 6% (Cane et al. in press). Maintenance costs in commercial-scale GX buildings are also low. For 25 buildings with adequate records, the average cost was $0.065/ft^2 for in-house labor, and $0.096 for contract maintenance (Cane et al. 1997). Energy savings are significant, too. (Cane et al. in press).

GX technology is gaining broader acceptance. Shipments in 1997 grew by over 20% (Skerl 1998). And there are many "leading indicators" of increased interest: increasing sales of ASHRAE publications on GX technology, and a doubling of the number of GX technical sessions at ASHRAE national meetings in the last two years (Phetteplace 1998).

This paper focuses on the results of monitoring innovative GX alternatives to "traditional" closed and open loops. We include systems that divert municipal sewage plant effluent, hybrid systems that use air-cooled condensers to supplement the ground heat exchangers, systems that can be integrated into the supporting structure of a building to reduce installation costs, and systems that make incremental improvements to the GX heat exchanger. Some of these systems have rather broad potential. All help demonstrate the efficient ways available for exchanging heat with the environment.

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[2] A third, much less common GX design eliminates the water by burying one of the heat pump's refrigerant heat exchangers in the ground. This approach, referred to as Direct Exchange (DX), is most appropriate for residential and light commercial applications and will not be discussed here.

GX Technology Innovations

Case Study #1 - Reducing GX Heat Exchanger Size: the Use of Grouts with High Thermal Conductivity

Groundwater protection is critical, so the GX industry has worked to develop strong borehole completion requirements. Current guidelines (McCray 1997) at minimum require a surface seal (typically 20' to 50' of high-solids bentonite grout with a permeability less than 10^{-7} cm/sec) where there is only a single aquifer. Some jurisdictions require high-solids bentonite grout installed in the entire depth of the borehole to prevent mixing of water from different strata.

Although bentonite grouts are excellent sealants, their low thermal conductivity compared to most soil and rock types impedes heat transfer from the heat exchanger to the ground. Enhanced bentonite grouts are now available with thermal conductivities up to twice that of the conventional grout (0.85 *vs.* 0.43 Btu/hr-ftF). The hypothesis that these enhanced grouts can permit downsizing the geothermal heat exchanger is being tested in a multi-year field study at the Choptank Elementary School, Cambridge, Maryland.

The school is a 45,840 ft^2 building heated and cooled by a 137-ton geothermal system that includes 38 water-to-air heat pumps ranging from 2 tons to 15 tons. Two water-to-water heat pumps, which are part of the GX system, supplement the hot-water service to the school. The installed cost for the all HVAC components, including the ground loop, at the Choptank Elementary School was $20 per ft^2. The cost included sizing the borehole heat exchanger to 120% of load to allow a future 6000 ft^2 addition.

The closed GX loop comprises 100 vertical boreholes. Each borehole has a 4.5 inch diameter and 275 foot length, in two 5 x 10 arrays with at least 15 feet between borehole centers. One-inch diameter, SDR 11 polyethylene tubing is used for the vertical GX heat exchangers. These heat exchangers are piped into ten circuits that are connected in parallel. Within each circuit, the GX heat exchangers are also connected in parallel.

Although the short-term heat transfer characteristics of boreholes with high conductivity grouts have been measured in the field (Spilker 1998), estimates of the impact of the enhanced grout on the size of the loop have relied on computer modeling of the complete GX system. The test at the Choptank Elementary School is intended to validate these computations with a field test. The test circuit has nine boreholes backfilled with enhanced bentonite with thermal conductivity that is between 50% and 100% higher than that of a conventional bentonite grout (e.g., 0.65 to 0.85 Btu/h-ft-F versus 0.43 Btu/h-ft-F). The "control" circuit has 11 boreholes filled with conventional bentonite grout. Except for the different grouts, the two sets of boreholes were identical. Furthermore, the boreholes were interspersed in the 5 x 4 subsection of borehole field, so that on average, the two circuits saw the same ground conditions.

A variable-speed "booster" pump was installed in the enhanced-grout circuit so that its flow could be independently controlled. This pump was controlled so that the temperatures of the heat-transfer fluid returning from the two circuits were equal. Since both circuits were fed with a common supply, the temperature change across them was equal.

With the preceding control implemented, two possible outcomes can be quantified. If the average total flows through the two circuits are equal, both circuits are transferring the same amount of heat. The enhanced grout is then exactly compensating for the 18.2% smaller heat exchanger area of the 9-hole circuit. At the other limit, if the average total flow in the enhanced-grout circuit is only 9/11 that of the other circuit, then the heat transfer per foot is the same in the enhanced grout boreholes as in the standard grout boreholes. In this limit, the enhanced grout would be providing no benefit. To a rough approximation, a linear interpolation of flow rates between these two limits can be converted into a measure of loop reduction provided by the enhanced grout.

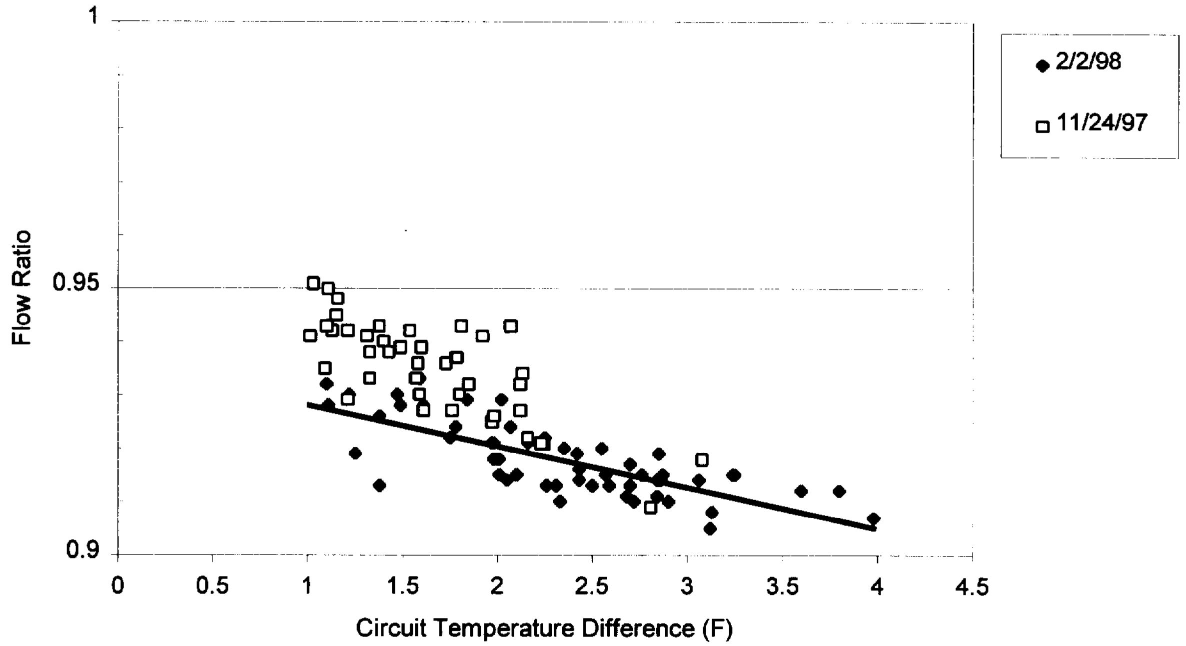

Figure 1. Grout Effectiveness as a Fuction of Circuit Temperature Difference

Figure 1 presents data from two 12-day periods, one starting on November 24, 1997 and the other on February 2, 1998. Each data point is a one-hour average of the flow ratio between the two circuits and the temperature difference across the circuit. Only data after 9 am is included in the figure so that the transient that occurs when the geothermal system starts up each morning is excluded.

Two important trends appear in Figure 1. The data for November 24 tends to fall above the February 2 data. Although the effect is not very pronounced, it does show that the enhanced grout is more effective during the start of the heating season than towards the end. This would be expected since the accumulated heat transfer to the ground per bore-hole is greater for the enhanced grout circuit, which will counteract its superior thermal performance.

Also shown in Figure 1 is a decrease in the enhanced grout's performance as the circuit's inlet/outlet temperature difference increases. Using the data for February, at a temperature difference of 2°F, the flow ratio is 0.925. Interpolating between the flow-ratio limits of 1.0 (18.2% reduction in loop length) and 0.818 (no reduction), yields a 10.7% reduction in loop length. However, if the circuit operates with a 10°F difference and the downward trend in flow ratio shown in Figure 1 continues, the enhanced grout would offer only a 4.1% reduction in loop length.

It is important to note that the benefits offered by high thermal conductivity grouts depend strongly on both the geometry of the boreholes and the conductivity of the surrounding ground.[3] For the Choptank site, the initial data presented here indicate a potential reduction in loop length of between 5% and 10%. The impact of this on the cost to install the ground loop must await a more comprehensive analysis that includes the cost premium for the advanced grout and possible changes in the grouting procedure. To test the hypothesis that the benefit also depends on the loading of the field, two ten-borehole circuits have been closed off for the summer. With the heat exchanger reduced to 80% of its size, the heat transfer requirements are correspondingly increased, and the effects of the thermal grout may be greater.

In addition to evaluating the advanced grout, the field test at the Choptank Elementary School has also collected data on the overall performance of the GX system. For the eight-month period from September 1997 through April 1998, HVAC energy use totaled about 4.0 kWh/ft^2. Energy for the circulating pump has averaged 18% of the total HVAC use. Assuming that the school is occupied during the summer, annual HVAC energy use should be on the order of 6 kWh/ft^2.

Case Study #2 - A Building-Integrated GX Heat Exchanger

The Ramada Inn Lakefront Hotel in Geneva, New York, contains 149 guest rooms, a restaurant and convention rooms. The hotel heats, cools, and provides all hot water from a closed-loop heat pump system coupled to the ground through ground-coupled heat exchangers. Space conditioning is provided by 202 heat pumps with a total capacity of 324 tons, and water heating is provided by three 10-ton heat pumps. The GX heat exchanger is unusual in that the structural building pilings contain circulating loops accounting for half the heat exchanger length. This design reduced the initial system cost $100,000 by eliminating the need for 120 borehole heat exchangers.

The GX heat exchanger beneath the buildings uses 198 structural pilings. Each piling is 85 feet deep and consists of an eight-inch diameter capped steel tube that was driven into the ground. A 1¼-inch polyethylene u-tube was inserted into the piling before it was filled with a modified concrete slurry. In addition to the GX heat exchanger in the pilings, a conventional bore field consisting of 120 boreholes (6" nominal diameter) at an average depth of 138 feet was installed beneath what is now the hotel's parking lot. A 1¼-inch polyethylene u-tube was inserted into each borehole before it was sealed with a bentonite grout[4].

The total length of pipe in the bore field and pilings is about equal. The bore field contains 16,560 feet of bore length. The pilings contain 16,830 feet of total piling depth. The spacing between pilings varies from 2 to 15 feet, while the bore field spacing is fixed at 15 feet. Both ground loops span about the same surface area, with the bore field square and the piling field rectangular.

Although both the pilings and the bore-field GX heat exchangers had approximately the same area in contact with the ground and the same fluid flow rates, a significantly higher fraction of the heating loads was carried by the pilings. During the heating season, the conventional bore field extracted energy at about 8.5 Btu/h per foot of bore length (8.2 watts/meter) while the building pilings extracted energy at about 17 Btu/h per foot of bore length (16.4 watts/meter).

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[3] Unfortunately, a scheduled in-situ test of the ground conductivity at the Choptank Elementary School has been delayed until summer, 1998.

[4] One group of 12 boreholes uses an enhanced grout with a thermal conductivity that is more than twice that of the conventional grout. The performance of these boreholes will be discussed in the final paper once more data has been collected.

The heat rejection rate was more variable in cooling. On average the pilings rejected 19 Btu/h-ft compared to 16 Btu/h-ft for the bore field. However, under the largest loads the bore field increased its heat rejection rate faster than the pilings and actually exceeded the piling heat transfer rate during the highest load. (The cause of this unexpected behavior will be investigated during the second year of the field test.)

In addition to the pilings and conventional (bentonite-grouted) borehole heat exchangers, the site has one of its ten circuit completed with high thermal conductivity grout, as at the Choptank School. One of the ten bore field circuits used thermally enhanced grout to demonstrate its impacts. This high solids grout increased thermal conductivity of 0.85 BTU/h-ft-F compared to 0.42 BTU/h-ft-F for standard 20% solids grout. We undertook an observational approach determining the impact of the grout by measuring the temperatures returned from each of the bore field circuits. The analysis showed the enhanced grout circuit having improved heat transfer rates from 6.2% to 14.4% better than the standard grout circuits. The median improvement was 10.0%. While the flow to each circuit was balanced using circuit setters, there may still be some imbalance leading to the variability in results between circuits. Furthermore the exact lengths of the circuits may vary as well as the geological conditions spanning the field both leading to circuit heat transfer variations. This observed improvement in heat transfer rates supports the assertion that the thermally enhanced grout could have reduced the design length of the bore field by about 10% at this site.

Annual total energy use at the hotel averaged 16.2 kWh/ft^2 with the HVAC and water heating using 4.8 kWh/ft^2. Table 1 presents a monthly summary of the performance of the GX system since monitoring began in June 1997. The table shows that one key to energy efficiency is the use of variable speed drives (VSD) on the circulating pumps, together with solenoid valves on 85% of the heat pumps. The solenoids only allow water through the heat pumps while they operate. Although the design called for three 30 hp circulating pumps, with the VSDs the peak power draw of the loop pumps was under 11 kW (15 hp). Flow has been below 40% of design with most of the operation below 30%. The VSDs were critical in minimizing pump energy as there were three 50 hp loop pumps installed. These data illustrate the load diversity in having 202 heat pumps supplying the building load and the value of variable speed drives in part-load operation.

Table 1. Monthly Performance Summary

	Electricity Use (MWh)				Loop Energy Flows (10^6 Btu)					
Date	Total Building	Water Heating	Loop Pump	Heat Pumps	Heat Rejected to Ground	Piling Heat Transfer Portion	Heat Extracted from Ground	Piling Heat Transfer Portion	Heat Taken from Loop for Water Heating	Hot Water Use (10^3 gal)
Jun-97	122	8.4	3.1	28	425	56%	0	0%	81	n/a
Jul-97	136	8.3	3.5	35	504	56%	0	0%	87	n/a
Aug-97	139	9.8	3.5	32	438	56%	0	0%	94	190
Sep-97	126	9.1	3.1	18	223	54%	6	75%	83	191
Oct-97	135	11.2	2.7	17	88	51%	75	73%	102	226
Nov-97	125	10.0	2.5	23	1	0%	203	71%	75	155
Dec-97	137	9.5	3.0	28	0	0%	260	70%	64	125
Jan-98	145	13.1	3.4	36	0	0%	326	68%	82	134
Feb-98	139	13.3	3.5	30	2	0%	255	63%	88	144
Mar-98	151	13.8	3.9	27	21	45%	212	61%	96	160
Apr-98	128	15.3	3.0	16	28	45%	91	67%	127	189
May-98	141	14.3	3.5	19	274	55%	4	66%	83	208
Total	1,624	135.9	38.5	307.8	2,004	-	1,432	-	1,062	-

Water heating was a significant portion of the loop load. The water heating system recovered 20% of the heat rejected from the building, benefiting the system by removing the need to reject this heat in the loop field. On the other hand the water heating system used 30% of the heat extracted from the ground. While the ground loop was sized to meet the heat rejection for cooling, the impact of the water heating system tended to equalize the ground load between heating and cooling. The net annual load on the ground loop was closer to zero with water heating. The combination of building loads, water heating and climate produced return temperatures from the ground loop ranging from 40°F to 80°F during the first year of operation

Case Study #3 - A Hybrid GX System for Cooling Dominated Buildings

As with conventional HVAC systems, a GX system must be sized to maintain indoor comfort at design-day outdoor conditions. For commercial buildings, which commonly have high internal heat gain, the peak cooling loads will often determine the size of critical HVAC components.

However, unlike air-cooled condenser systems, the design-day analysis for GX systems must also account for seasonal imbalances between the heat extracted and the heat rejected to the ground. If the seasonal cooling load is significantly greater than the heating load and the heat rejected is high for the heat exchanger size, the GX system heat sink may warm by several degrees Fahrenheit in the first few years of operation. The size of the GX heat exchanger may have to increase by 30% or more to compensate for this long-term change in ground temperature (Kavanaugh & Rafferty 1997).

Sizing it to meet the design-day cooling load, which occurs only a few hours each year, can tip the economic analysis in favor of an alternative technology. In these instances, a "hybrid" system that supplements the GX heat exchanger with either a cooling tower or fluid cooler can significantly lower first costs while maintaining high seasonal operating efficiencies[5]. In addition to handling part of the peak load, the supplemental cooler can be used during periods of relatively low wet-bulb temperature to reject heat to the atmosphere rather than the ground, thereby maintaining a better balance between heat rejected to and absorbed from the ground.

The Paragon Center in Allentown, Pennsylvania uses a geothermal hybrid system (Kavanaugh 1998). This 80,000 ft^2 office building was originally intended to be totally geothermal, but underground caverns at the rear of the property eliminated a portion of the planned bore field. A fluid cooler *(i.e.,* an evaporatively cooled heat exchanger) was added to the system to supplement a GX heat exchanger that is undersized by 60%. Loop water flows to the fluid cooler when the loop exceeds 85°F. Monitoring during 1996 and 1997 revealed that control of the fluid cooler of a hybrid system is important. At the Paragon Center, the loop tended to run at 85°F—the setpoint at which the fluid cooler began to operate. However, loop temperatures could have been lowered and operating costs reduced if the fluid cooler was allowed to operate longer.

In general, a cooling tower or fluid cooler in a hybrid GX system should be allowed to operate whenever it lowers overall operating costs. GHPC and the building owner plan two tests for 1998-1999: (1) Operating the fluid cooler at the Paragon Center nearly continuously at low speed during the cooling season, to test the hypothesis that unloading the ground loop will improve heat pump performance. (2) Night operation to "cool" the loop with off-peak energy, which may make sense in some cli-

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[5] A cooling tower will have much lower installed cost than that for the GX heat exchanger. It will, however, have significantly higher maintenance costs.

mates. At low fan speed, the energy required to operate the tower is small compared to the added heat rejection.

The installed cost for the GX system at the Paragon Center was \$12 per ft^2, with very high efficiency heat pumps. Payback when compared with a water loop heat pump system (with boiler and cooling tower) was calculated as less than 4 years for the incremental cost, which was \$2 /ft^2 (Singh 1998). Without optimizing the operation of the fluid cooler, annual HVAC energy use was 6.2 kWh/ ft^2 (based on occupied space). At the local utility rate of \$0.08 per kWh, HVAC costs averaged \$0.50 per ft^2 per year. The variable speed loop pump and fluid cooler accounted for approximately 5% and 3%, respectively, of the HVAC energy use.

Case Study #4 - A Low-Cost Open-Loop Option: Standing-Column Wells

Where adequate groundwater is available, large "open loop" heat exchange systems may cost less than closed loop alternatives, because less drilling is required. In general, these systems draw ground water from a near-surface aquifer. Most reject that water to a nearby recharge well[6]. Some, including the 4700 ton Galt House complex in Louisville and the Dubuque County Courthouse in Iowa, are near rivers connected to the respective aquifers, and discharge to storm sewers that return to the Ohio and Mississippi Rivers, respectively[7]. Operating costs are also very attractive, since the loop tends toward a very constant temperature, that of the "undisturbed" ground. These open loop systems require a relatively shallow aquifer capable of supplying in the range of 2 gpm per ton of block load (Rafferty 1996).

Standing-column wells are an alternative open-loop GX configuration that can further reduce installation costs where conditions are favorable[8]. In these systems water is drawn and returned to the same well, thus avoiding the cost of a separate injection well. In general, water is drawn from the bottom of the standing-column well and returned near its top. The return should be beneath the static water level to avoid aerating the circulating water. By drawing from and returning to opposite ends of the well, the circulating water can exchange heat with the ground before it is delivered back to the heat pumps.

In some applications, heat exchange within the standing-column well is not adequate to prevent loop temperatures from getting either too high or too low during peak load periods. If this should happen, more temperate ground water can be drawn into the well by discharging a portion of the loop flow to a separate sink (rather then returning it to the well). This discharge is typically only a small fraction of the total recirculated water, and so the standing-column well retains an important advantage over conventional open-loop systems.

The GHPC has been studying the performance of standing-column wells at two GX sites. The first site, the Haverhill Public Library, is a 28,000 ft^2 two-story building in Haverhill, Massachusetts.

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[6] In addition to state/local drilling and water extraction permits, return of water to an aquifer will require an EPA or delegated state "Class V Underground Injection Control" permit. Where the groundwater is of acceptable quality, this is routine, since the water is not changed in the HVAC use except in its temperature.

[7] Discharge to surface waters may require a "PDES (Pollution Discharge Elimination System" permit. Again, since nothing is added to or removed from the water except heat, this is generally routine.

[8] Standing column wells work best with a competent rock column to minimize the use of well casing. They are often employed where wells produce too little water to support a two-well system (supply and recharge). They must be developed in a single aquifer that yields acceptable water, and thus have been most commonly installed in igneous or metamorphic rock terraines, such as New England.

A standing-column well system replaced the original air-cooled chillers, electric boiler and electric duct heaters. Six new 10-ton water-to-water heat pumps use the existing piping and fan air-handler coils to provide 90°F water in heating and 45°F water in cooling (The heat pumps can supply 120°F water, but the system was able to meet the heating load with 90°F water).

Two 1500 ft deep wells with a static water level 40 feet below grade supply water to the heat pumps through a 5-hp well pump. Under most operating conditions the water is discharged back into the well. Whenever the water temperature drops below 40°F approximately 10% of the total flow is diverted away from the wells. The well water temperature ranged from 38°F to 70°F during the first six months of operation when only one well was operating. When the second well was placed into service the temperatures were maintained between 45°F and 66°F, and the need for bleed cycles was eliminated.

Compared to the HVAC system it replaced, the standing-column well GX system reduced the annual energy use at the library by 130 MWh, saving $11,350 per year. The monthly winter demand dropped by 50kW to 100 kW. The annual HVAC energy use was 3.2 kWh/ft^2—2.6 kWh/ft^2 for the heat pumps and 0.6 kWh/ft^2 for the well pumps--with the energy use equally divided between heating and cooling. The total system cost was $209,000 or $7.50 per ft^2, a relatively low figure. The standing column well costs ranged from $900 to $1,200 per ton, reflecting high drilling costs at the site. System performance justified using standing column wells for a recent addition to the building

Another standing-column well GX system, now being monitored for the GHPC, is the Maine Audubon Society's Gilsland Farm Nature Center, located just north of Portland, Maine. In February of 1996, a new, 5,400 ft^2 visitors center was opened at the site. The building is equipped with a 15-ton geothermal heat pump system to meet its heating and cooling loads. The HVAC system at the site uses three 5-ton water-to-water geothermal heat pumps that either receive or reject heat to a 6-inch diameter, 600 foot standing column well. A 5-hp pump located 120 feet from the top of the well draws water through a 4-inch diameter pipe from the well bottom. This pump charges two pressure tanks that are located inside the building's mechanical room. When a heat pump receives a call for heating or cooling, a solenoid valve in its well-side water line opens delivering water from the pressure tanks to the heat pump. Most of the water is returned to the top of the well, with approximately 5 gpm bled to a drain[9].

Most of the heat to the building is provided by hot water delivered from the heat pumps to a radiant floor on the building's ground level. (Only 690 ft^2 of conditioned space are on the second level.) The heat pumps also deliver hot water to a cabinet unit heater, two fan-coil units and coils in the supply ducts of two heat recovery units. During the summer, the heat pumps provide chilled water to the fan-coil units and the heat recovery unit coils to handle the building's relatively light cooling load. A desuperheater on the lead heat pump provides most of the domestic hot water for the building.

In both heating and cooling, the operation of the three heat pumps is staged to reduce cycling. The lead heat pump will start when there is a call for heating or cooling. If the load has not been met after four minutes, the second heat pump turns on. The third heat pump follows after another four minutes.

The installed cost of the geothermal HVAC system was $19.56/ft^2. If the visitors' center had used a conventional boiler and chiller, installed HVAC costs would have been $16.71/ft^2. Although the incremental cost was $2.85/ft^2, the customer's decision was based on other values: energy efficiency and projected low maintenance/high reliability.

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[9] The GX system at this site is not a "pure" standing-column well since a constant flow of water is bled from the loop. However, this bleed is relatively small, ranging from 10% to 25% of the recirculated flow.

Measurements of the supply well-water temperatures indicate that the standing-column well performed well during the 1997/98 winter. As shown in Figure 2, the daily average of the heat-pump entering water temperature never dropped below 47.5°F during the winter[10]. However, it should be noted that the past winter was extremely mild with the number of degree days for December through February being 13% below normal.

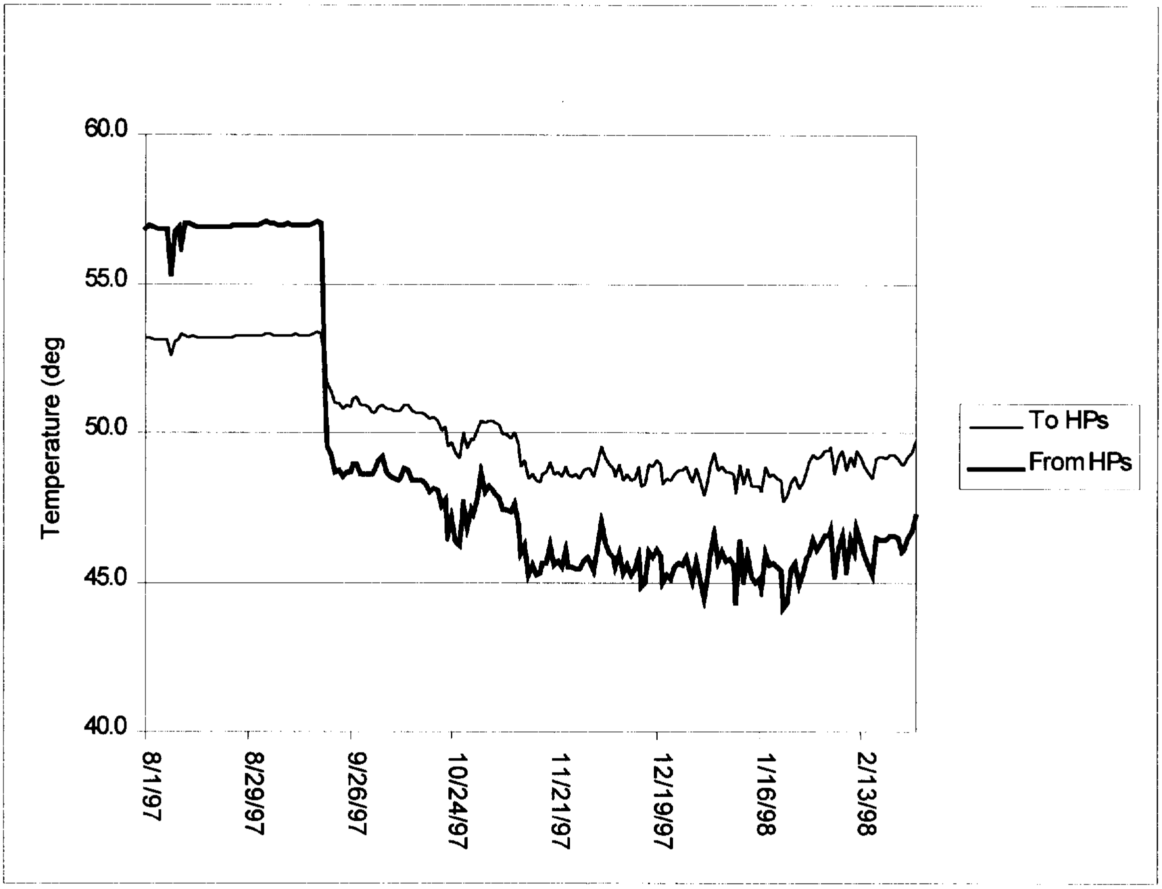

Figure 2. Supply and Return Well-Water Temperatures

Based on the period from August 1997 through April 1998, annual HVAC energy use is estimated to be 6.9 kWh/ft^2, and energy use for the total building is estimated to be 9.6 kWh/ft^2. Approximately 16% of the HVAC energy use is for the well pump and 35% for indoor fans and circulating pumps. With the well and circulating pump accounting for almost half of the total HVAC energy use, this site is an excellent candidate for variable speed drives and advanced control strategies that limit pump operation. One or more of these options will be explored in the second year of the field test.

Case Study #5 – Waste Water as an Alternative Sink/Source

The cost of drilling wells or burying long lengths of pipe can be avoided when a suitable water source is available at the building site. This was the case at the Water Tower Square office building,

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[10] The loop temperature drops in mid September when the HVAC switches from cooling to heating.

located in Williamsport, Pennsylvania. The four-story, 140,000 ft^2, brick building was built in the 1920s as a factory, and recently converted to office space. Its location on the banks of the Susquehanna River near the Williamsport Sanitary Authority waste-water treatment plant offered a unique opportunity to use the sanitary effluent as a heat source and sink for the building's water-loop heat pump system.

The office building uses heat pumps, sized from 2 to 8 tons, arranged in zones to suit the needs of tenants. Each heat pump is controlled independently by zone thermostats. When a heat pump is not operating a valve shuts off its water to minimize pumping power. Blowers run continuously during occupied hours to circulate and introduce fresh air. Several sensible heat recovery units supply fresh air to each floor through the return air plenum (the space above the dropped ceiling).

As shown in Figure 3, up to three 15-hp variable-speed pumps circulate water to the heat pumps. The pressure in the loop controls the speed of these pumps. The combination of the variable speed drives, shut-off valves in the heat pumps, and heat exchanger bypass minimizes the energy used for pumping.

Also shown in Figure 3 are two plate-frame heat exchangers that temper the building loop with effluent pumped about 1,200 feet from the water-treatment plant discharge. Two 30-hp variable-speed pumps can circulate up to 1.5 million gallons of effluent through these heat exchangers each day. While this represents 30% of the typical daily discharge from the waste-water treatment plant, the building often uses less than 400,000 gallons per day. The effluent returns by gravity back to the discharge line.

The temperature of the building loop water sets the effluent pump speed. The pumps are off when the loop temperature is between 50°F and 80°F. The effluent temperature varies through the same range over the course of a year. One pump operates at low speed when outdoor temperatures are near 32°F to avoid freezing stagnant water in the heat exchangers.

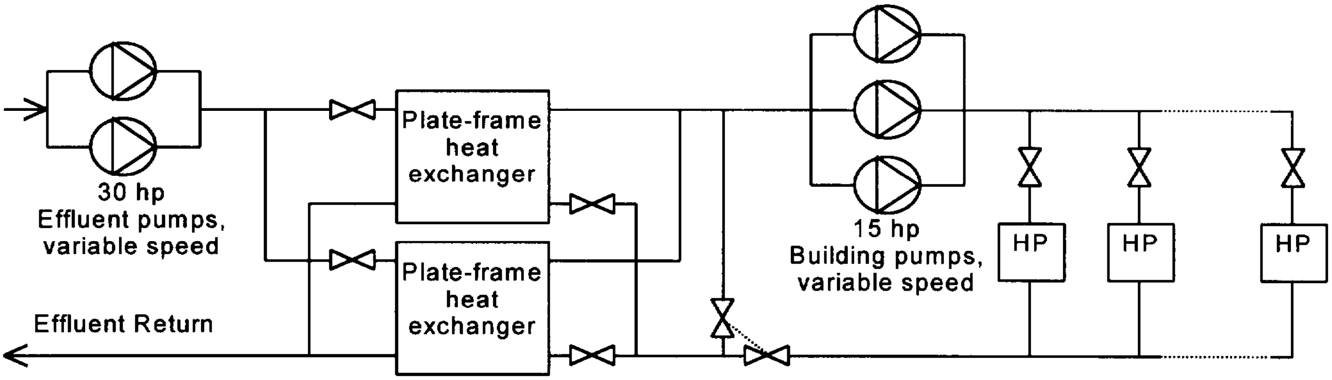

Figure 3. Heat Pump System Schematic

The coupling of the water loop system to the treated effluent line eliminated the need for a boiler and a cooling tower. This configuration reduced the central plant equipment and maintenance needs. It also provided more temperate water at lower cost than coupling the loop directly to the ground through a bore field. It involved less permitting than coupling the loop to the river. This system is an example of the designers paying close attention to their surroundings to find the most effective heat source and sink for the building.

Using a water-loop heat pump system in a speculative office building offered advantages to the developer and tenants. The system provides efficient operation due to the moderate loop temperatures and the ability to operate different zones in heating and cooling simultaneously. This zoning flexibility also allowed the developer to postpone equipment expenses for the heat pumps until the space was leased.

Conclusions

The buildings presented in this paper were sold to public and private owners as cost-effective HVAC solutions with lower life-cycle costs than alternatives offering the same amenity. Each of these buildings represents some risk to the designer, the owner, and the construction team, since each was a "first." The Paragon Center was designed as a standard closed-loop system, but became the first known commercial hybrid because local geological conditions limited the size of the closed-loop heat exchanger. To our knowledge, Geneva Lakefront Hotel is the first use of building pilings as heat exchangers in North America. Water Tower Square is the second known use of sewage effluent in North America[11] Although we analyze Choptank School for its enhanced grout, it was also the first GX school in Maryland and the first GX project undertaken by its engineer.

The most important outcome of our work is the demonstration that GX is a viable HVAC option for commercial buildings. It offers significant advantages over conventional central station equipment. These include: greater design flexibility (reduced duct size, reduced mechanical space requirements, lack of rooftop condensers); and attractive energy savings. In addition, operations and maintenance savings are substantial, with these costs averaging $0.07 - $0.11/square foot per year for 25 commercial buildings (Cane et al. 1997).

The second outcome is to show that GX is not a single "canned" design, but a suite of options. The goal is not to install pipe in the ground, but to provide an economical and reliable heat source and heat sink for efficient heat pumps. This source and sink should be sought opportunistically. The designer should start with a solid understanding of building energy needs, both in capacity and in equivalent full-load operating hours per year. This information is critical for designing the heat exchanger. Next, she should commission one or more test boreholes and a thermal conductivity test at the site. This will give "baseline" information on the cost of a closed-loop system. If the test boreholes reveal availability of a substantial water resource, an open-loop system can be evaluated. For larger systems, this will lead to reduced costs (the nearer the water to the surface, the better the first-cost and life-cycle cost advantages). With this "baseline" information, the designer can consider less conventional options, such as those discussed in this paper.

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[11] A training facility for a major industrial firm in the Seattle area uses municipal wastewater for cooling the condenser of a large central chiller.

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[12] References available from "GHPC" can be ordered, without charge, by requesting the document number from the Geothermal Heat Pump Consortium. Call 1-888-333-4472 or send e-mail to <info@ghpc.org>