Groundwater Heat Pump Systems: Experience at Two High Schools

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ABSTRACT

Groundwater integrated Heating, Ventilation, and Air-conditioning (HVAC) systems have been operating in the Northwest for nearly 50 years, and experiences with the early central plant installations have been well documented in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) literature. This paper focuses on two of the more recent systems. Both of unitary design, one serves a high school in northern California and the other a high school in western Oregon. The California site, a 144-ton (506 kW), 57°F (14°C) groundwater system in operation for two years, demonstrates the importance of verifying the groundwater resource prior to final mechanical design. The Oregon site, a 118-ton (415 kW) system, employs a 54°F (12°C) production well and an injection well. It has been in operation for approximately eight years. The energy performance and maintenance requirements are detailed. Experience with these two systems indicates that properly designed groundwater systems are efficient, low maintenance, and cost-effective.

INTRODUCTION

Of the many types of ground-source heat pump designs, groundwater systems are among the oldest, with some in service for nearly 50 years. Despite this history of operation, pitfalls still are encountered by current designers. In this paper, the experiences with two groundwater systems are examined. Both systems are located in high schools, employ groundwater of less than 60°F (15°C), and serve buildings in which annual energy use is dominated by heating requirements. Although these systems serve efficiently and reliably, in each case minor modifications can be made to enhance performance.

JUNCTION CITY HIGH SCHOOL

In late 1988, a groundwater heat pump system was installed in the east wing of the Junction City, Oregon, high school (JCHS) to replace an aging gas boiler/unit ventilator design. Junction City is located in western Oregon's Willamette Valley, an area characterized by mild climate (4800°F HDD, 261°F CDD [2570°C HDD, 145°C CDD]).

The school, originally constructed in the late 1930s, was finding it difficult to maintain space temperature at adequate levels with the old boiler system. An existing 54°F (12°C) irrigation well, coupled with the region's low electric rates, made the groundwater system a natural choice (ACR 1990).

The east wing of the school includes 55,000 ft^2 (5,100 m^2) of classrooms, offices, gym, cafeteria, and miscellaneous areas. The 118-ton (415 kW) system was installed largely in the attic area with heat pump units hung from the wooden structure. Flexible ductwork connects the units to ceiling diffusers, and an uninsulated (PVC) piping loop distributes a water/antifreeze mixture to the units. Ventilation air is ducted directly to the return air connection of the heat pump units without preconditioning. Fixed dampers regulate the flow of outside air to the units. All the central mechanical equipment is contained in a 10 ft by 10 ft (3 m by 3 m) mechanical room. Figure 1 provides a simplified flow scheme (Grimes 1988) for the system.

Loop design includes a 15-hp (11 kW) circulating pump sized for 300 gpm @ 100 ft (19 L/s @ 30 m). This pump serves a loop consisting of 29 individual heat pumps (1 to 5 tons [3.5 to 18 kW]) with a nominal installed capacity of 118 tons (415 kW). Each unit is equipped with an automatic flow control valve for balancing purposes. No formal central control system was installed, but programmable thermostats (with remote temperature sensors) for all zones are located in a single maintenance room for tamper-proof operation.

Groundwater well pump control is a double-aquastat arrangement. In the cooling mode, the well pump is started when the loop temperature rises to 80°F (27°C) and stopped when it falls to 75°F (24°C). The corresponding temperatures in the heating mode are 52°F (11°C) and 55°F (13°C) (Grimes 1988).

OPERATING RESULTS AND POTENTIAL IMPROVEMENTS

The performance of the system over the past seven years has been excellent. A single fan motor has been the only failure among the 29 heat pump units, and no problems have been encountered with the groundwater portion of the system. The primary regular maintenance procedures include air filter changes every 90 days, semiannual loop water chemistry check

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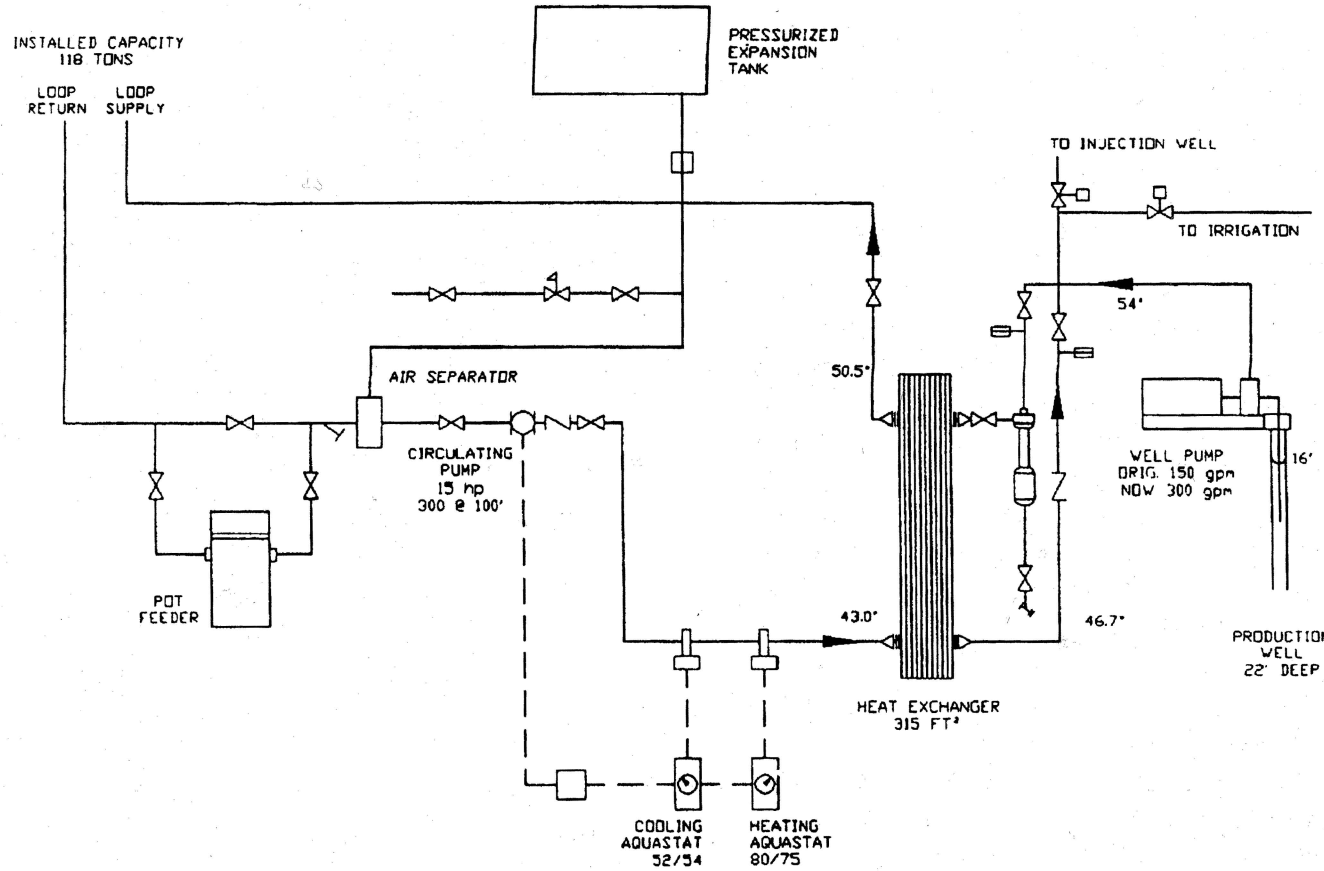

***Figure 1** JCHS simplified flow scheme (heating mode).*

and adjustment, weekly groundwater strainer blowdown, and annual tear down and examination of the two system pumps (Nail 1995).

After five years of operation, the plate heat exchanger was dissembled for cleaning. A "brown stain" was removed from a few plates, and the unit was reassembled. No evidence of scaling was found, and the unit has not been opened since.

Figure 2 presents a plot of historic electrical use at the school. In the last year prior to the installation of the heat pump system, electricity consumption amounted to 330,770 kWh with a peak demand in February of 152 kW for an annual cost of $19,127. Gas consumption in the same year was 35,506 therms at a cost of $20,023. In the first year the heat pump system was used, gas use declined to 3904 therms (all non-space-heating use) for a cost of $2,045 and electricity consumption rose to 588,240 kWh at a cost of $29,905. Electrical demand rose to peak of 230 in February. Energy utilization index (total site energy use divided by building floor area) values before and after the installations are 85,082 Btu/ft^2 yr (258 kWh/m^2 yr) and 43,601 Btu/ft^2 yr (137 kWh/m^2 yr). Total energy costs dropped from $0.71/ft^2 ($0.066/m^2) prior to the heat pump system to $0.56/ft^2 ($0.052/m^2) after retrofit.

Based on the original installed capacity and performance (3.5 COP @ 45 EWT [7.2°C EWT]), the installed demand of the heat pumps totals 158 kW (Grimes 1988). The well and circulating pumps add another 15 kW for a system total of 173 kW. Based on the change in actual demand of 78 kW (230-152), the metered demand reflected a rise of only 45% of the installed demand.

The original well pump for this system was sized for an irrigation duty of 150 gpm at 115 ft (9.5 L/s at 35 m). It is probable that during the heating mode, the flow produced for the heat pump system was greater than 150 gpm (9.5 L/s) due to the lower head loss through the injection well and disposal piping. However, operation in excess of 2.0 gpm (0.037 L/s kW) per ton during this period is unlikely.

In 1993, the original irrigation pump was replaced with a new pump (300 gpm @ 100 ft [19 L/s @ 30 m]) identical to the system's circulating pump (Nail 1995). The additional flow was not necessary, and the selection was made to reduce spare parts inventory and maintenance practices. Cavitation developed at installation, and a discharge throttling valve was added to stabilize pump operation. Evidently, no consideration was given to the effect this arrangement would have on pump electricity consumption.

The loop design for the system is based on a flow of 2.9 gpm per ton of installed capacity. A 15 hp (11 kW) pump operates 24 hours a day at constant flow (Nail 1995). Each heat pump is equipped with an automatic flow control valve for balancing. Based on the original specifications for this pump, it imposes an electrical load of approximately 9.1 kW.

At continuous operation, this results in an annual consumption of 79,500 kWh per year. Metered use for the entire building suggests that the addition of the heat pump system resulted in an increase of 257,470 kWh per year. As a result, the circulating pump alone is responsible for 31% of the total heat pump system consumption.

This level of consumption is excessive. In this case, it is a function of a combination of factors. The loop flow is 2.9 gpm per ton of installed capacity. This value is on the upper end of the 2.0 to 3.0 gpm/ton (0.037 to 0.055 L/s kW) range normally used. Due to the constant flow arrangement, the modification of the loop flow toward the lower end of this range could reduce pump electrical consumption 30% to 60%. In addition to high flow, piping head loss appears high. Allowing 10 ft (3 m) for the heat pump and 20 ft (6 m) for the heat exchanger, the piping system consumes the remaining 70 ft (21 m). Although this figure is in excess of what one would expect in a new construction project, the extended nature of the building and the difficulties of retrofit pipe routing no doubt had some impact on piping pressure drop.

Loop temperature control is based upon a dual-aquastat arrangement as discussed above. When determining the setpoints, part of the strategy should be to consider the impact on the overall electric consumption of the system. For a groundwater design, the well pump should be started only when it produces conditions under which the total system energy consumption is reduced by its operation. One method of evaluating this is to plot system electrical demand with and without the well pump vs. some convenient parameter such as loop temperature. Figure 3 presents a heating-mode plot for the JCHS system (based on 75% of the heat pumps in operation). Although the present controls bring on the well pump at 52°F (11°C), the performance of the system is such that no benefit is derived from pump operation until the loop return temperature reaches 40°F (4°C). The potential for condensation becomes a factor at low loop temperatures. In this particular case, the piping is installed in an attic space above the building insulation. The ambient temperature in this area closely tracks outdoor air temperature.

Figure 4 presents a similar plot of system performance for the cooling mode (based on 75% of the heat pumps in operation). In this case, it appears that it would be beneficial to initiate well pump operation at a lower temperature than is currently practiced. In this case, a pump start in the 70°F (21°C) rather than 80°F (27°C) range would be more efficient. The optimum well pump setpoints for aquastat-type control are influenced by heat exchanger area, heat pump performance, and groundwater temperature.

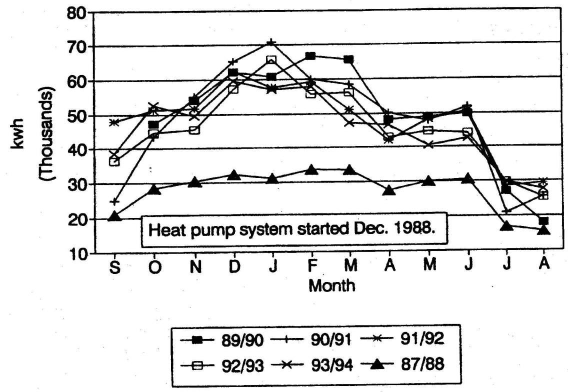

Figure 2 JCHS electricity consumption.

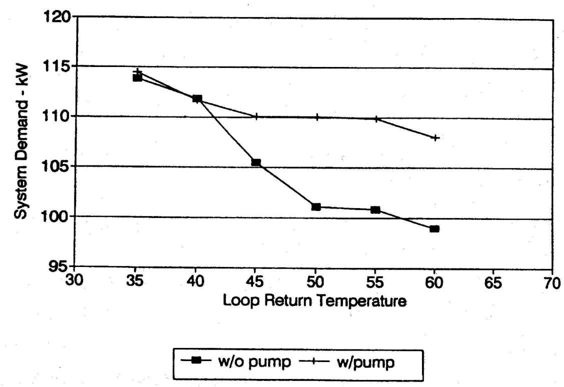

Figure 3 Well pump setpoint optimization (heating mode).

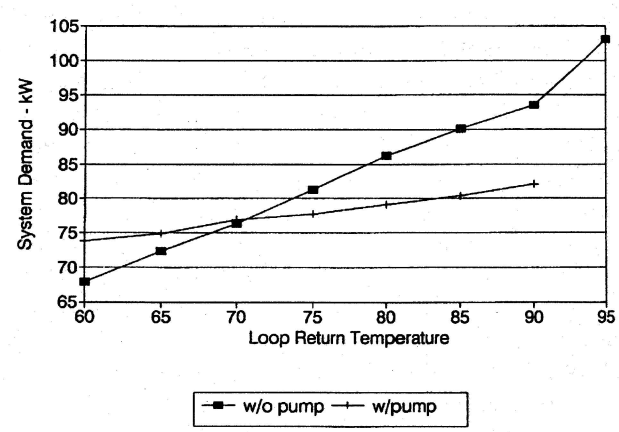

Figure 4 Well pump setpoint optimization (cooling mode).

YREKA UNION HIGH SCHOOL

In early 1993 design began on a retrofit groundwater heat pump system to serve a portion of the Yreka Union High School (YUHS) in Yreka, California. The site, located in extreme northern California, is situated at 2500 ft (760 m) elevation and is characterized by moderate climate (5395°FHDD, 597°FCDD [3000°CHDD, 332°CCDD]). A heat pump system was chosen to replace the existing boiler system as the result of another nearby groundwater system, an electric utility loan program, and propane heat costs that exceeded $\$25/10^6$ Btu (0.024 $/MJ). The high school consists of eight major buildings comprising 56,000 ft^2 (5,200 m^2). Of this, only 32,000 ft^2 (2,970 m^2) was connected to the heat pump system.

The design for the system appears in Figure 5 (Turley 1993). A 200 ft (51 m), 8 in. (315 mm) production well delivers 57°F (14°C) groundwater to a plate heat exchanger for interface with the heat pump loop. The well is equipped with a 20 hp (15 kW) pump capable of producing a maximum of 125 gpm (7.9 L/s). Groundwater effluent is discharged to a drainage ditch. A total of 34 individual heat pumps (1 to 8 tons [3.5 to 28 kW]) are installed in attic and rooftop locations. The installed capacity of the heat pumps is 144 tons (506 kW). As a result, the groundwater flow capacity amounts to 0.87 gpm per ton (0.016 L/s kW) of installed capacity.

The loop circulating pump is sized for 422 gpm (27 L/s) at 115 ft (35 m) and is equipped with a 20 hp (15 kW) motor. Loop flow is constant. In the occupied mode, the pump runs continuously. During unoccupied periods, the start of any individual heat pump initiates loop flow.

Ventilation is supplied at the rate of 320 cfm (151 L/s) to the typical classroom and is ducted directly to the return air connection of the heat pump. Air is drawn (by the heat pump unit fan) directly from an unpressurized outdoor air plenum. No preconditioning of the ventilation air is included in the design.

An energy management system was installed along with the heat pump system. It includes a central microcomputer from which it is possible to monitor instantaneous loop parameters and plot past trends in these values. All zone setpoints are controlled from the console as well. No space adjustable thermostats are included in the system.

OPERATING EXPERIENCE AND POTENTIAL IMPROVEMENTS

The system recently has completed its second winter of operation, and the heat pumps have performed well. With the exception of some faulty high-pressure controls on a few units, no problems have been experienced with the heat pump equipment. After the first few months of operation, it was discovered

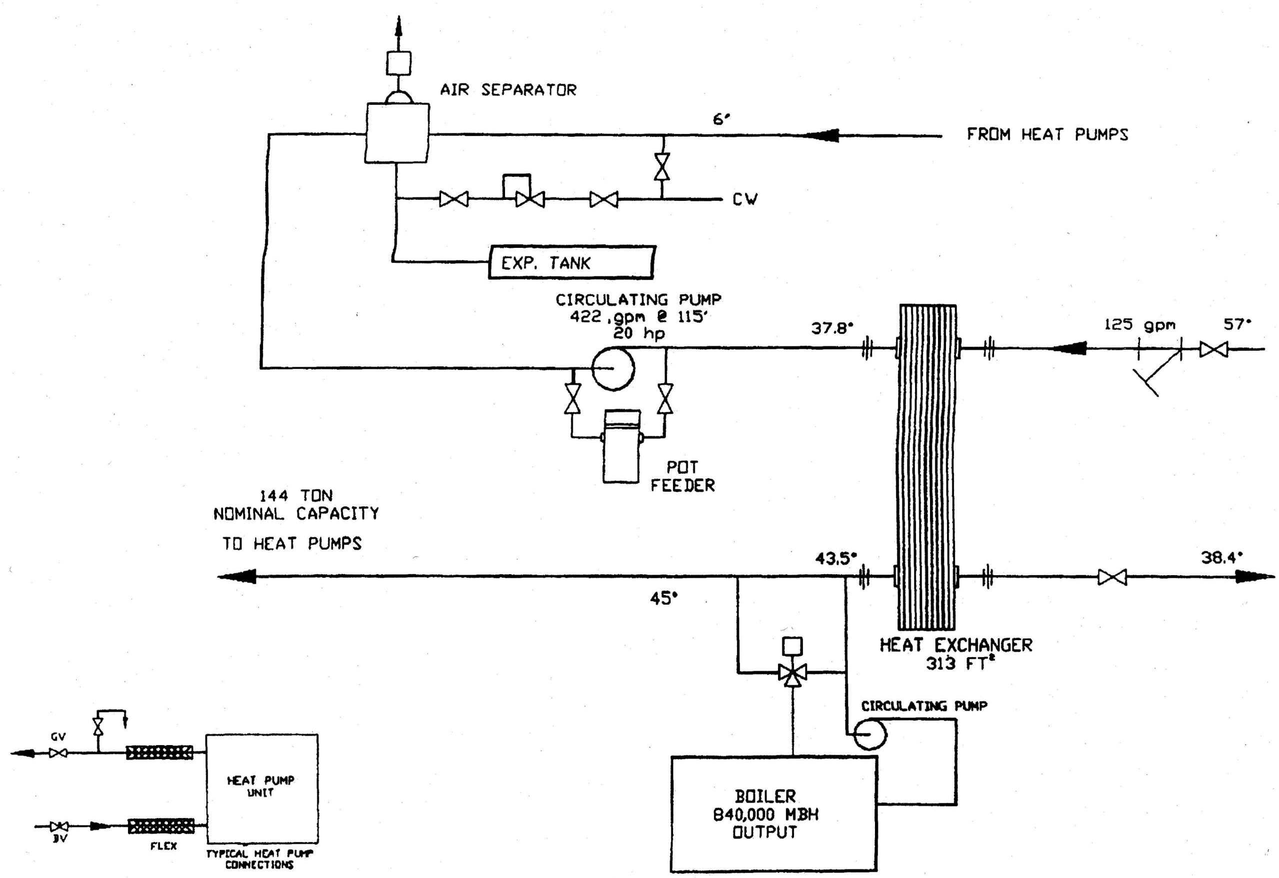

Figure 5 *YUHS simplified flow scheme (heating mode).*

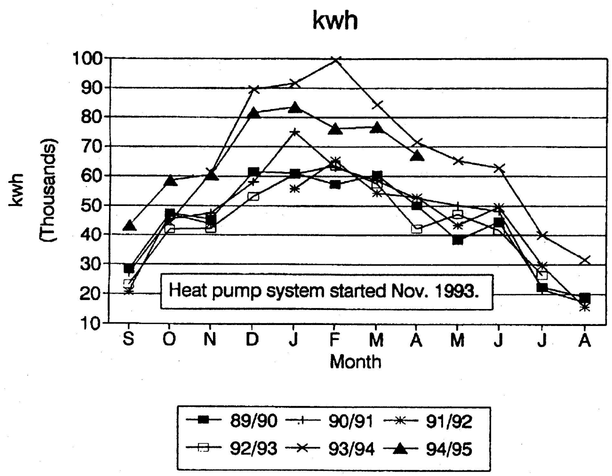

Figure 6 Yreka High School electricity consumption (kWh).

that some of the units installed in the attic area had faulty return air connections, which allowed air to be drawn in from the attic to the return. Four others were discovered to have air filter access blocked by electrical equipment (Rogers 1995). Filters are now changed on a regular basis, a procedure that is complicated by the poor unit access resulting from the attic installation (Waters 1995).

Due to the single metering of both electricity and propane and the fact that only a portion of the school was connected to the heat pump system, the performance of the retrofit is difficult to determine. Figure 6 presents a plot of electricity consumption at the school over the last six years. Propane consumption over the past four years appears in Table 1.

The heat pump system went on-line in November 1993. Using an average of the two years previous to installation of the heat pump system, the annual electricity consumption was 527,000 kWh/yr with a peak of 264 kW in February. Propane consumption for the same period averaged 952,000 ft^3 (27,000 m^3) at 1410 Btu/ft^2 (52.2 MJ/m^3). For the two years following the installation, the corresponding values are 734,000 kWh/yr with a peak of 373 kW in February. Propane consumption averaged 412,000 ft^3 (11,700 m^3); however, there is substantial difference between the first year (313,000 ft^3 [8,900 m^3]) and the second year (510,000 ft^3 [14,500 m^3]). This issue is discussed below. Average energy utilization index values before and after the installations are 56,088 Btu/ft^2 yr (177 kWh/m^2 yr) and 55,108 Btu/ft^2 yr (173 kWh/m^2 yr).

TABLE 1 Propane Consumption YUHS (1410 Btu/ft^3 [52.2 MJ/m^3])

	Electricity	Propane
1991/1992	528,800 kWh ($ 42,690)	888,720 ft^3 ($26,660)
1992/1993	525,401 kWh($41,990)	1,014,480 ft^3($30,434)
1993/1994	784,800 kWh ($59,610)	313,000 ft^3 ($9,390)
1994/1995	712,080 kWh ($57,120)	510,000 ft^3 ($15,300)

Installed demand of the system based on the average COP of the heat pumps (3.4 at 45°F EWT [7.2°C EWT]) amounts to 128 kW plus 24 kW for the pumps for a total of 134 kW. Metered demand for the building rose 109 kW after the installation, or 72% of the installed demand.

This system, like many others, was designed prior to the completion of a production well. Initial design was based on a groundwater requirement of 125 gpm (7.8 L/s) in the cooling mode and 292 gpm (18.4 L/s) in the heating mode. Well drilling commenced in the spring of 1993 with an unsuccessful 60 ft (18 m) test well. Shortly thereafter, a second 200 ft (61 m) well was completed and 60 ft (18 m) of 8-in. (315 mm) casing installed. With the driller still on site, a brief test was done at an estimated 120 gpm (7.6 L/s). At 4.5 ft (1.4 m) of drawdown (distance between static water level and pumping water level), it appeared the well had good productivity. Some weeks later, a second test was initiated at a rate closer to the peak required by the heat pump system. Table 2 presents a summary of the results. It is apparent that some event during the test resulted in a precipitous decline in both flow and specific capacity (gpm divided by ft of drawdown). Normally, this type of performance in a well with open-hole completion would be interpreted as a cave-in; however, a post-test check indicated no change in well depth. The conclusion was that a collapse had occurred in the water-bearing unit near the well.

At this point, the well portion of the system was at its budget limit and a decision was made that if a groundwater system was to be installed, it would have to operate with the available flow of 125 to 150 gpm (7.9-9.5 L/s).

The original design was based on a groundwater flow of 292 gpm (18.4 L/s) from 57°F to 48°F (14°C to 8.9°C) in the heating mode, with a loop flow of 45°F to 51.5°F (7.2°C to 10.8°C)—1,371,500 Btu/h (402 kW)—(Turley 1993). A re-evaluation of the heat exchanger (369 ft^2 [34.2 m^2]) at the lower flow rate suggested that it could raise the loop supply temperature to 48.4°F (9.1°C)—725,000 Btu/h (212 kW)—at the 45°F (7.2°C) return temperature. This was insufficient to meet building needs.

TABLE 2 Summary of Production Well Flow Test Results (Valley Pump, 1993) *

Time	Pumping Level (ft)	Flow (gpm)	Clarity
1:45	40 (12.1 m)	350 (22 L/s)	Clear
1:50	41 (12.5 m)	350 (22 L/s)	Clear
2:05	43 (13.1 m)	350 (22 L/s)	Clear
2:20	45 (13.7 m)	350 (22 L/s)	Cloudy
2:30	45 (13.7 m)	260 (16.4 L/s)	Cloudy
2:45	145 (44.2 m)	220 (13.9 L/s)	Cloudy
3:00	145 (44.2 m)	205 (12.9 L/s)	Cloudy
3:10	145 (44.2 m)	Broke Suction	
3:20	145 (44.2 m)	210 (13.3 L/s)	Cloudy
3 :45	150 (45.7 m)	Lost Water	
4:00	150 (45.7 m)	120 (7.6 L/s)	Cloudy

* Pre-test static water level - 36 ft (11 m)

Operating the loop at a 45°F (7.2°C) supply temperature (37.8°F [3.2°C] return) would allow the groundwater to supply 1,160,000 Btu/h (340 kW) to the loop. This would meet 75% of the installed capacity (heat of absorption at 45°F EWT [7.2°C EWT]) of the heat pumps. To allow for occurrences of greater than 75% load, the loop could be connected to the existing boiler to maintain a 45°F (7.2°C) EWT. Operation at the lower water temperature reduced heat pump capacity by approximately 3% but had no impact on COP, which remained at 3.4. All zones had sufficient capacity to meet the heating load under these conditions. Analysis of weather data indicated that even with only 75% of the peak capacity met, the groundwater could supply more than 98% of the annual heating requirement. Peaking fuel (propane) requirements were projected to be less than $ 1000 per year.

Connection of the heat pump loop to the existing boiler proved to be unsuccessful due to the size and age of the boiler and pressurization issues. As a result, the system ran for the first winter with only the groundwater as a heat source. No problems were encountered despite the fact that the system was operating with less than 1 gpm per ton (0.0184 L/s kW) of system installed capacity. In the fall of 1994, a new smaller boiler was installed to back up the groundwater well, which the operators felt was diminishing in capacity.

The EMCS installed with the heat pump retrofit is a powerful tool for managing and operating the system. Unfortunately, the operating personnel have not been fully instructed in the use of the system (Waters 1995). As a result, performance of the heat pump system has been compromised. The control sequence for the new boiler is a good example of this. The boiler is enabled when the loop supply temperature drops to 51°F (10.6°C) and turned off when the loop rises to 54°F (12.2°C) (Waters 1995). By maintaining the loop in this temperature range, the heat contribution from the groundwater is substantially reduced. This is reflected in the propane consumption figures for 1993-1994, when the system operated on only groundwater, and 1994-1995 when the boiler was available. Propane use at the school rose 40% in 1994-1995 year. Based on the difference in cost between propane-supplied heat at $\$25.30/10^6$ Btu (1410 Btu/ft^3 at 80% at $\$0.03/\text{ft}^3$) and groundwater-supplied heat at $\$0.94/10^6$ Btu (well pump at 11.7 kW at $0.08/kWh), the boiler should only be used to prevent the loop temperature from falling below the minimum required 45°F (7.2°C). Current utility operating cost for the heat pump system (1994-1995) amounts to $72,420. For the last year prior to the system installation, cost was $72,424.

The loop circulating pump for this system is sized for 422 gpm (26.6 L/s) at 115 ft (35 m), or about 2.93 gpm per ton (0.054 L/s kW) of installed capacity. It operates continuously at constant flow during occupied hours. In unoccupied hours, the start of any individual heat pump initiates loop flow. This strategy no doubt reduces pump electricity consumption relative to continuous operation; however, the circulating pump remains a major electrical load. Assuming the pump operates only 50% of the time during unoccupied hours, its annual consumption would amount to 83,500 kWh/h. Based on the annual energy figures cited above, this amounts to nearly 40% of the total heat pump system energy consumption. As discussed for the JCHS system, modification of the loop flow to a value closer to the 2 to 2.5 gpm per ton (0.037 to 0.046 L/s kW) range would substantially reduce pump electricity consumption. In cases such as these, it is also useful to evaluate the benefit of variable-pumping retrofit for the loop.

CONCLUSIONS

The JCHS system was a cost-effective and efficient solution to the aging boiler system. Reducing site energy use by 49% and reducing annual operating costs by $7200 (18%), it has served its owner reliably for the past six years. For the YUHS system, the greatest benefit has been the availability of air conditioning. Cost of operation and site energy use are virtually unchanged with the heat pump system compared to the previous boiler system.

The experiences of these two systems suggest that the following issues be given careful consideration by future designers of groundwater heat pump systems.

- Groundwater flow requirements for systems should be based on building peak block load and not installed capacity. Arbitrary use of a 3 gpm/ton (0.0184 L/s kW) of installed capacity rule (intended for only loop flow) grossly overestimates groundwater flow requirements.
- Drilling and adequate testing of wells should take place prior to mechanical design, if at all possible. In the event that this is not feasible, some flexibility should be present in the design to accommodate groundwater flows and temperatures that depart from original assumptions.
- Care should be exercised in the design of the closed-loop piping and loop flow rate to minimize system energy use. Poor design (high water flow rates and excessive piping pressure drop) can result in a system in which the circulating pump consumes 25% or more of total system energy. Serious consideration should be given to variable-flow design for the loop.
- Commissioning is an important process for any HVAC system. It is critical to unusual designs such as groundwater systems. Key to its success is providing the operators of the system with an understanding of not only how to operate the system but why and, more importantly, what the implications are of seemingly minor changes.
- Care should be used in the selection of the well pump temperature control setpoints. The well pump should be operated only under conditions that result in lower overall system energy consumption.
- Properly designed groundwater systems are not characterized by excessive maintenance requirements or equipment fouling.

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QUESTIONS AND COMMENTS

Elliott Spilker, Supervisor of Customer Programs, Omaha Public Power District, Omaha, Neb.: Why did you not use a return water system rather than the propane backup? With 57°F water, you could increase your capacity of the well by maybe 50%, eliminating the need for the propane system.

We are monitoring several closed systems: pumping power is critical. One system has a variable-speed, 30-hp pump and shutoffs at each heat pump. So far the pump has only pulled 5 hp—a large savings. Also, engineers should be specifying extended-range heat pumps to reduce energy consumption.

Kevin Rafferty: Because the groundwater was already being reduced to 38°F there wasn't much room for further temperature drop without the danger of freezing. The problem was compounded by the need to maintain a 45°F water temperature to the heat pumps.