Benchmark for Performance: Geothermal Applications in Lincoln Public Schools

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ABSTRACT

Vertical-bore, geothermal heat pumps (GHPs) have been providing heating and cooling to four new elementary schools located in Lincoln, Nebraska since 1995. According to representatives of the local utility and school district, the systems are providing a comfortable, complaint-free environment with utility costs that are nearly half of that of other schools in the district. Performance data collected from on-site energy management systems and district billing and utility records for all fifty schools in the Lincoln district indicate that only five consume less energy than the best performing GHP school; however, these five cool less than 10% of their total floor area, while the GHP schools cool 100% of their floor area. When compared to other new schools (with similar ventilation loads), the GHP schools used approximately 26% less source energy per square foot of floor area. Variations in annual energy performance are evident amongst the four GHP schools, however, together they still consume less source energy than 70% of all schools in the district. These variations are most likely due to operational differences rather than installed equipment, building orientation, or environmental (bore field) conditions.

INTRODUCTION

Currently, there are over 400 installations of geothermal heat pump (GHPs) systems located at public school facilities across the nation. Vertical-bore, ground-coupled GHP systems were installed at four new elementary schools located in Lincoln, Nebraska in 1995 (Figure 1). The schools have identical floor plans, each with 69,000 square feet of area dedicated to classrooms, offices, meeting rooms, a cafeteria, and a gymnasium (Figure 2). Approximately 500 students attend each school. The performance of these installations is well-documented by electric and gas utility data (in 15-minute and monthly intervals) and 10-minute energy management system (EMS) data. Additionally, the situation at Lincoln is unique in that the district maintains records on facility design, energy performance, and maintenance activities for all facilities within the district. This study is part of a thorough effort to review the design and performance of the GHP systems located at Lincoln Public Schools (LPS), and to compare the performance of these schools to others within the district.

SYSTEM DESIGN

The design of the schools' mechanical systems was the result of a collaborative effort between the engineer, the school district, and the local electrical utility (Bantam and Benson 1995). Life cycle costs for five alternative designs were analyzed using energy consumption and demand profiles estimated from simulations performed with a commercially-available software package, operating costs estimated using utility rate schedules, and assumptions about

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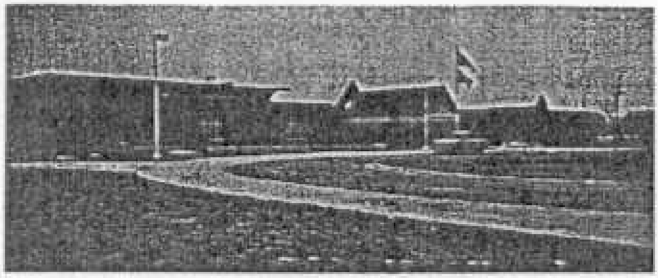

Figure 1 GHP elementary school, built in 1995 and located in Lincoln, Nebraska.

maintenance and equipment replacement intervals and installed costs estimated with a commercially-available cost estimating guide. These designs included: a variable air volume (VAV) system with air-cooled chillers, a VAV system with water-cooled chillers, gas-fired absorption chillers, vertical GHPs, and water-loop heat pumps. Various time-consuming adjustments were needed during the feasibility study in order to overcome shortcomings in GHP representations in available software tools. Considering capital costs and likely operating and maintenance costs, vertical GHPs were determined to be the best alternative.

Because their annual operating schedules may fluctuate from year to year, heating and cooling loads were estimated assuming full-year operation of the facility. According to the loads calculated during the design process, under full-year operation, the building was expected to be dominated by cooling loads. The total block cooling load for the 32-zone building was estimated to be 150 tons, while the peak block heating load was 940,000 Btu/hr (Kavanaugh 1994). Full-load heating and cooling hours were estimated at 500 and 750, respectively.

Fifty-four heat pumps of various sizes meet the heating and cooling loads at each of the schools. Table 1 presents the sizes and quantities of each heat pump installed at the four schools. Because the heat pumps at the Campbell and Maxey schools are from one manufacturer, and those at Cavett and Roper from another, there is some difference in the nominal capacities installed, but this difference is minimal and is not expected to alter building performance in any significant manner.

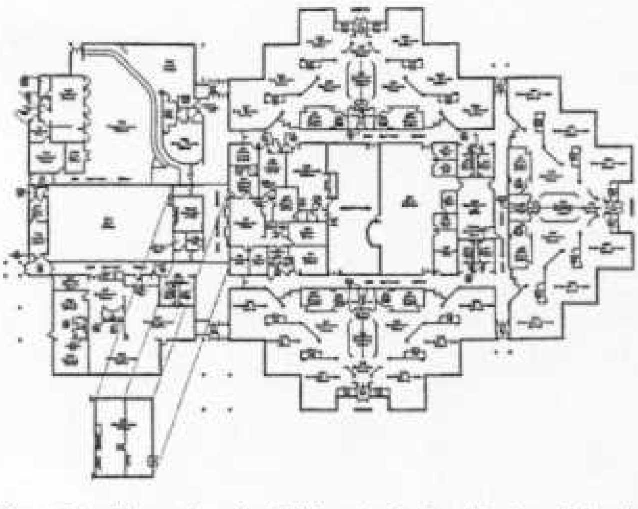

Figure 2 Floor plan for GHP schools in Lincoln, Nebraska (69,000 ft²).

The schools were designed to meet ASHRAE Standard 62-1989, which calls for at least 15 cfm of fresh air per person. At each school, pre-conditioned outdoor air is provided to classroom and office heat pump units by two nominal 15-ton heat pumps (with two 7.5 ton compressors each), located within a mechanical room. Each large unit operates on 100% outdoor air and feeds this preconditioned air into local heat pumps through two central ducts running along the schools' main corridors. Additional outdoor air is provided to assembly areas, such as the multi-purpose cafeteria and gymnasium, by a nominal 10-ton unit operating on 40% outdoor air and a nominal 4.5-ton unit with 45% outdoor air. In all outdoor air units, preheat is provided by a hot water coil when ambient temperatures fall below 40 °F. Hot water is also supplied to terminal units located in vestibules and other perimeter areas. Hot water is produced by gas-fired boilers, 4 per school, each with a capacity of 330,000 BTU/hr.

The remaining heat pumps, ranging in size from 1.4 to 4.5 nominal tons, serve individual zones: classrooms, offices, and common group study areas. For the most part, these units are located above the central corridors outside the zones they serve, and are easily accessible to maintenance personnel.

At all four schools, the heat pumps absorb and reject heat through a common loop to a bore field consisting of 120 bores arranged in a 12 by 10 pattern with 20 foot spacing. Figure 3 presents a site plan including a layout of the bore field, which is located under the school's soccer field. The bores are 240 feet deep, with diameters of 4 1/4 inches on the lower 220 feet, and 6 inches on the top 20 feet. Fine gravel pack was used to back fill the boreholes to within 10 feet of the surface, at which point a bentonite plug was provided in order to prevent groundwater contamination from the surface (in compliance with Nebraska State regulations, where a surface plug is acceptable if only one aquifer is penetrated). Fine gravel pack was judged to provide adequate pipe thermal contact because the static water level was considered to be between 20 to 40 feet (and in most instances closer to 20 feet). The loops consist of thermally-fused, 1-inch diameter high density polyethylene piping (SDR-11). At each school, approximately 10,000 gallons of water containing 22% propylene glycol are circulated through the system by a 30 horsepower pump controlled by a variable-frequency drive (VFD).

ENERGY PERFORMANCE

Total annual energy consumption per square foot is presented for each school in Table 2. Because the schools consume both natural gas and electricity, the appropriate form of energy consumption used in benchmarking analyses

TABLE 1
Schedule of Water to Air GHP Units Located at Four Lincoln Elementary Schools

Campbell and Maxey GHP Units				Cavett and Roper GHP Units			
(Manufacturer A)				(Manufacturer B)			
Unit	Quantity	Tons/Unit	Total Capacity	Unit	Quantity	Tons/Unit	Total Capacity
HP1H.1	1	1.4	1.4	HP1H.1	1	1.4	1.4
HP1H.2	4	1.4	5.6	HP1H.2	4	1.4	5.6
HP1V	1	1.4	1.4	HP1V	1	1.4	1.4
HP2H	4	2.0	8.0	HP2H	4	1.8	7.2
HP2V	2	2.0	4.0	HP2V	2	1.8	3.6
HP3H.1	1	2.0	2.0	HP3H.1	1	2.3	2.3
HP4H.1	34	3.5	119.0	HP4H.1	34	3.0	102
HP4H.2	1	3.5	3.5	HP4H.2	1	3.2	3.2
HP4V	1	3.5	3.5	HP4V	1	3.0	3.0
HP5V.1	1	4.5	4.5	HP5V.1	1	4.6	4.6
HP5V.2	1	4.5	4.5	HP5V.2	1	4.6	4.6
HP6V	1	10.0	10.0	HP6V	1	10.0	10.0
HP7V	2	15.0	30.0	HP7V	2	16.0	32.0
Total	54		197.4	Total	54		180.9

is source energy. This format accounts for the average efficiency of producing electricity from fossil fuel and delivering it to the site, assumed to be 33%. With an average annual energy consumption of 85.3 kBtu/ft^2, Campbell school is the lowest consumer of energy amongst the four GHP schools. Maximum annual consumption (at 102.7 kBtu/ft^2) occurred at Cavett in 1997.

In order to study the performance of the Lincoln GHP schools in comparison with the rest of the schools in the district, energy consumption and cost data were collected for all schools. This included 37 elementary schools, 11 middle schools, and 5 high schools. Additionally, physical characteristics on each school, such as floor area, age and number of

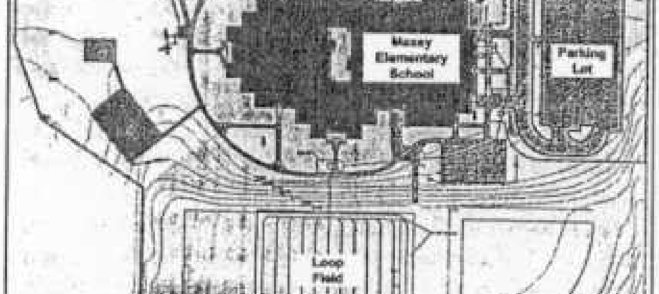

Figure 3 Site plan for Lincoln GHP schools, including bore field layout.

expansions, and HVAC system types and ages were collected. Using multiple sources of information (utility account data, 1996 and 1997 LPS billing records, facility reports, and equipment inventories) a rigorous verification of the energy and building characteristics information resulted in a qualified data set of 50 schools.

Energy costs per square foot for the four GHP schools have already been reported to be about half that of other schools in the Lincoln District (Feuerbach and Bantam 1998). Figure 4 compares the schools' average annual source energy use per square foot with that of other schools in the Lincoln school district. The data indicate that the GHP schools are exceptionally low energy users. Campbell school is the lowest: only 12% of the schools in the district use less energy per square foot. Even for the highest average energy user of the four, Maxey school, only 30% of the schools in

TABLE 2
Annual Energy Consumption (1996, 1997, and average), per Square Foot of Floor Area, for all Four Lincoln GHP Schools

School	1996 Source Energy Consumption (kBtu/ft2)	1997 Source Energy Consumption (kBtu/ft2)	Average Annual Source Energy Consumption (kBtu/ft2)
Campbell	84.7	85.8	85.3
Roper	95.9	93.5	94.8
Cavett	90	102.7	96.4
Maxey	101.4	96.1	98.2

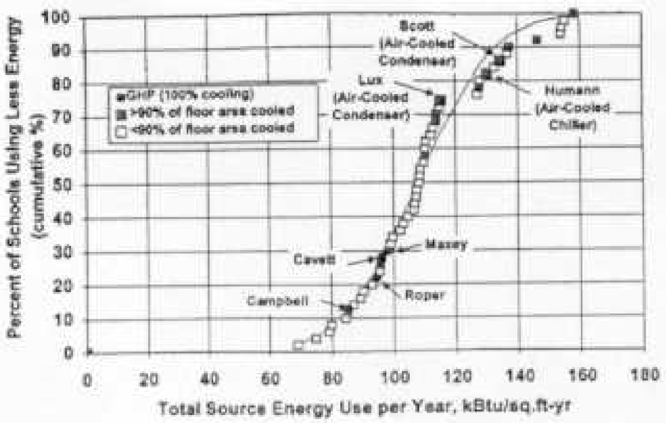

Figure 4 Distribution of average annual source energy consumption for K-12 schools located in the Lincoln Public School District (Lincoln, NE). Schools that provide space cooling to over 90% of their total floor area are identified using solid data markers. Three schools built in the 1990's, with conventional HVAC systems, are also identified.

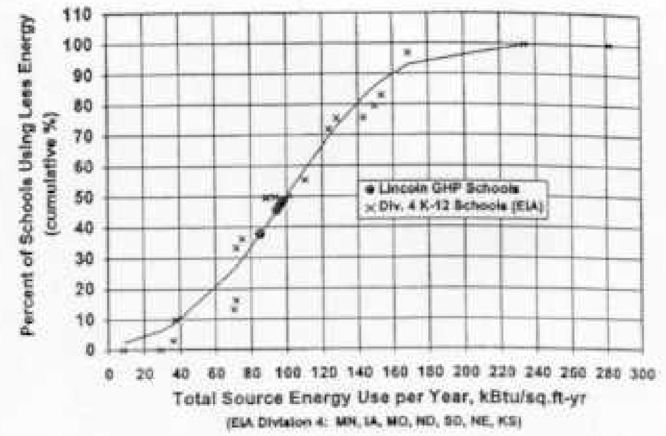

Figure 5 Distribution of average annual source energy consumption for K-12 schools located in EIA Census Division 4.

the district use less energy per square foot. These numbers are even more impressive when it is considered that most of the schools ranking below the GHP schools cool less than 15% of their total floor area (only 2 cool between 70% and 90% of their floor area). In fact, 48% of the schools in the Lincoln district cool less than 25% of their respective floor areas. Only seven schools (including the four GHP schools) air condition 100% of their floorspace. The average source energy use for schools that air condition less than 25% of their floorspace is 100.9 kBTU/ft^2; for schools that air condition more than 70% of their floorspace, the average source energy use is 120.4 kBTU/ft^2. The average annual source energy consumed by each of the four GHP schools is 93.7 kBTU/ft^2.

In addition to floor space cooled, older schools do not deliver the same levels of outdoor air per person. Figure 4 also provides a comparison of source energy use for all Lincoln schools built in the 1990's. This is useful because both the percent of floorspace cooled and ventilation air delivered are similar for the new schools. The non-GHP schools rely on either air-cooled chillers or air-cooled condensers to cool 79%–100% of their floor area. On average, the GHP schools use 26% less source energy per square foot, per year, than the non-GHP schools.

Using statistical representations of census data collected by the Energy Information Administration (EIA), Figure 5 compares the GHP schools' average annual source energy use per square foot with the energy use of elementary schools located in U.S. Census Region 4 (EIA, 1995). This region includes Nebraska, North Dakota, South Dakota, Minnesota, Iowa, Missouri, and Kansas.[1] It is evident that 37% of schools in the census region use less energy than Campbell school, while 49% use less energy than Maxey school. Further investigation into the EIA data suggests that 49% of the Region 4 schools cool less than 35% of their total floor area. Conversely, only 30% of the schools cool 100% of their buildings.

As Figure 6 indicates, the energy use of the Lincoln GHP schools compares favorably with the energy use of all elementary schools in the U.S.[2] Based on data collected from K-12 schools from across the United States (EIA, 1995), only 27% use less energy than the Campbell school, while 37% use less energy than the Maxey school. On a national basis, 49% of the schools cool 100% of their floor area, while 33% cool less than 20% of their floor area.

The variation in consumption behavior between Campbell and the other three schools is not insignificant. The drivers behind this variation in performance are more likely due to operational differences than installed equipment, or facility or environmental conditions. For instance, the heat pumps used in Campbell and Maxey were produced by a different manufacturer than those used in Cavett and Roper, so the difference does not correlate with manufacturer. Additionally, the difference does not seem to correlate to building orientation or number of portable buildings. Cavett and Roper face east, Maxey faces west, and Campbell faces south; Cavett and Roper each have two portable classroom buildings on-site as well. Finally, no strong correlation can be drawn from the small amount of data available on site soil conditions. Recent in-situ tests conducted at Campbell and Maxey estimated thermal conductivities at 1.20 $\pm$0.06 Btu/hr-ft-°F and 1.35$\pm$0.15 Btu/hr-ft-°F, respectively. This suggests that bore field heat transfer ability at Maxey is

[1]Census Division 4 includes the states of Nebraska, North Dakota, South Dakota, Minnesota, Iowa, Missouri, and Kansas. EIA data for Division 4 is based on a weighted statistical sample of 21 schools estimated by EIA to represent the entire building population of the census division (in this case 9,787 schools).
[2]EIA data for the entire U.S. is based on a weighted statistical sample of 449 schools estimated by EIA to represent the entire building population of the U.S. (162,689 schools).

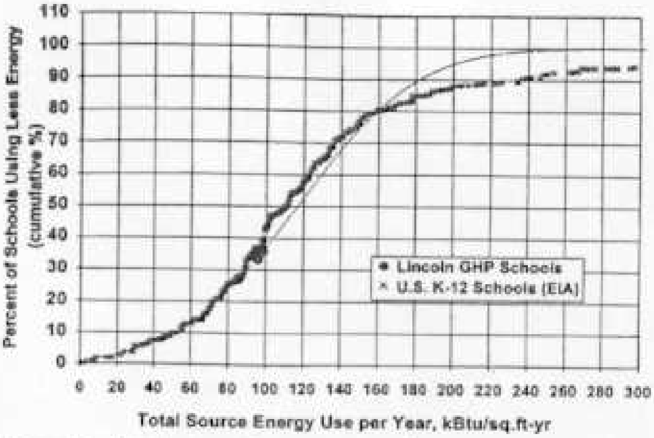

Figure 6 Distribution of average annual source energy consumption for all U.S. K-12 schools (from EIA census data). Data from 300 to 1,500 kBtu/sq. ft-yr were omitted for clarity.

higher than at Campbell; however, the overlap of the confidence intervals makes it difficult to draw any solid conclusions. Additionally, boring logs prepared for the geotechnical survey indicated that moisture content (using 120 ft bores) was highest for the soil samples collected from Campbell and Cavett schools.

In order to more closely examine the reasons for variation in performance of the four GHP schools, daily electrical consumption was studied as a function of daily average outdoor air temperature. This exercise was first attempted for the entire data set, but there appear to be significant differences in the way the four schools are operated on days when classes are not in session. It may be that temperature setback functions are not always implemented on weekends and holidays, especially during colder winter months; or that the schools are used for other purposes (adult education, community meetings, etc.) during these periods. Because of these variations it was decided to analyze the electrical energy use data for official schooldays only. Figure 7 presents the 1996 and 1997 daily electrical use for the HVAC systems (all components) of each school vs. the average temperature on that day, for regular schooldays only. All four schools show a typical profile for buildings heated and cooled by heat pumps. Daily electrical energy use for HVAC, E, for each school was fit to a function of daily average temperature, T_{avg}, of the form:

$$E = \begin{cases} E_o + m_H(T_{avg} - T_H) & \{T_{avg} < T_H\} \\ E_o & \{T_H \le T_{avg} \le T_C\} \\ E_o + m_C(T_{avg} - T_C) & \{T_{avg} > T_C\} \end{cases}$$

where E_o is the baseline daily electrical energy use (i.e. that portion of the energy use which is not dependent on outdoor temperature), T_H and T_C are the electrical heating and cooling balance temperatures respectively, and m_H and m_C are the slopes of the daily electrical energy use vs. daily temperature lines in heating and cooling modes, respectively.

The parameters for each school are presented in Table 3. The average electric heating balance point temperature of 42°F is most likely due to a number of factors: high occupancy, high interior lighting requirements, other interior loads such as computers and closed-circuit classroom monitors, and of course the existence of the outdoor air preheat coils, which are heated by natural gas. In comparing parameters from one school to the next, only E_o seems to partially explain lower energy consumption at Campbell school, (without examination of corresponding gas consumption data, which was not available). E_o for Campbell is 698.4 kWh/day, which is 5%–9% lower than the other three GHP schools.

Data for the four schools on non-HVAC-related daily electrical energy use (for lights and other electrical equipment) on school days are presented in Figure 8. The daily electrical use is seen to be fairly constant, with a slight negative correlation with outdoor air temperature. Table 4 presents the average daily non-HVAC electrical consumption, for each school. Campbell is the lowest non-HVAC consumer at 922 kWh per day, while Roper is the highest, at 1,171 kWh per day.

Because the EMS system was not programmed to collect natural gas use, the only gas data available are monthly billing records. In Figure 9, monthly (1996) natural gas use in therms is plotted against heating degree days per month, with a positive trend in consumption with increasing degree day. Annual gas consumption in 1996 was highest at Roper (15,927 therms/year) and lowest at Cavett (10,916 therms/year). This represents a nearly 45% difference in natural gas consumption. These differences are most likely due to variations in set point and setback control by the energy management systems.

EMS DATA

The energy management system located at each school is capable of collecting 10-minute data for numerous controller channels. While EMS data were collected for all schools from system initialization in 1995 through 1997, the data set collected in 1996 for Maxey was the most complete and reliable (Carlson 1998). A review of this data provides some additional insight into the operation and performance of Maxey's GHP system.

As mentioned earlier, the GHP systems at Lincoln were designed to satisfy the cooling-dominated loads expected for a schedule based on full-year operation. While some activities do occur during the summer months, Maxey generally operates on a traditional September through June schedule. As a result of this schedule shift, the actual loads exhibited by the building slightly favor heating. This is verified by loop flow rate and temperature data collected by the EMS. In 1996, the total amount of energy rejected by the ground loop was 880 MMBtu, while the total energy absorbed was 1,004 MMBtu, a 13% difference. In contrast, the original design documents indicate that, on a full-year operating basis, annual cooling loads were expected to be nearly three times the size of annual heating loads.

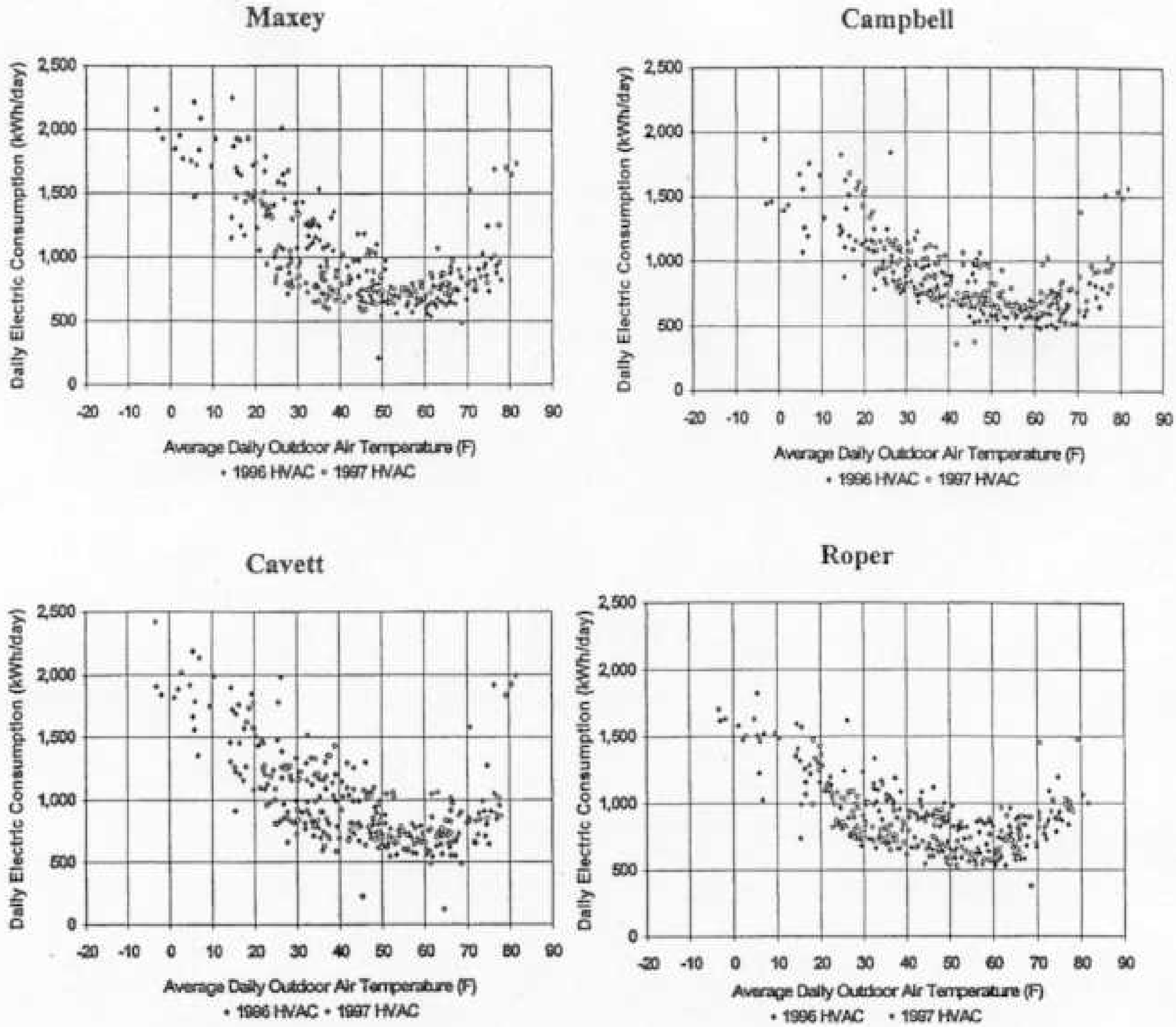

Figure 7 Daily electrical energy use by all HVAC equipment for days when classes are in session (1996–1997).

As a consequence of traditional September through June operation, the loop water temperatures entering the heat pumps never approach the cooling design temperature of 90 °F. Figure 10 illustrates the distribution of entering water temperatures (EWTs) throughout the year. According to the EMS data, loop temperatures remain below 65 °F for nearly 90% of the year. (This distribution is also impacted by the use of night time setback, during which EWTs remain relatively constant.) The maximum recorded value of EWT was 78 °F, while the minimum was 45 °F.

A 30 hp pump controlled by a variable-frequency drive varies the loop water flow to maintain supply/return differential pressure as 2-way, motorized, ball valves open and close with compressor cycles at each heat pump. According to test and balance reports and EMS data, the total loop flow through the 54 heat pumps, with all 2-way valves open, was 552 gpm. This corresponds to approximately 2.8 gpm per installed ton of capacity, rather than the maximum percent of installed capacity that operates simultaneous at peak block load (about 86.3% of installed heating capacity and 56.8% of installed cooling capacity). Figure 11 shows the distribution of loop flow rates in 1996. The maximum flow rate recorded was 552 gpm. Loop flow rates remain below 300 gpm for

TABLE 3
Curve Fit Parameters for Daily HVAC Electrical Energy Use for Four Lincoln GHP Schools

Curve fit Parameter	Maxey	Campbell	Cavett	Roper
E_0	744.7	698.4	767.5	740.2
T_H	43.10	42.61	43.32	39.26
T_C	69.95	74.38	75.10	66.10
m_H	−29.09	−21.17	−25.85	−21.17
m_C	60.20	119.1	183.59	23.97

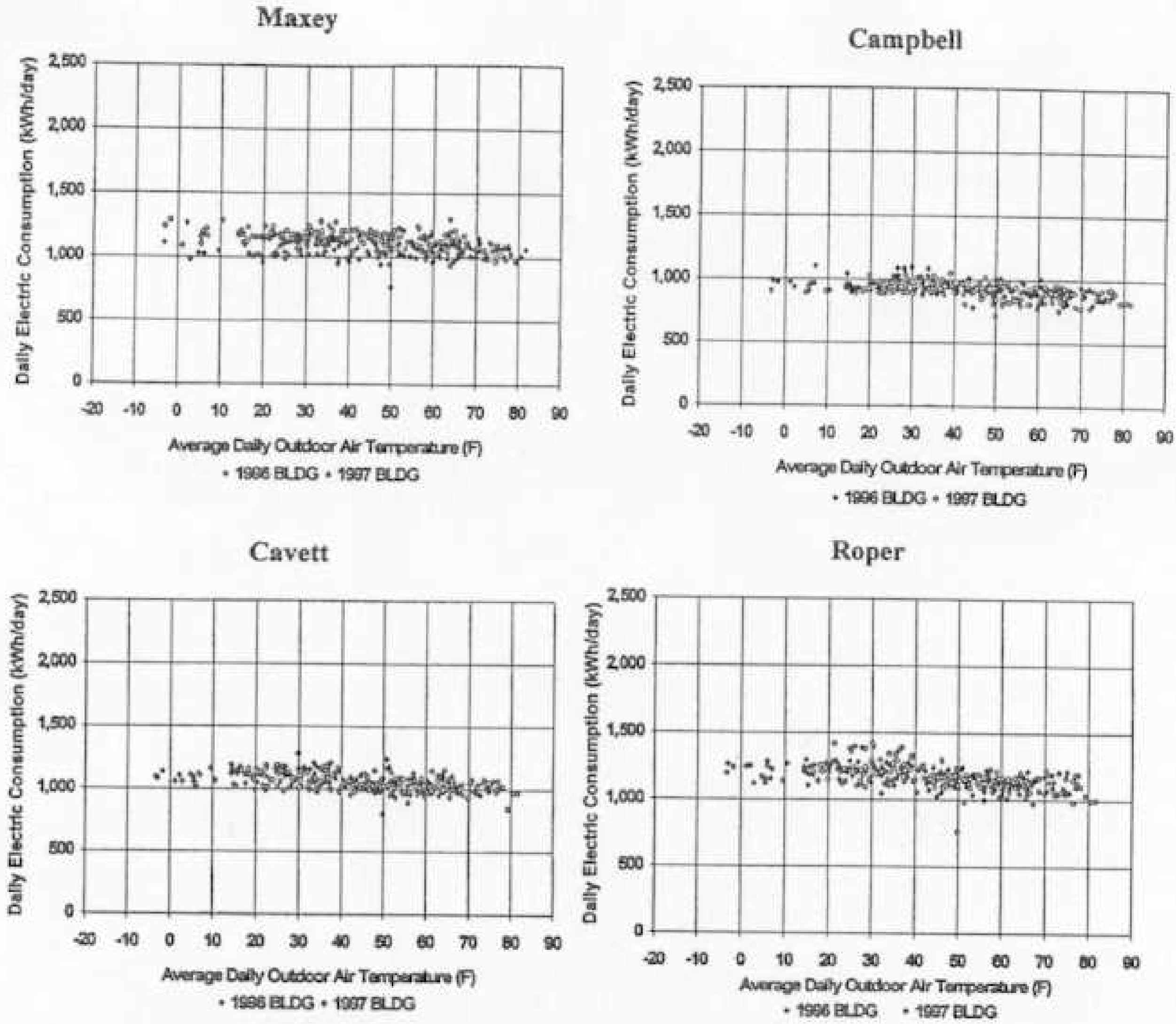

Figure 8 Daily electrical energy use by all non-HVAC equipment (lights, computers, etc.) for days when classes are in session (1996–1997).

78% of the year, and below 150 gpm for 50% of the year. Again, a night time system setback impacts this distribution with minimal after-hour flow rates and larger flow rates during recovery periods. Clearly, the potential for energy savings is significant with the use of the variable-frequency drive. Unfortunately, Lincoln reports that the packing on many of the motorized 2-way valves has failed causing variable flow operations to be halted while valves are left in the open position. EMS data confirms that flow rates for Maxey remained constant after April 1997.

TABLE 4
Average Daily Building-Related (non-HVAC) Electrical Energy Consumption by Four Lincoln GHP Schools

	Maxey	Campbell	Cavett	Roper
Average Daily Bldg-Related Electrical Consumption	1,106 kWh	922 kWh	1,057 kWh	1,171 kWh

CONCLUSIONS

Energy data collected over a two-year period indicate that the four new elementary schools located in Lincoln, Nebraska, out perform others in the school district. Of fifty schools studied, only five consume less energy than the best performing GHP school; however, these five cool less than 10% of their total floor area, while the GHP schools cool 100% of their floor area. When compared to other new schools (with similar ventilation loads), the GHP schools used approximately 26% less source energy per square foot of floor area. A variation in performance between the four

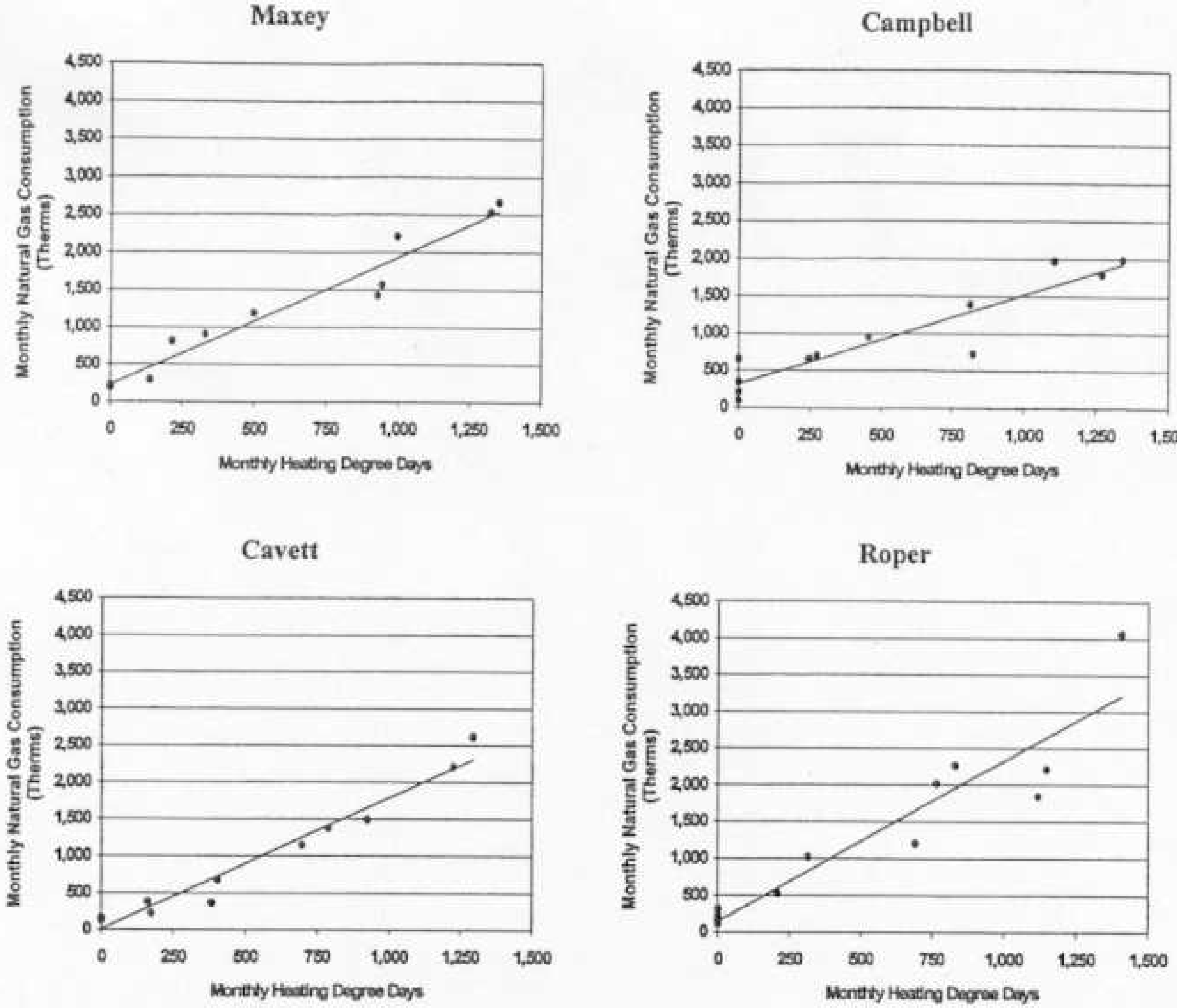

Figure 9 Monthly natural gas use versus monthly heating degree days for GHP schools (1996).

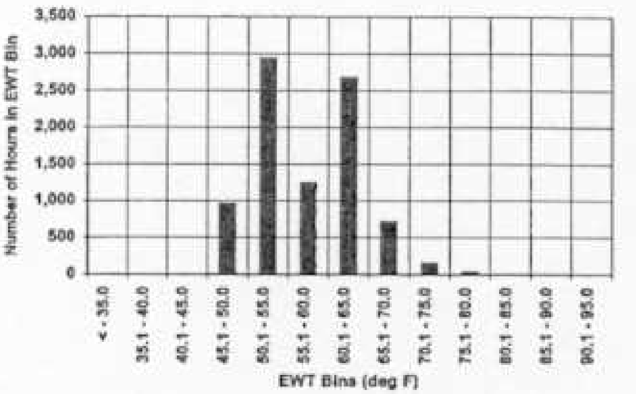

Figure 10 Distribution of 1996 heat pump entering water temperatures (EWT), as recorded by the Maxey EMS. Total hours of operation were 8,760.

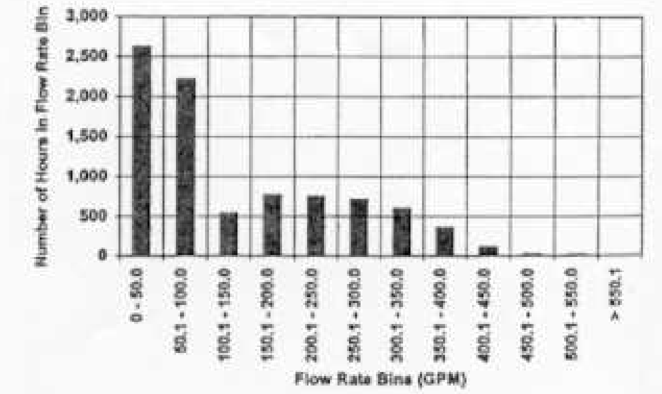

Figure 11 Distribution of 1996 loop flow rates, as recorded by the Maxey EMS. Total hours of operation were 8,760.

GHP schools is evident, and is most likely due to differences in occupancy and equipment loading and scheduling.

The data collected from the GHP schools is presently being used to study the ability of simulation tools (DOE-2, TRNSYS) to model GHP systems with vertical borehole heat exchangers. Following a validation of these models, a side-by-side comparison of vertical-bore GHPs with conventional heating and cooling systems will be performed using calibrated loads taken from the Lincoln GHP schools.

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