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Comparative Analysis of Life-Cycle Costs of Geothermal Heat Pumps and Three Conventional HVAC Systems

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ABSTRACT

Because of their low operating and maintenance costs, geothermal heat pumps (GHPs) are an increasingly popular choice for providing heating, cooling, and water heating to schools and other institutions. Recognizing these benefits, the Lincoln, Nebraska, school district in 1995 commissioned four new identical 69,000 ft^2 (6400 m^2) elementary schools served by GHPs. The decision to use GHPs was based on an analysis that compared the estimated life-cycle cost of a number of different HVAC technologies. The existence of extensive operating data from the schools' energy management systems allowed the authors to develop a calibrated simulation model that accurately predicts the energy use of all major building subsystems, including the GHPs, for one of the four schools. This model, combined with independent estimates of installed costs and actual cost information from the school district's maintenance database, allowed a more rigorous comparison of the life-cycle costs of GHPs and three other space-conditioning options. This paper presents the results of that comparison and shows that when capital, operating, and maintenance costs are considered for the Lincoln application, geothermal heat pumps have the lowest life-cycle cost, about 15% lower than the next most attractive option. The GHPs also have the lowest source energy consumption and the lowest total pollutant emissions of any of the technologies considered. For this application, geothermal heat pumps also have a lower first cost than any of the other systems currently used for space conditioning in new schools.

INTRODUCTION

In the fall of 1995, the Lincoln, Nebraska, school district opened four new elementary schools (Campbell, Cavett, Maxey, and Roper) served by geothermal heat pumps (GHPs). The schools have identical floorplans, each with approximately 69,000 square feet (6400 m^2) of space dedicated to classrooms, offices, meeting rooms, a cafeteria, and a gymnasium (the actual floor space at each school varies slightly due to differences in space usage). Each school serves approximately 500 students.

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 conceptual designs were analyzed using energy consumption inputs from simulations performed with a commercially available software package. Considering estimated capital, operating, and maintenance costs, the analysis showed the geothermal heat pumps to have the lowest life-cycle cost.

Based on our experience, pre-construction estimates of energy consumption by space-conditioning equipment may vary by 20% or more from the actual energy consumption of an occupied building. Maintenance costs are also difficult to estimate, especially for geothermal heat pumps, which do not have a long history of application in schools compared with other space-conditioning technologies. For these reasons, we decided to repeat the comparison of life-cycle costs using actual energy consumption data from the schools and maintenance costs from the school district's maintenance database.

The energy consumption data allowed us to develop a calibrated simulation model that accurately predicts hourly heating and cooling loads for one of the schools based on occupancy and ambient weather conditions. These loads were used to design three alternative conventional space-conditioning systems for the schools, and independent construction cost

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estimates were prepared for the GHP system and for the three alternatives. The calibrated simulation was then used to predict the annual energy consumption of the school in a typical year with space-conditioning loads served by each of the four system types. Actual maintenance costs for the installed geothermal heat pumps were used, and maintenance costs of the conventional alternatives were determined from the cost of maintaining similar equipment at other schools in the district. This information was used to calculate the life-cycle cost of each system.

DESCRIPTION OF THE SCHOOL AND BASELINE GHP SYSTEM

Of the four GHP schools in the Lincoln district, Maxey elementary school was chosen as the basis for this study, primarily because of the completeness of the energy consumption data available. Figure 1 is a photograph of the front entrance of the school, and a floorplan is presented in Figure 2. The total floor space of the school is 69,670 ft^2 (6472 m^2).

Space-conditioning loads in the school are met by 54 geothermal heat pumps ranging in size from 1.4 to 15 tons (4.9 to 53 kW), with a total cooling capacity of 180 tons (630 kW). Four gas-fired boilers, each with a capacity of 330,000 Btu/h (97 kW), provide hot water for pre-heating of outdoor air and to terminal heating units in vestibule areas. Humidification is provided by electric spray humidifiers, and domestic hot water for the kitchen and wash basins is provided by gas-fired hot water heaters. Introduction of outdoor air conforms to ASHRAE Standard 62-1999.

The heat pumps absorb and reject heat by way of a variable-speed pumping system to a borefield consisting of 120 vertical heat exchangers arranged in a 12-by-10 pattern with 20 ft (6 m) spacing. The bores are 4¼ in. (11 cm) in diameter by 240 ft (73 m) deep with fine gravel backfill to within 10 ft (3 m) of the surface and the remainder filled with a bentonite plug. The vertical loops consist of thermally fused SDR-11 high-density polyethylene pipe, and the heat exchange fluid is water with 22% (by volume) propylene glycol. Complete details of the system design and operation have been published in Shonder et. al. (1999).

CONVENTIONAL SPACE-CONDITIONING ALTERNATIVES

Three alternative conventional space-conditioning systems were chosen for comparison with the baseline GHP system. An important concern was to maintain consistency

Figure 1 *Maxey elementary school, Lincoln, Nebraska.*

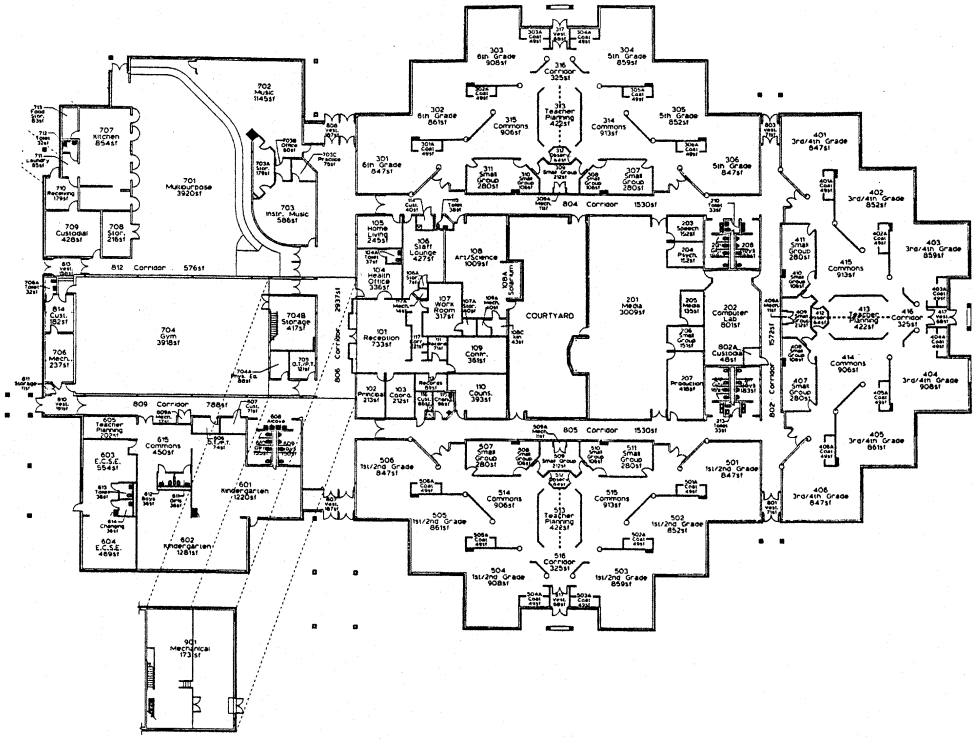

Figure 2 *Floor plan of Maxey elementary school.*

with the systems installed in other schools in the Lincoln district. At present, there is some uncertainty in the engineering community about maintenance costs for HVAC equipment in general and geothermal heat pumps in particular. A number of publications (e.g., Cane et al. 1997; Shonder and Hughes 1997; Martin et al. 1999) have appeared that indicate maintenance costs for GHPs may be considerably lower than the values given by ASHRAE (1999) for water-source heat pumps. ASHRAE is known to be reexamining the issue. To minimize the uncertainty in the life-cycle cost analysis, we decided to use actual maintenance cost data from the school district's maintenance database. This influenced the choice of the alternative systems, which are described below.

Option 1: Air-Cooled Chiller with VAV Air-Handling System (ACC/VAV)

This system consists of a central air-handling unit with filter, cooling and heating coils, and a supply air fan. A duct system distributes supply air to variable air volume terminal units located in the zones, which are identical to the zones supplied by GHPs in the baseline system. A reheat coil is included in each zone. An air-cooled centrifugal chiller with capacity of 150 tons (530 kW) and an efficiency of 1.0 kW/ton (COP = 3.57) produces 44°F (7°C) water for the cooling coils. Heating coils are supplied by a 2800 MBH (820 kW) hot water boiler with 82.5% efficiency. Terminal units in the vestibules, identical to those installed in the baseline design, are also supplied by the boiler. As in the baseline GHP design, humidification is provided by electric spray humidifiers, and gas-fired water heaters are used for domestic hot water.

Option 2: Water-Cooled Chiller with Constant Volume Air-Handling System (WCC/CV)

In this system, constant volume forced-flow heating and cooling is provided to individually controlled zones (again, identical to the zones supplied by GHPs in the baseline system installed in the school) from an air handler consisting of a filter, heating and cooling coils, and a draw through supply fan. A reheat coil is installed in the supply air distribution duct serving each zone. Chilled water at 44°F (7°C) is provided to the cooling coils by a 150 ton (528 kW) centrifugal chiller with an efficiency of 0.6 kW/ton (COP = 5.86). The cooling tower includes two-speed fan control. A 2800 MBH (820 kW) hot water boiler with 82.5% efficiency provides hot water for heating coils, vestibule units, and outdoor air pre-heating by way of variable-speed circulation pumps. As in the baseline GHP design, humidification is provided by electric spray humidifiers, and gas-fired water heaters are used for domestic hot water.

Although systems like this are no longer commonly installed in schools, it is actually the most common system in the Lincoln school district due to the age of the building stock. The extensive maintenance cost data for this type of equipment allowed us to calculate the annual rate of increase in maintenance costs, and the system was therefore included in the comparison to maintain consistency with the database.

Option 3: Water-Cooled Chiller with VAV Air-Handling System (WCC/VAV)

This system is identical to Option 1, except that the 150 ton (528 kW) chiller is water-cooled and has an efficiency of 0.6 kW/ton (COP = 5.86). Two-speed fan control is provided for the cooling tower.

DEVELOPMENT OF THE SIMULATION MODEL

The simulation model of the school was developed using the DOE-2 software, which is an hourly simulation tool used widely in the building industry to evaluate energy use and cost alternatives in building construction and associated HVAC systems (Winkelman et al. 1993). A representation of geothermal heat pump systems was introduced in 1995 in version DOE-2.1E (Gates and Hirsch 1996) and later incorporated without change into version DOE-2.2, the engine that runs PowerDOE (Gates and Hirsch 1997). Version 2.1E was used for this study.

Modeling of the school began with as-built construction plans from which construction details and material specifications were obtained for floors, walls, ceilings, and windows. Internal loads were estimated based on occupancy schedules and an on-site survey of light fixtures, computers, and other heat-generating equipment.

In parallel with this effort, 15-minute interval data on water flow rate and inlet and outlet temperatures from the borefield, collected from the school's energy management system, were used to perform an independent calibration of the borefield model in DOE-2. The actual dimensions of the installed borefield (diameter, depth, spacing, and configuration) were entered into the model, and the operation of the borefield was simulated for one year using fluid flow rate and the inlet fluid temperature to the borefield as inputs. Soil formation thermal properties (far-field temperature, thermal conductivity, and volumetric heat capacity) were adjusted until the predicted outlet temperatures matched the measured outlet temperatures in a least-squares sense for the entire year. Details of this calibration have been presented by McLain and Martin (1999).

Shonder and Beck (2000) present results from an independent, 50-hour soil formation thermal property test performed at Maxey school. In that test, the thermal conductivity was measured at 1.36 Btu/h·ft·°F (2.35 W/m·K) with a deep earth temperature of 55.7°F (13.2°C). It is important to note that the soil thermal conductivity that resulted in the best fit to the outlet water temperature data using the DOE-2 borefield model was 1.60 Btu/h·ft·°F (2.77 W/m·K), some 18% higher than the measured value. Calibrations of the borefield model in another building simulation package using the same data did in fact converge to soil properties very close to the measured values (Shonder et al. 2000). One possible reason why the DOE-2 borefield model seems to require a higher

conductivity is that the software does not allow the user to specify the borehole backfill material; effectively, the loops are assumed to be surrounded by soil. Since the thermal conductivity of the fine gravel used to backfill the bores at the site is somewhat higher than the conductivity of the soil, the algorithm in the DOE-2 model may be compensating by requiring a higher soil thermal conductivity in order to replicate the field data. Although further calibration exercises at other sites would be required to determine whether this is a general problem with the software, engineers using DOE-2 to design geothermal heat pump systems should be aware of the situation.

The building model, the calibrated borefield model, and representations of the heat pumps and associated equipment were combined to form the overall simulation model. The schedule for the 1995-1996 school year was used to model occupancy, and a year of operation was simulated using actual weather conditions for the period. Based on the initial run, minor adjustments were made to outdoor air infiltration rates and other parameters such as window shading until the annual energy use matched the monitored energy use at the site.

The utility data and EMS data included the electrical use of the space-conditioning system separately from the total electrical use. Actual electrical use by the space-conditioning systems from August 1995 to July 1996 was 322,111 kWh, whereas the calibrated DOE-2 model predicted 316,412 kWh, which is an error of less than 2%. The accuracy of the simulation is illustrated in Figure 3, which presents measured and predicted daily electrical energy use by the space-conditioning systems vs. daily average temperature.

Figure 4 presents a comparison of measured and simulated natural gas consumption per month for the study period. Since the utility data did not separate the use of gas specifically for space conditioning, this figure includes the use for domestic water heating as well. Measured gas consumption for the monitored period was 14,258 therms (1504 GJ), while the predicted consumption was 14,274 therms (1506 GJ), an error of less than 1%.

ENERGY AND WATER USE

Once the simulation was calibrated with measured data, the model was run again using typical meteorological year data for Lincoln, Nebraska, and occupancy based on the school calendar for the 1995-1996 school year. The GHPs were then replaced with each of the conventional space-conditioning systems in turn, and the simulation was repeated for the typical meteorological year. The annual gas and electric use as calculated by the DOE-2 simulations for the baseline GHP system and the three conventional alternative systems is presented in Table 1. The annual source energy use of each option (assuming 70% losses in conversion, transmission, and distribution of electricity) is presented graphically in Figure 4. The baseline GHP system installed at the school is the lowest user of energy, consuming 17% less source energy than the

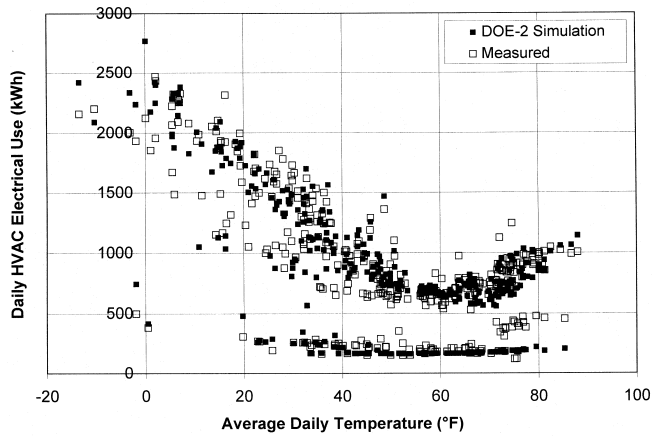

Figure 3 *August 1995-July 1996 daily energy use by geothermal heat pump system vs. daily average temperature. Simulation results and site-monitored data.*

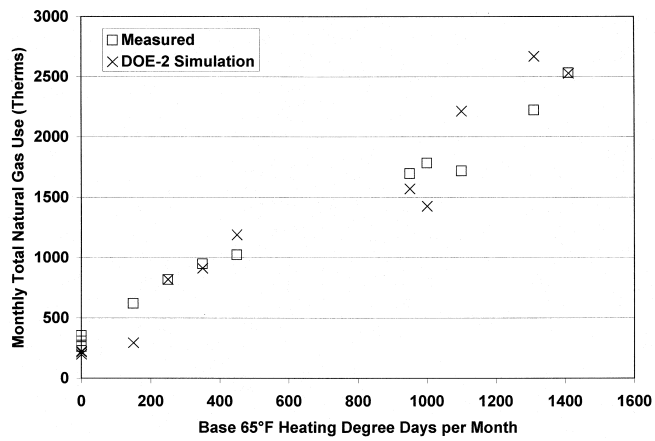

Figure 4 *August 1995-July 1996 total monthly gas use vs. base 65°F degree-days. Simulation results and site-monitored data.*

next highest system, a water-cooled chiller/gas boiler combination.

Since the DOE-2 component for the cooling towers does not calculate water loss due to evaporation, makeup and blowdown losses for Options 2 and 3 were estimated to be 2% of annual water flow. The losses are approximately 260,000 gallons (984,000 liters) per year for each system. In the life-cycle cost analysis, the cost of water and water treatment is included as an annual recurring cost for these two systems.

INSTALLED SYSTEM COSTS

The installed costs of the baseline system and the three alternatives were estimated using designs produced to meet the loads seen in the calibrated DOE-2 simulation. In general, total costs were built up from the individual costs of all system components including chillers, boilers, piping, valves, ductwork, air-handling units, controls, and electrical equipment plus installation costs, management costs, and overhead. In

TABLE 1
Annual Energy Use for Baseline GHP System and Three Conventional Alternatives*

	Baseline Geothermal	Option 1 ACC/VAV	Option 2 WCC/CV	Option 3 WCC/VAV
Electrical use				
Non-HVAC	255,807	255,807	255,807	255,807
HVAC systems	288,197	306,855	613,392	280,006
Total electrical use, kWh	**544,004**	**562,662**	**869,199**	**535,813**
Natural gas use				
HVAC systems, therms (GJ)	7535 (795)	22,648 (2389)	49,021 (5172)	22,781 (2403)
Domestic hot water, therms (GJ)	5547 (585)	5547 (585)	5547 (585)	5547 (585)
Total gas use, therms (GJ)	**13,082 (1380)**	**28,195 (2974)**	**54,568 (5757)**	**28,328 (2979)**
Source energy use, kBtu/ft^2 (kJ/m^2)	99.1(9.7)	123.5 (12.1)	206.6 (20.2)	119.7 (11.7)

*Calculated by DOE-2 simulations.

most cases, quoted prices from suppliers and manufacturers in the Lincoln area were used as the basis for the estimates. Based on current labor rates in Lincoln, Nebraska, an average rate of $20 per hour was used. General contractor total overhead was assumed to be 25% on labor and 10% on materials, and construction management fees were assumed to be 3% of the construction cost. Because the schools are government owned, the estimates did not include sales taxes. For the geothermal systems, the price for installation of the ground heat exchangers was assumed to be the actual installation cost of $5.93 per bore foot ($19.46 per bore meter) charged for the original installation. Costs for all other components of the geothermal systems were independently estimated, without reference to actual installed costs.

The cost estimates were examined by the principal of a Knoxville, Tennessee, engineering firm with extensive experience in design and cost estimating for geothermal heat pumps and other HVAC systems for schools. A number of suggestions were made to improve both the designs and the estimates (Regen 1999). Revised cost estimates were then produced based on these suggestions. The final cost estimates for the baseline geothermal system and the three conventional alternatives are presented in Table 2. Except for the constant volume system, which is no longer commonly installed in school applications, the baseline GHP system had the lowest installed cost, about 9.5% lower than the next most attractive option.

The per unit area cost estimates for the three alternative systems compares well with data presented by Means (1997), which lists a range of $9.55 to $30.55 per ft^2 ($102 to $329 per m^2) for HVAC systems installed in schools, with a national average of $21.65 per ft^2 ($233 per m^2). However, Kavanaugh and Rafferty (1998) have published information indicating that the cost to install the geothermal heat pumps in the Lincoln schools was approximately

TABLE 2
Installed Cost Estimates for the Baseline GHP System and the Three Conventional Alternatives

	Baseline Geothermal	Option 1 ACC/VAV	Option 2 WCC/CV	Option 3 WCC/VAV
Engineering				
Title I & II	$41,774	$44,664	$33,270	$45,922
Title III	$20,887	$22,332	$16,635	$22,961
Total engineering	$62,661	$66,996	$49,905	$68,883
Construction Phase				
Loop system	$170,910	$ –	$ –	$ –
HVAC system	$756,356	$1,028,792	$761,059	$1,060,944
Construction Management	$31,330	$33,498	$24,952	$34,441
Total Estimated Cost	**$1,021,257**	**$1,129,286**	**$835,916**	**$1,164,268**
Cost per ft^2 (cost per m^2)	**$14.66 (1.36)**	**$16.21 (1.51)**	**$12.00 (1.11)**	**$16.71 (1.55)**

$9.44 per ft^2 ($102 per m^2). This figure is based on costs in three broad categories reported as well-field contractor, HVAC contractor, and other fees. We were unable to determine whether the information presented by Kavanaugh and Rafferty included such components as design fees, power and control electrical wiring, and system controls as our estimate did.

MAINTENANCE COSTS

Using the Lincoln school district's database, Martin et. al. (1999, 2000) analyzed two to three years of maintenance records for 20 schools to isolate the costs associated with maintaining HVAC systems of various ages and types. Data for 16 of these schools are presented in Table 3 (4 of the 20schools used gas-fired steam boilers, which are not considered here). Of the four system types considered in the present study, there are four schools using geothermal heat pumps (the baseline system), two using air-cooled chillers and gas-fired hot water boilers with VAV air handlers (Option 1), nine using water-cooled chillers and gas-fired hot water boilers with constant volume air handlers (Option 2), and three using water-cooled chillers and gas-fired hot water boilers with VAV air handlers (Option 3).

The nine cases of systems similar to Option 2 provided sufficient data to develop a correlation between maintenance cost and system age. The data are plotted in Figure 5 and are fit to a curve of the form $c = c_0(1 + r)^{n-1}$, where c is the system maintenance cost in year n, c_0 is the first-year maintenance cost, and r is the annual rate of increase in maintenance cost. Although the data show a great deal of variation from this curve, both the first year maintenance cost of 16.6 cents per cooled square foot ($1.79 per cooled square meter) and the 1.5% annual rate of maintenance cost increase appear reasonable.

TABLE 3
Total Preventive and Corrective Maintenance Costs Per Unit Area for 16 Schools*

School Name	Cooling System Age	Air-Handler Type	Total HVAC Maintenance Cost, ¢/yr-cooled ft^2 ($/yr-cooled m^2)
Geothermal Heat Pumps			
Campbell	3	VAV	9.50 (1.02)
Cavett	3	VAV	9.57 (1.03)
Maxey	3	VAV	10.04 (1.08)
Roper	3	VAV	7.97 (0.85)
Air-Cooled Chiller and Gas-Fired Hot Water Boiler			
Belmont	5	VAV	12.77 (1.37)
Humann	8	VAV	8.09 (0.87)
Water-Cooled Chiller and Gas-Fired Hot Water Boiler			
Zeman	24	Constant Volume	13.91 (1.49)
Everett	6	VAV	10.80 (1.16)
Fredstrom	15	VAV	13.85 (1.49)
Goodrich	8	Constant Volume	21.48 (2.31)
Hill	22	Constant Volume	12.13 (1.30)
Kahoa	26	Constant Volume	18.12 (1.95)
McPhee	3	Constant Volume	18.94 (2.04)
Morley	23	Constant Volume	44.77 (4.82)
Park	8	VAV	8.28 (0.89)
Pyrtle	32	Constant Volume	42.36 (4.55)
Rousseau	2	Constant Volume	16.51 (1.78)
Bryan	26	Constant Volume	27.40 (2.95)

* From the Lincoln School District Maintenance Database

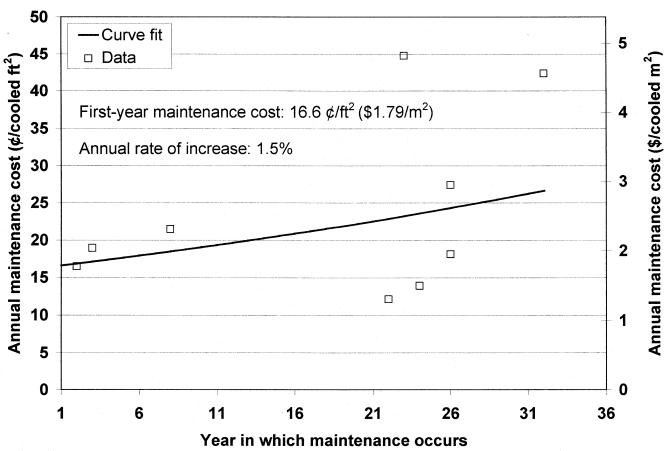

Figure 5 *Maintenance costs per unit cooled area vs. cooling system age for schools with water-cooled chiller/gas-fired hot water boiler/constant volume air distribution systems.*

Since insufficient data were available to perform similar correlations for the other three system types, the 1.5% annual rate of increase was assumed to apply for the geothermal heat pumps and for the other alternatives. For the two schools with systems like Option 1 and the three schools with systems like Option 3, the data were correlated to curves of the form $c = c_0(1.015)^{n-1}$ to determine first-year maintenance costs. For the GHP schools, the maintenance cost in year three was assumed to be the average of the maintenance costs presented for the four GHP schools; the first year maintenance cost was determined by bringing this average back to year 1 assuming a 1.5% rate of annual increase. Based on these calculations the first-year maintenance costs are as follows:

Baseline system (GHP):	9.0 ¢/ft^2 (0.97 \$/m^2)
Alternative 1 (ACC/VAV):	9.5 ¢/ft^2 (1.03 \$/m^2)
Alternative 2 (WCC/CV):	16.6 ¢/ft^2 (1.79 \$/m^2)
Alternative 3 (WCC/VAV):	9.7 ¢/ft^2 (1.04 \$/m^2)

It is recognized that these are less than half the costs reported by ASHRAE (1999) for similar system types. Data from a 1994 survey of commercial buildings performed by the Building Owners and Managers Association (BOMA 1995) are also higher than the figures above, with an average annual HVAC maintenance cost of 29 ¢/ft^2 (3.12 \$/m^2) for federal, state, and local government buildings. However, in a report prepared for a utilities company (KUC 1994) several mechanical contractors provide estimates of installation, maintenance, and operating costs of geothermal and other HVAC systems to support life-cycle cost comparisons. Here the first year maintenance costs are estimated to be from 10.0 to 10.8 ¢/ft^2 (1.08-1.16 \$/m^2) for geothermal heat pumps and from 13.0 to 45.0 ¢/ft^2 (1.40-4.84 \$/m^2) for other system types. Cane et al. (1997) report a range of 0.94 to 22.66 ¢/ft^2 (0.10-2.43 \$/m^2) and an average of 4.13 ¢/ft^2 (0.44 \$/m^2) for annual maintenance costs for a sample of 15 schools using geothermal heat pumps. The wide variation in maintenance costs reported in the literature may be due to a number of factors, including whether scheduled maintenance is performed vs. a "fix it when it breaks" philosophy, the use of contract vs. in-house labor, differences in labor and material costs across regions, and differences in accounting practices that sometime make it difficult to separate HVAC maintenance costs from other maintenance costs. Because the Lincoln database was analyzed in detail, we are confident that these figures represent the best estimate of the costs required to maintain the various system types in that particular school district.

ENERGY AND WATER COSTS

Current gas and electric costs were obtained from the local utility (LES 1998). For electricity, the school district is charged 2.5 cents per kWh and a demand charge of $8.50 per kW. There is also a customer charge of $17 per month. Gas rates are $0.493 per therm, with a $12 monthly customer charge. The life-cycle cost analysis considers only the cost of operating the space-conditioning systems since the cost of operating other equipment is the same for each option. The customer charges are not included in the analysis.

Water rates charged by the Lincoln Water System are $1.20 per thousand gallons for the first 120,000 gallons and $1.48 per thousand gallons thereafter. In the life-cycle cost analysis, makeup water for the cooling tower was assumed to be charged at the lower rate. Since the school district's maintenance database includes the costs of boiler water treatment and cooling tower water treatment as a maintenance item, these costs are accounted for as necessary in the annual maintenance cost used for each system type.

LIFE-CYCLE COST ANALYSIS

Once all initial and recurring costs were determined for the baseline GHP system and the three conventional alternatives, the life-cycle cost of each one was calculated using the BLCC software (NIST 1995a) for a 20-year system life. In accordance with NIST guidelines for life-cycle cost analysis (NIST 1995b), BLCC calculates present value in constant dollars, using the current (1999) U.S. Department of Energy (DOE) real discount rate of 3.1% based on the long-term Treasury Bond rates (net the inflation rate, which currently stands at approximately 2.5%) averaged over the 12-month period from April 1998 to March 1999.

The life-cycle cost analysis considered only the gas and electricity (both demand and energy) used by the space-conditioning systems. Since the energy use of all non-HVAC loads is identical across the four simulations, this does not affect the comparison. To determine future gas and electric rates, BLCC uses energy price escalation rate projections from the Energy

Information Administration. The current projections were published in April of 1999 (NIST 1999).

Maintenance costs for all systems were assumed to increase at an annual rate of 1.5% above the inflation rate, as determined from the database. The cost of water (for the two systems that include cooling towers) was assumed to rise only at the general rate of inflation.

The systems were assumed to have no salvage value at the end of their 20-year life. All calculations begin with a base date of 1/2000, when the systems are assumed to be installed and begin operation. End-of-year discounting was used throughout the analysis.

Table 4 summarizes the inputs for the BLCC analysis of the baseline GHP system and the three conventional systems, as well as their life-cycle costs. Of the four systems analyzed for this application, the geothermal heat pump system has the lowest life-cycle cost, which is $1,498,835 over the 20-year life of the system. The next most attractive option, the VAV system with a water-cooled chiller/gas hot water boiler combination, has a life-cycle cost about $230,000 higher—or about 15% higher—than the life-cycle cost of the GHP system. There is only a small difference in life-cycle cost (less than 1%) between the two VAV systems that use water-cooled and air-cooled chillers. The system with the lowest first cost (the constant volume system) has the highest life-cycle cost of all the options examined, about 26% higher than the life-cycle cost of the GHP system.

POLLUTANT EMISSIONS

Life-cycle pollutant emissions for the four technologies, as calculated by BLCC using U.S. average emission factors, are presented in Table 5. In terms of carbon emissions, geothermal heat pumps are the lowest producer of pollutants. Over the 20-year life of the equipment, GHPs produce

TABLE 4
Summary of Inputs and Outputs from BLCC for the Four Systems

	Baseline Geothermal	Option 1 ACC/VAV	Option 2 WCC/CV	Option 3 WCC/VAV
Initial Cost	**$1,021,257**	**$1,129,286**	**$835,916**	**$1,164,268**
First year maintenance cost	$7,383	$7,824	$13,651	$7,928
First year electric cost	$22,138	$23,037	$34,152	$19,448
First year gas cost	$3,533	$10,963	$23,944	$11,034
Water cost			$385	$385
Total Annual O&M Costs	**$33,054**	**$41,824**	**$73,826**	**$38,795**
Life-Cycle Cost	**$1,498,835**	**$1,734,327**	**$1,912,297**	**$1,728,736**

TABLE 5
Life-Cycle Emissions in Pounds (Kilograms) for Baseline GHP and Three Conventional Alternatives, Using U.S. Average Emission Factors

	Baseline Geothermal	Option 1 ACC/VAV	Option 2 WCC/CV	Option 3 WCC/VAV
Electricity				
CO_2	12,320,000 (5,587,000)	13,118,000 (5,949,000)	26,222,000 (11,892,000)	11,970,000 (5,429,000)
SO_2	39,500 (18,000)	42,000 (19,070)	84,000 (38,000)	38,000 (17,000)
NO_x	37,000 (17,000)	40,000 (18,000)	79,000 (36,000)	36,000 (16,000)
Natural Gas				
CO_2	1,673,000 (759,000)	5,190,000 (2,354,000)	11,335,000 (5,140,000)	5,223,000 (2,369,000)
SO_2	7 (3)	20 (9)	44 (20)	20 (9)
NO_x	1300 (590)	4000 (1800)	8800 (4000)	4000 (1800)
Total				
CO_2	13,993,000 (6,346,000)	18,308,000 (8,303,000)	37,557,000 (17,032,000)	17,193,000 (7,798,000)
SO_2	39,500 (18,000)	42,000 (18,000)	84,000 (38,000)	38,000 (17,000)
NO_x	38,000 (18,000)	44,000 (20,000)	88,000 (39,829)	40,000 (18,000)

437 equivalent tons of carbon less than the next highest producer, Option 3. Geothermal heat pumps also produce about 1700 pounds less NO_x than Option 3 over the equipment life. However, the analysis indicates that geothermal heat pumps produce a small amount more of SO_2 than the equipment of Option 3. This is due to the fact that while the GHPs use 17% less source energy than the water-cooled chiller/gas-fired boiler combination, they do use slightly more electricity (about 1.5%).

DISCUSSION AND CONCLUSIONS

The objective of this paper was to use site-monitored energy use data, actual maintenance cost data, and independent, consistent installed cost estimates to determine the life-cycle cost of geothermal heat pumps and three alternative conventional space-conditioning systems for an elementary school in Lincoln Nebraska. The results show that the geothermal heat pump system installed in the four Lincoln schools has a lower life-cycle cost than other space-conditioning systems commonly used in the school district would have had in the same application, saving about $235,000 over the next most attractive option for a 20-year system life. Except for one system no longer commonly installed in schools, geothermal heat pumps have the lowest first cost as well. The geothermal heat pumps also have the lowest annual operating and maintenance costs of all the systems analyzed and the lowest consumption of source energy.

Maintenance costs for all four system types were determined from the school's maintenance database. From a sample of nine systems, the annual rate of increase in maintenance costs was determined to be 1.5%. As Figure 5 indicates, there was a great deal of variation in this small sample. To determine the effect of a higher rate of cost increase, the life-cycle cost analysis was repeated using a rate of 3%. Life-cycle costs of the baseline GHP system and Options 1, 2, and 3 increased by 1.4%, 1.2%, 2.2%, and 1.5%, respectively, but the ranking of the options did not change. Thus, the rate of maintenance cost increase has only a small effect on life-cycle cost for this analysis.

A discount rate of 3.1% was used in the study to maintain consistency with DOE guidelines. This rate is based on the long-term yield of U.S. Treasury bonds, but school construction projects are commonly financed with tax free municipal bonds. A survey of 20-year school bonds in the state of Nebraska (see Bonds in reference list) shows their average rate of return to be 5.65%, which corresponds to a real discount rate of 3.15%. Thus, the use of the DOE discount rate appears warranted.

Because system renovation costs involve even greater uncertainty than first cost, we did not attempt to carry the analysis past 20 years. No salvage value was assumed for any of the systems at the end of this period, but it is likely that the geothermal heat pump system would have some salvage value if the decision were made to install similar equipment. The loops that exchange heat with the borefield are warranted for 50 years and would not have to be replaced. On the other hand, centrifugal chillers generally have a useful life longer than 20 years, so the conventional systems would have some salvage value as well. Further analysis would be required to determine renovation costs, but we feel that they would not significantly affect the life-cycle cost comparison.

Table 4 clearly shows that the installed cost of the space-conditioning systems is the most important parameter in the life-cycle cost analysis. Although every effort was made to produce accurate, complete, and consistent cost estimates for the four systems, we recognize that different estimators might produce estimates that differ from ours, perhaps by as much as 5%. Nevertheless, we are confident that the figures presented here provide an accurate comparison of the four systems. The figures show that for school districts such as the one in Lincoln Nebraska, geothermal heat pumps offer clear advantages in first cost, operating and maintenance costs, and life-cycle cost. Also, given their lower source energy consumption and reduced pollutant emissions, the technology offers further advantages for the nation as a whole.

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NOMENCLATURE

Abbreviations

ACC = air-cooled chiller

ASHRAE = American Society of Heating, Refrigerating and Air-Conditioning Engineers

BLCC = building life-cycle cost computer program

BOMA = Building Owners and Managers Association

CV = constant volume air-handling system

DOE = U.S. Department of Energy

GHP = geothermal heat pump

HVAC = heating, ventilating, and air conditioning

LCC = life-cycle cost

NIST = National Institute of Standards and Technology

VAV = variable air volume air-handling system

WCC = water-cooled chiller

Symbols

c = annual maintenance cost per unit area

c_0 = first year maintenance cost per unit area

r = annual rate of increase of maintenance cost per unit area

n = year in which maintenance cost occurs

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