

# Update on Maintenance and Service Costs of Commercial Building Ground-Source Heat Pump Systems

**Douglas Cane, P.Eng.**  
Member ASHRAE

**Jeremy M. Garnet**

## ABSTRACT

*An earlier paper showed that commercial ground-source heat pump systems have significantly lower service and maintenance costs than alternative HVAC systems. This paper expands on those results by adding 13 more buildings to the original 25 sites and by comparing the results to the latest ASHRAE survey of HVAC maintenance costs. Data from the 38 sites are presented here including total (scheduled and unscheduled) maintenance costs in cents per square foot per year for base cost, in-house, and contractor-provided maintenance. Because some of the new sites had maintenance costs that were much higher than the industry norm, the resulting data are not normally distributed. Analysis (O'Hara Hines 1998) indicated that a log-normal distribution is a better fit; thus, the data are analyzed and presented here as log-normal. The log-mean annual total maintenance costs for the most recent year of the survey ranged from 6.07 cents per square foot to 8.37 cents per square foot for base cost and contractor-provided maintenance, respectively.*

## INTRODUCTION

Ground-source heat pump systems significantly reduce energy bills in commercial buildings. In a recent report (ASHRAE 1995) buildings with ground-source heat pump systems had average total energy bills of 97 cents per square foot compared to 117 cents per square foot for the same buildings with conventional systems.

Earlier work (Cane et al. 1998) strongly suggested that ground-source heat pump systems also can have significantly lower service and maintenance costs compared to alternative HVAC systems. The combined energy and maintenance savings associated with ground-source heat pump systems in

commercial buildings mean a faster payback, offsetting the higher first cost. Recognition of this would significantly improve the competitive position of ground-source heat pump systems and build the confidence and acceptance of design teams and potential end users.

This paper updates the results of an earlier survey to include 13 additional sites. Thus, a total of 38 commercial and institutional buildings with ground-source heat pumps systems throughout the United States and Canada were surveyed. The results are compared with data on other HVAC systems selected from the recently completed ASHRAE Research Project 929 (ASHRAE 1999).

## THE SURVEY

### Data Collection

The survey consisted of two approaches:

- A detailed two-part survey document was prepared. The first part consisted of a fax letter sent to buildings known by the investigators to have ground-source heat pump systems asking whether building personnel were willing to participate in the survey. Where agreement was obtained by return fax, a second detailed questionnaire was forwarded for their completion. Considerable follow-up was required to encourage these sites to complete the package;
- A parallel activity was launched involving site visits to the headquarters of a school district in Ontario, Canada, and a similar visit to an engineering contracting company serving the northeastern United States. In this phase, detailed service and maintenance cost data were gathered on a total of six schools and another nine commercial/multi-unit residential ground-source systems.

---

**Douglas Cane** is a principal research engineer and **Jeremy Garnet** is an associate research scientist with Caneta Research Inc., Mississauga, Ontario, Canada.

## Survey Questionnaire and Approach

The detailed survey questionnaire included a preamble explaining the importance of the survey to the ground-source heat pump industry, how the information would be ultimately published, and offering assistance to help with the data extraction, if needed. Financial support was also offered to offset reasonable costs incurred in assembling the data.

The survey questionnaire was designed to collect the following items of data:

- Contact information
- Ground-source system and building information, including: type of systems, type of building, location, building and system size, year installed, service provider(s)
- Scheduled and unscheduled maintenance activities, materials, and components
- Labor, material, and equipment costs for the identified scheduled and unscheduled maintenance, service, and repair

The survey questionnaire defined what was meant by ground-source heat pump system components and also provided definitions for the maintenance, service, and repair activities. These are defined as follows:

- *Ground-source heat pump system components* were defined to include heat pumps and their components, controls, zone thermostats, air filters, duct connections, ventilation units, electrical supply wiring and disconnects to the heat pumps, pressure/temperature ports, hose kits, supply/return piping, antifreeze, valves and drainouts, manual or automatic air vents, central pumps and associated valves, air separator, blowdown drains, strainer, expansion tank, fill or makeup liquid line, supply and return headers, ground heat exchanger or water wells, pumps, plate-frame heat exchanger or pond-loop heat exchanger.
- *Scheduled maintenance*—preventative and corrective activities that are planned, budgeted, and scheduled.
- *Unscheduled maintenance*—maintenance activities that were not planned, budgeted, or scheduled but were undertaken to correct conditions of impending failure.
- *Service*—an action, not involving component repair or replacement, triggered by failure, to restore operation.
- *Repair*—an action involving component or equipment repair or replacement, following failure, to restore operation.

### Site Visits to School District/ Mechanical Contracting Firm

The two multiple-site data gathering trips involved reviewing and gathering information from accounting files, work orders, invoices, and discussions with maintenance and service supervisors and staff. The data were entered into the

detailed survey questionnaire database with the other data and analyzed.

## ANALYSIS OF SURVEY DATA

### Characteristics of the Sample

Tables 1, 2, and 3 summarize building locations, occupancy type, and characteristics. The sample consisted of 38 buildings located in the Northeast (13), Midwest (4), South (4), and West Coast (1) of the United States and four provinces in Canada (total 16). Specific state/province locations are identified in Table 1.

The building type or occupancy (Table 2) was dominated by schools (16) and offices (13), followed by multi-family residential (4), warehouses (2), restaurants (2), and an ice arena (1).

**TABLE 1**  
**Locations of Buildings**

Region	State/Prov.	Number
N.E. United States	New York	1
	New Jersey	3
	Connecticut	1
	Pennsylvania	7
	Maryland	1
Midwest	Ohio	2
	Minnesota	1
	Indiana	1
Southern U.S.	Missouri	2
	Virginia	1
	Arkansas	1
West Coast	Oregon	1
Canada	Manitoba	1
	Ontario	11
	New Brunswick	1
	Nova Scotia	3

**TABLE 2**  
**Building Type**

Type	Number
School	16
Office	13
Multi-residential	4
Warehouse	2
Restaurant	2
Arena	1

**TABLE 3**  
**Building Characteristics**

	<b>Mean</b>	<b>Median</b>	<b>Minimum</b>	<b>Maximum</b>
<b>Floor area</b>	61604	32000	750	420000
<b>Age of system</b>	1990 (8 years)	1991 (7 years)	1995 (3 years)	1972 (26 years)
<b>Age of reported data (years since installation)</b>	5.6 years	5 years	1 year	24 years
<b>Heats pumps per building, Total Number—2238</b>	59	23	1	527
<b>Tons per 1000 ft<sup>2</sup></b>	2.7	2.5	1	5.5
<b>Tonnage, Total—6279</b>	165	77.5	2.5	1118
<b>Tons per heat pump</b>	5.8	3.2	1.1	60

Table 3 summarizes a number of important characteristics of the sample buildings. Floor area ranged from 750 to 420,000 square feet, with a median floor area of 32,000 square feet and an average floor area of 61,604 square feet. The ground-source heat pump systems had been installed as many as 24 years earlier, with one system completing only its first year of operation. The average age of the buildings in the sample was 5.6 years, 0.7 years more than the median. There were a total of 2238 individual heat pumps in the 38 buildings, ranging from only one unit (three sites) to as many as 527 heat pumps in a large retirement community. Installed heat pump tonnage averaged 2.7 tons per 1000 square feet, for a total of 6279 tons over the 38 projects. Table 4 provides details on the individual sites and also indicates the system type (groundwater or closed-loop). In the sample there are 31 sites with closed-loop systems and 7 with groundwater systems.

To account for the geographical variation of labor and equipment cost, the data for each site were divided by the appropriate location factor to normalize the result to the U.S. national average. This was done using the location factors given by Means (1998). Since these factors represent Canadian currency for the Canadian locations, exchange factor effects between the US and Canadian dollar are taken care of automatically. Results specific to a given location can then be obtained by multiplying the values given in this report by the appropriate location factor from Means (1998).

The results (Tables 5 to 13) indicate a considerable range in the maintenance costs from site to site (see minimum and maximum values). An analysis (O'Hara Hines 1998) indicated that the distribution is not normal but more closely fits a log-normal distribution. The log-mean is, therefore, included in these tables instead of the normal mean and standard deviation. For a log-normal distribution, the variation in the data is given by the confidence interval rather than by the standard deviation. For the total maintenance costs, averaged over all years for all buildings where the labor is in house, the data have a confidence interval of 5.682 to 11.583 for a confidence level of 95%. Note that the log-mean has a value similar to that of the median.

### **Total Maintenance and Repair Costs— Averaged Over All Years**

Of the 38 buildings reported, only 5 used an outside contractor for service. In the remaining cases, inside service and maintenance staff were used. In the latter cases, the labor cost incurred was merely the workers' wages and fringe benefits. This is termed the "Base Cost" in Table 5, which summarizes the base cost data, as gathered in the survey, averaged over all years, by building type in cents per square foot. Most respondents with in-house labor indicated a labor rate of approximately \$26 per hour.

A more appropriate labor rate to use for inside workers should include some measure of overhead and additional benefits in addition to wages and fringe benefits. Means (1996) reports an average of 36% of base wages to cover the overhead and additional benefits of in-house labor. Table 6 presents the total maintenance costs averaged over all years by building type. The table uses a 36% modifier to account for both overhead and additional benefits in addition to the base wages in Table 5.

Where an outside contractor performs the service and maintenance, Means (1996) suggests an average of 66% of base wages to cover overhead, benefits, and profit. Table 7 presents the total (labor plus material) maintenance cost from the summary, averaged over all years by building type, for the case of a 66% modifier to account for contractor overhead, benefits, and profit in addition to the wages reported in the survey.

The division of the data by building type indicates that the costs for offices were substantially higher than those for other building types. Although there are more groundwater (rather than closed-loop) systems in this group than in the others (see Table 4), there is no clear correspondence between groundwater systems and high maintenance costs within the office building subgroup itself. This indicates that the high costs probably are associated with organizational factors rather than technical differences among systems. In other words, private organizations (e.g., offices) may be more likely to spend on maintenance than public institutions (e.g., schools). This is reinforced by the fact that several of the offices had unnecessarily elaborate scheduled maintenance schemes. All this

**TABLE 4**  
**Detailed Characteristics of Survey Sites**

<b>Building Type</b>	<b>Location</b>	<b>Tonnage</b>	<b>Size (ft<sup>2</sup>)</b>	<b># of H.P</b>	<b>Year Inst.</b>	<b>Groundwater (GW) or Closed-Loop (CL)</b>
School	Ontario	93	52000	31	1991	CL
School	Ontario	81	42000	27	1992	CL
School	Ontario	69	37000	23	1991	CL
School	Indiana	250	89000	74	1994	CL
College	New York	101	21910	91	1995	CL
School	Oregon	60	57915	1	1981	GW
Office	Ohio	94	25620	19	1994	CL
School	Minnesota	284	83000	94	1995	CL
School	Arkansas	90	42585	34	1993	CL
School	Ontario	105	40000	38	1992	CL
School	Ontario	74	39000	24	1992	CL
School	Ontario	81	32000	23	1991	CL
School	Ontario	65	32000	20	1993	CL
School	Ontario	41	34000	11	1992	CL
School	New Jersey	412	110000	36	1990	CL
Restaurant	Pennsylvania	36	6500	6	1987	CL
Retirement home	Pennsylvania	840	420000	316	1990	CL
School	New Jersey	59	24000	21	1988	CL
Office	Pennsylvania	252	104000	43	1990	CL
Retirement home	Pennsylvania	89	25000	76	1990	CL
Retirement home	Pennsylvania	1118	390000	527	1990	CL
Multi-residential	Pennsylvania	194	88000	74	1990	CL
Office	Maryland	120	38410	23	1995	CL
Warehouse	Missouri	33	13000	8	1989	CL
Hangar	Missouri	40	18000	4	1987	CL
Office	Connecticut	1094	265000	476	1972	GW
Office	Ohio	58	15719	28	1991	CL
Office	Virginia	101	26688	23	1993	GW
Office	Nova Scotia	2.5	750	1	1991	CL
Arena	Manitoba	150	83370	14	1990	GW
Office	Pennsylvania	42	17500	17	1993	CL
Club house	Ontario	28	18000	3	1992	GW
Office	Ontario	40	20000	10	1993	CL
Office	Ontario	15	5000	1	1988	CL
Office	New Brunswick	12	4660	4	1989	GW
Office	Nova Scotia	8.5	5120	6	1991	CL
School	New Jersey	35	10200	8	1991	CL
Office	Nova Scotia	12	4000	3	1992	GW

**TABLE 5**  
**Total Maintenance Costs Averaged over all Years by Building Type**  
**(Base Costs as Given in Survey)**  
**(Cents per Square Foot)**

	Number of Buildings	Median Cost	Minimum Cost	Maximum Cost	Log-Mean
All buildings	38	7.44	0.73	87.78	6.73
Schools	16	3.92	0.73	12.31	3.46
Offices	13	12.88	2.91	87.78	15.88
Residence/retirement homes	4	9.29	4.72	12.02	8.37
Other	5	4.73	1.60	13.19	5.12

**TABLE 6**  
**Total Maintenance Costs Averaged Over All Years by Building Type**  
**(In-house labor costs modified to account for benefits)**  
**(Cents per Square Foot)**

	Number of Buildings	Median Cost	Minimum Cost	Maximum Cost	Log-Mean
All buildings	38	8.97	0.80	114.36	8.11
Schools	16	4.94	0.80	15.87	4.16
Offices	13	16.88	3.87	114.36	18.75
Residence/retirement homes	4	12.23	6.13	15.59	10.93
Other	5	5.45	1.95	17.32	6.13

**TABLE 7**  
**Total Maintenance Costs Averaged Over All Years by Building Type**  
**(Contractor O&P labor costs modified to account for contractor overhead and profit)**  
**(Cents per Square Foot)**

	Number of Buildings	Median Cost	Minimum Cost	Maximum Cost	Log-Mean
All buildings	38	10.31	0.85	136.50	9.21
Schools	16	5.38	0.85	18.91	4.71
Offices	13	20.44	4.68	136.50	21.01
Residence/retirement homes	4	14.68	7.30	18.56	13.07
Other	5	6.05	2.23	20.76	6.96

points to the need for maintenance guidelines that the industry can use as a standard.

Table 8 gives the total maintenance costs averaged over all years by system type (groundwater versus closed-loop). Although the number of sites is small, the table still indicates a somewhat higher log-mean maintenance cost for groundwater systems.

**Total Maintenance and Repair Costs—  
Most Recent Year**

One goal of the survey and analysis was to allow comparison between the total maintenance costs of the ground-source heat pump systems and data from competing HVAC systems. ASHRAE (1999) recently supported such an undertaking in a survey of 351 individual facilities and 11 chain store organi-

zations. Of the 351 individual sites, total maintenance cost data are given for different HVAC cooling equipment types for the sites that have in-house HVAC maintenance personnel (294 sites). Table 9 presents a comparison of the total maintenance and service costs from the current study (for the most recent year) with the ASHRAE data for selected competing HVAC systems. The most recent complete year for the present survey as a whole is 1996, and this year was chosen, therefore, as the most recent year (except for one site where the 1997 results were used due to insufficient data for 1996).

The ASHRAE (1999) sample systems are, on average, older than the ground-source systems analyzed in the present study. The ASHRAE study indicates that systems installed before 1950 have 3.6 times the median maintenance cost of systems installed in 1990 or later. This suggests that equip-

**TABLE 8**  
**Total Maintenance Costs Averaged Over All Years by System Type**  
**(Cents per Square Foot)**

	Number of Buildings	Median Cost	Minimum Cost	Maximum Cost	Log-Mean
<i>Base Cost</i>					
Groundwater	7	7.75	1.95	38.37	9.05
Closed-loop	31	6.98	0.73	87.78	6.30
<i>In-house labor</i>					
Groundwater	7	8.61	1.95	50.08	10.07
Closed-loop	31	9.33	0.80	114.36	7.72
<i>Contractor O&amp;P</i>					
Groundwater	7	9.33	1.95	59.85	10.86
Closed-loop	31	11.28	0.85	139.50	8.87

**TABLE 9**  
**Comparison of Total Maintenance Costs\***  
**(Cents per Square Foot)**

Current Study							
Type of Equipment	No. of Buildings	Average Age of System	Log-Mean Cost	Median Cost	Minimum Cost	Maximum Cost	Standard Deviation
Ground-source heat pump—Base	38	5.6	6.07	6.60	0.00	137.57	n/a
In-house	38	5.6	7.35	8.43	0.00	179.37	n/a
Contractor O&P	38	5.6	8.37	10.18	0.00	214.20	n/a
ASHRAE RP-929 (ASHRAE 1999)							
Type of Equipment	No. of Buildings	Average Age of System <sup>†</sup>	Mean Cost	Median Cost	25th Percentile Cost	75th Percentile Cost	Standard Deviation
Water-source heat pump	23	-	63.27	45.00	17.20	73.10	76.44
Packaged air-to-air heat pump	10	-	39.51	27.00	17.00	49.60	33.85
Split system heat pump	10	-	34.47	35.10	25.20	41.50	14.73
Reciprocating chiller	99	-	56.03	35.10	18.20	68.00	84.36
Open drive centrifugal chiller	29	-	49.58	43.70	26.90	61.50	35.03
Hermetic centrifugal chiller	33	-	40.73	18.90	8.60	45.30	58.57
High-pressure centrifugal chiller	33	-	43.14	29.30	18.40	42.60	50.79
Low-pressure centrifugal chiller	59	-	38.30	35.10	21.30	49.20	26.28
Single-stage absorption chiller	20	-	41.73	37.20	26.80	42.65	25.86
Two-stage absorption chiller	6	-	31.72	33.95	22.30	37.00	8.77
Direct-fired absorption chiller	6	-	86.02	54.95	39.20	97.10	82.41

\* From the most recent year of the present study and for select systems from ASHRAE RP-929 (ASHRAE 1999).

† Age is not given for specific equipment type in the ASHRAE study.

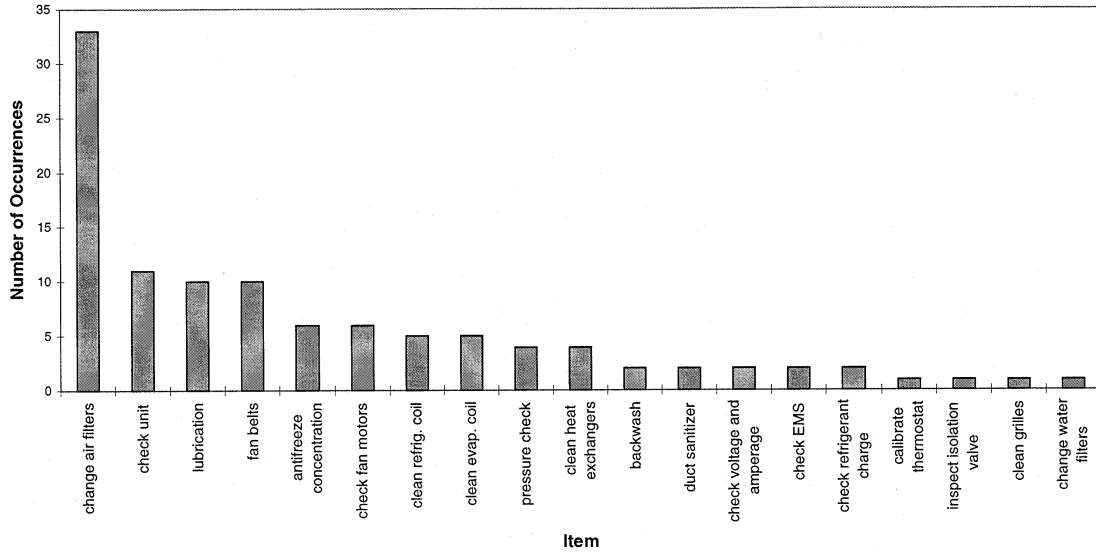


Figure 1 Reported scheduled maintenance tasks.

**TABLE 10**  
Scheduled Maintenance Costs Averaged Over All Years (Cents per Square Foot)

	Median Cost	Minimum Cost	Maximum Cost	Log-Mean
Base data	1.34	0.00	62.91	1.82
In-house wage multiplier (36%)	1.64	0.00	85.55	2.23
Contractor wage multiplier (66%)	1.94	0.00	104.42	2.55

**TABLE 12**  
Unscheduled Maintenance Costs Averaged Over All Years (Costs per Square Foot)

	Median Cost	Minimum Cost	Maximum Cost	Log-Mean
Base data	3.98	0.00	96.60	3.67
In-house wage multiplier (36%)	4.79	0.00	110.74	4.38
Contractor wage multiplier (66%)	5.31	0.00	122.52	4.89

**TABLE 11**  
Scheduled Maintenance Costs Reported for the Most Recent Year of the Survey (1996) (Cents per Square Foot)

	Median Cost	Minimum Cost	Maximum Cost	Log-Mean
Base data	1.10	0.00	65.60	1.15
In-house wage multiplier (36%)	1.40	0.00	89.22	1.40
Contractor wage multiplier (66%)	1.61	0.00	108.90	1.61

**TABLE 13**  
Unscheduled Maintenance Costs Reported for the Most Recent Year of the Survey (1996) (Cents per Square Foot)

	Median Cost	Minimum Cost	Maximum Cost	Log-Mean
Base data	3.70	0.00	71.97	2.23
In-house wage multiplier (36%)	3.91	0.00	90.15	2.75
Contractor wage multiplier (66%)	4.06	0.00	105.30	3.17

ment age is a significant determinant in HVAC system maintenance costs.

### Scheduled and Unscheduled Maintenance Cost Components and Nature of Maintenance and Repairs

Tables 10 and 11 present the scheduled cost component of the total maintenance and service cost reported earlier for both the averaged overall years and most recent year cases.

Similarly, in Tables 12 and 13, the unscheduled cost components of the total maintenance and service cost are presented.

The number of occurrences of the scheduled or preventative maintenance tasks reported by the sites is presented in Figure 1. Table 14 summarizes the number of occurrences of unscheduled service, maintenance, and repairs (corrective actions) reported by the sites. The table divides this into

**TABLE 14**  
**Corrective Actions by Component**

Item	Failure of Part	Maintenance or Service of Part	Total Corrective Actions	Percentage of all Corrective Actions	Number of Sites with the Problem	Corrective actions per 100 unit-years	
						Ground-water	Closed-loop
Compressor	210		210	290	17	0.53	1.30
Blower, belts, motor	59	10	69	9.5	21	3.23	1.07
Refrigerant leak		64	64	8.9	12		2.58
Pump, motor, coupler	53	8	61	8.4	17	1.21	0.81
Switches or solenoids	17	35	52	7.2	28	0.77	0.90
t-stats	37		37	5.1	11	3.23	0.81
Adjustments/misc.		36	36	5.0	10	3.57	0.79
Shaft seals	31		31	4.3	3	0.31	0.08
Expansion valves	25		25	3.5	8	0.77	0.24
Piping, pipe material		23	23	3.2	7	1.47	0.16
Insulation		22	22	3.0	8		0.31
Controllers	7	5	12	1.7	3		0.06
Hoses	5	4	9	1.2	4		0.25
Electrical wiring	7	1	8	1.1	4	3.83	2.63
Heat pump (entire unit)	7		7	1.0	1	0.03	
Antifreeze leak		6	6	0.8	3	0.26	0.15
Flush loop		6	6	0.8	4	1.90	0.27
Timer	3	2	5	0.7	3	0.76	0.06
Transformer	3	1	4	0.6	4		0.7
Condenser	4		4	0.6	3	0.95	0.12
Reversing valve	2	2	4	0.6	2		0.12
EMS	3	1	4	0.6	1	0.31	0.07
Automatic air vents		3	3	0.4	2		0.17
Pressure gauges	1	2	3	0.4	3		0.05
Repressurize loop		3	3	0.4	3		0.22
Coil (clean)		2	2	0.3	1		<0.01
Solenoid valve	2		2	0.3	2		0.04
Temp. controls		2	2	0.3	2		0.67
HP loop valves	2		2	0.3	2	1.2	
Ductwork		1	1	0.1	1		0.01
Heat exchanger		1	1	0.1	1		<0.01
Heater motor		1	1	0.1	1		0.06
Line dryers		1	1	0.1	1		<0.01
Check superheat		1	1	0.1	1	0.26	
Sediment filter		1	1	0.1	1		0.04
Expansion tank	1		1	0.1	1	0.95	
<b>Total</b>	<b>479</b>	<b>244</b>	<b>723</b>				

components that failed and were replaced (failure of part) and those that simply required maintenance (maintenance or service of part). Also included is a list of the number of sites reporting each problem and the percentages for each corrective action.

Table 14 also includes two columns comparing the corrective actions of groundwater systems to those of closed-loop systems. Since the sample sizes of these two were quite different (7 for groundwater, 31 for closed-loop), the data are given per 100 unit-years. This means that the number of occurrences at each site is divided by the number of heat pump units at the site and also by the number of years the site was surveyed. The result was then averaged over all sites of the same system type and multiplied by 100. Thus a value of 2.00 would indicate that, if an installation had 100 heat pumps, the particular corrective action would have to be done, on average, twice a year. Note that a blank entry indicates insufficient data and not that the problem is not specific to the system type. Although the sample size is small, these columns indicate, on average, a greater number of corrective actions for groundwater systems than for closed-loop systems, but note that, on average, the groundwater systems are older than the closed-loop systems. Although the individual comparisons between groundwater and closed-loop systems in this table may be interesting, one is cautioned that the groundwater sample is small.

## CONCLUSIONS AND RECOMMENDATIONS

Ground-source heat pump systems, in the sample of 38 presented here, have log-mean annual service and maintenance costs anywhere from 6.73 cents per square foot to as much as 9.21 cents per square foot, depending on whether the work is done by in-house personnel (base cost) or by an outside contracting organization.

The large variance among buildings in the results reflects higher costs within the office subgroup and, in particular, two

or three sites that had maintenance contracts of a complexity and cost that was well in excess of the others. As a result, a statistical analysis (O'Hara Hines 1998) indicates that the data set is closer to log-normal than normal in its distribution. Thus, the log-mean is a more appropriate indicator than the normal mean. The larger dispersion of maintenance costs points to the need for the development of standardized maintenance guidelines for this relatively new technology.

The comparison with the ASHRAE RP-929 results (ASHRAE 1999), presented in Table 9, suggests that ground-source heat pump system service and maintenance costs are significantly lower than those for conventional HVAC systems. It is important to further investigate the impact of age of equipment on maintenance cost.

## REFERENCES

- ASHRAE. 1999. *HVAC maintenance costs (RP-929)*. Prepared for ASHRAE, Inc., Technical Committee 1.8 final report (draft version 2) by ADM Associates, Inc. June.
- ASHRAE. 1995. *Operating experiences with commercial ground-source heat pumps (RP-863)*. Prepared for ASHRAE, Inc., Technical Committee 6.8 final report by Caneta Research, Inc. November.
- Cane, D., A. Morrison, and C.J. Ireland. 1998. Maintenance and service costs in commercial building ground-source heat pump systems. *ASHRAE Transactions* 104 (2): 699-706.
- Means. 1998. *Mechanical cost data*. Kingston, Mass.: R.S. Means Company, Inc.
- Means. 1996. *Facilities maintenance and repair cost data*. Kingston, Mass.: R.S. Means Company, Inc.
- O'Hara Hines, R.J. 1998. Department of Statistics and Actuarial Science, University of Waterloo, Waterloo, Ontario, Canada. Data analysis, November.