Comparing Maintenance Costs of Geothermal Heat Pump Systems with Other HVAC Systems: Preventive Maintenance Actions and Total Maintenance Costs

Michaela A. Martin, P.E.
Member ASHRAE

Melissa G. Madgett
Associate Member ASHRAE

Patrick J. Hughes, P.E.
Member ASHRAE

ABSTRACT

Total annual heating, ventilating, and air-conditioning (HVAC) maintenance costs were determined for 20 schools in the Lincoln, Nebraska, Public School District. Each school examined provides cooling to over 70% of its total floor area and relies on one of the following heating and cooling systems to provide the majority of space conditioning: vertical-bore, geothermal heat pumps (GHPs), air-cooled chiller with gas-fired hot water boiler (ACC/GHWB), water-cooled chiller with gas-fired hot water boiler (WCC/GHWB), or water-cooled chiller with gas-fired steam boiler (WCC/GSB). A precursor to this study examined annual costs associated with repair, service, and corrective maintenance activities tracked in a work order database. This follow-up study examines costs associated with preventive maintenance (PM) activities conducted by the district. Annual PM costs were 5.87 ¢/yr·ft^2 (63.14 ¢/yr·m^2) for ACC/GHWB schools, followed by 7.14 ¢/yr·ft^2 (76.86 ¢/yr·m^2) for GHP, 9.82 ¢/yr·ft^2 (105.39 ¢/yr·m^2) for WCC/GSB, and 12.65 ¢/yr·ft^2 (136.30 ¢/yr·m^2) for WCC/GHWB. The results of the two analyses are combined to produce an estimate of total annual maintenance costs, by system type, for the 20 schools. Total annual maintenance costs were 8.75 ¢/yr·ft^2 (94.20 ¢/yr·m^2) for ACC/GHWB schools, followed by 9.27 ¢/yr·ft^2 (99.76 ¢/yr·m^2) for GHP, 13.54 ¢/yr·ft^2 (145.49 ¢/yr·m^2) for WCC/GSB, and 18.71 ¢/yr·ft^2 (201.61 ¢/yr·m^2) for WCC/GHWB. It should be noted that these costs represent only the trends seen in the maintenance database of the Lincoln School District. Because of differences in the number of schools using each system type, varying equipment age, and the small total number of schools included in the study, the maintenance costs presented here may not be representative of the maintenance costs seen for similar equipment in other locations.

INTRODUCTION

A recent study of maintenance activities associated with the operation of geothermal heat pumps reported average annual costs to be in the range of 7.32 ¢/yr·ft^2 (78.79 ¢/yr·m^2) to 9.56 ¢/yr·ft^2 (102.91 ¢/yr·m^2) (Cane et al. 1998). This study examined 25 buildings, including 15 schools, 3 offices, and 4 multi-family residences, with system ages ranging from 0 to 15 years. Average maintenance costs for conventional HVAC systems, from an older study commissioned by ASHRAE (Dohrmann and Alereza 1986), were higher at 32 ¢/yr·ft^2 (344.46 ¢/yr·m^2). The ASHRAE study surveyed 342 commercial buildings with ages ranging from 2 to 25 years and did not include any geothermal systems.

HVAC maintenance work orders, available from two databases at Lincoln Public Schools in Lincoln, Nebraska, have been reviewed to evaluate total maintenance costs for 20 schools utilizing four types of HVAC systems: vertical-bore, geothermal heat pumps (GHPs), air-cooled chiller with gas-fired hot water boiler (ACC/GHWB), water-cooled chiller with gas-fired hot water boiler (WCC/GHWB), and water-cooled chiller with gas-fired steam boiler (WCC/GSB).[1] Each school was selected using the criterion that it provided cooling to at least 70% of its total floor area. The review of mainte-

1. Some schools may utilize small amounts of supplemental heating or cooling equipment for temporary portable classrooms or under-conditioned spaces. The maintenance activities for these supplemental systems are included in the maintenance costs; however, the contribution to total costs was considered insignificant.

Michaela A. Martin is a development engineer and **Patrick J. Hughes** is a program manager at Oak Ridge National Laboratory, Oak Ridge, Tenn. **Melissa G. Madgett** is an engineer III at Oak Ridge National Laboratory, Oak Ridge, Tenn.

nance costs was divided into two components: unplanned (repair, service, and corrective maintenance) and planned (preventive maintenance) actions.

The first component of this approach reviewed a database containing maintenance work orders for repair, service, and corrective actions (Martin et al. 1999). Table 1 illustrates the average annual costs for these unplanned actions. Average costs for unplanned maintenance actions ranged from 2.13 ¢/ft^2 (22.90 ¢/m^2) to 6.07 ¢/ft^2 (65.30 ¢/m^2). While geothermal systems reported the lowest costs, they also reported an average cooling system age of 3 years, versus 7 years for ACC/GHWB, 12 for WCC/GSB, and 16 for WCC/GHWB.

In an effort to evaluate total maintenance costs for the sample of 20 schools, the second component of maintenance costs, specifically those from planned or preventive actions, were studied. The data used in this analysis are contained in a preventive maintenance database. A review of this database was conducted and the results were combined with the first component to calculate total maintenance costs for the 20 schools studied. Table 2 provides building, heating, and cooling characteristics for the 20 schools, as well as a count of the HVAC components receiving PM attention.

BACKGROUND ON AVAILABLE DATA

Preventive maintenance (PM) requirements for HVAC equipment are contained within a database that is used to identify and schedule PM requests to be carried out at each school. Annually, custodial and maintenance staff are responsible for over 20,000 PM tasks on mechanical equipment throughout the 50 schools within the district (Styskal 1998). For the 20 schools selected in this study, the number of HVAC-related PM requests totaled 8,392. Each database record includes information on equipment type, equipment identification number and location, date of request, sequence of activity, description of work to be performed, and craft responsible for the work. PM requirements are entered into the database at database inception, after installation of equipment or by request of on-site custodial or maintenance personnel, and are closely related to manufacturers' requirements. Additionally, PM tasks are removed after decommissioning of equipment occurs or, again, by request of on-site custodial or maintenance personnel.

PM requests are submitted to on-site personnel and completed on a monthly basis; however, actual labor and material expenditures are not recorded by the district. Therefore, no formal records of labor hours and material costs per PM request were available. In order to estimate annual PM costs for the 20 schools under consideration, labor effort and costs and material costs were developed for each request generated by the PM database. The majority of the supporting data on required labor effort and material costs were provided by cost guides (Means 1998a, 1998b), with supplemental material cost data collected from the district itself (when available) and from an industrial/commercial catalog (Grainger 1998).

TABLE 1
Annual Costs for Repair, Service, and Corrective Maintenance, Lincoln Public Schools* (I-P Units)

HVAC System Type	Average Age of Cooling System (yrs)	Annual Unplanned Maintenance Costs		
		Average (¢/ft^2·yr)	Minimum (¢/ft^2·yr)	Maximum (¢/ft^2·yr)
GHP	3	2.13	1.33	2.45
ACC/GHWB	7	2.88	1.98	3.79
WCC/GSB	12	3.73	2.65	4.8
WCC/GHWB	16	6.07	0.74	22.8

* Labor costs include base wages, workers' compensation, and overhead and are normalized using national averages.

TABLE 1a
Annual Costs for Repair, Service, and Corrective Maintenance, Lincoln Public Schools* (S-I Units)

HVAC System Type	Average Age of Cooling System (yrs)	Annual Unplanned Maintenance Costs		
		Average (¢/m^2·yr)	Minimum (¢/m^2·yr)	Maximum (¢/m^2·yr)
GHP	3	22.90	14.32	26.37
ACC/GHWB	7	31.05	21.31	40.80
WCC/GSB	12	40.10	28.53	51.67
WCC/GHWB	16	65.30	7.97	245.43

* Labor costs include base wages, workers' compensation, and overhead and are normalized using national averages.

For the majority of schools studied, it was evident that the scope of PM tasks identified by Means (in *Facilities Maintenance and Repair Cost Data*), on an equipment-by-equipment basis, did not consistently match those identified by the school district. This was not unexpected as the sources used by the two are different: Means is based on detailed records from the Navy and the Army Corp of Engineers, while the Lincoln tasks are related to their interpretations of manufacturers' specifications. Lincoln's tasks most often reflect a portion of those identified by Means. Additionally, while the Means facilities maintenance and repair data provides itemized estimates for labor effort on a task-by-task basis for each piece of equipment, material costs are annualized for the aggregated tasks. Itemized material costs for each PM task identified, from Means, the Navy, or the Army Corp, were unavailable. Therefore, itemized material costs were estimated using *Means Mechanical Cost Data*, the Grainger catalog, and limited costs obtained from Lincoln.

Labor costs were calculated using itemized estimates of effort for tasks identified on corresponding equipment from Means, labor rates for the craft responsible for the action, and

TABLE 2
Building and Heating and Cooling System Characteristics for 20 Schools in Lincoln, Nebraska (I-P Units)

Group A: Geothermal Heat Pumps (Vertical Bore)

School	School Type	Total Floor Area (ft^2)	Age of School (yrs)	Age of Primary Cooling System (yrs)	Fraction of Total Floor Area Cooled (%)	Age of Primary Heating System (yrs)	Number of Units Serviced
Campbell	Elem.	69,670	3	3	100%	3	76
Cavett	Elem.	72,550	3	3	100%	3	83
Maxey	Elem.	69,670	3	3	100%	3	75
Roper	Elem.	72,550	3	3	100%	3	79
Minimum		*69,670*	*3*	*3*	*100%*	*3*	*75*
Maximum		*72,550*	*3*	*3*	*100%*	*3*	*83*
Average		*71,110*	*3*	*3*	*100%*	*3*	*78*
Std. deviation		*1,663*	*0*	*0*	*0%*	*0*	*4*

Group B: Air-Cooled Chiller and Gas-Fired Hot Water Boiler

School	School Type	Total Floor Area (ft^2)	Age of School (yrs)	Age of Primary Cooling System (yrs)	Fraction of Total Floor Area Cooled (%)	Age of Primary Heating System (yrs)	Number of Units Serviced
Belmont	Elem.	104,724	75	5	87%	5	98
Humann	Elem.	89,523	8	8	79%	8	53
Minimum		*89,523*	*8*	*5*	*79%*	*5*	*53*
Maximum		*104,724*	*75*	*8*	*87%*	*8*	*98*
Average		*97,124*	*42*	*7*	*83%*	*7*	*76*
Std. deviation		*10,749*	*47*	*2*	*6%*	*2*	*32*

Group C: Water-Cooled Chiller and Gas-Fired Steam Boiler

School	School Type	Total Floor Area (ft^2)	Age of School (yrs)	Age of Primary Cooling System (yrs)	Fraction of Total Floor Area Cooled (%)	Age of Primary Heating System (yrs)	Number of Units Serviced
East	H.S.	367,826	31	2	85%	31	83
West Lincoln	Elem.	66,963	42	21	69%	42	92
Minimum		*66,963*	*31*	*2*	*69%*	*31*	*83*
Maximum		*367,826*	*42*	*21*	*85%*	*42*	*92*
Average		*217,395*	*37*	*12*	*77%*	*37*	*88*
Std. deviation		*212,742*	*8*	*13*	*11%*	*8*	*6*

Group D: Water-Cooled Chiller and Gas-Fired Hot Water Boiler

School	School Type	Total Floor Area (ft^2)	Age of School (yrs)	Age of Primary Cooling System (yrs)	Fraction of Total Floor Area Cooled (%)	Age of Primary Heating System (yrs)	Number of Units Serviced
Zeman	Elem.	52,640	24	24	96%	24	40
Everett	Elem.	91,163	70	6	83%	70	40
Fredstrom	Elem.	60,732	15	15	73%	15	28
Goodrich	M.S.	118,632	29	8	90%	29	120
Hill	Elem.	56,016	22	22	86%	22	38
Kahoa	Elem.	54,282	26	26	89%	26	45
McPhee	Elem.	47,784	33	3	100%	33	40
Morley	Elem.	56,391	37	23	78%	37	59

TABLE 2 (Continued)
Building and Heating and Cooling System Characteristics for 20 Schools in Lincoln, Nebraska (I-P Units)

School	School Type	Total Floor Area (ft^2)	Age of School (yrs)	Age of Primary Cooling System (yrs)	Fraction of Total Floor Area Cooled (%)	Age of Primary Heating System (yrs)	Number of Units Serviced
Park	M.S.	191,081	72	8	92%	8	46
Pyrtle	Elem.	44,276	34	32	100%	3	61
Rousseau	Elem.	73,065	34	2	91%	34	49
Bryan	H.S.	22,150	42	26	100%	42	31
Minimum		*22,150*	*15*	*2*	*73%*	*3*	*28*
Maximum		*191,081*	*72*	*32*	*100%*	*70*	*120*
Average		*72,351*	*37*	*16*	*90%*	*29*	*50*
Std. deviation		*44,596*	*18*	*10*	*9%*	*17*	*24*

TABLE 2a
Building and Heating and Cooling System Characteristics for 20 Schools in Lincoln, Nebraska (I-P Units)

Group A: Geothermal Heat Pumps (Vertical Bore)

School	School Type	Total Floor Area (m^2)	Age of School (yrs)	Age of Primary Cooling System (yrs)	Fraction of Total Floor Area Cooled (%)	Age of Primary Heating System (yrs)	Number of Units Serviced
Campbell	Elem.	6,472	3	3	100%	3	76
Cavett	Elem.	6,740	3	3	100%	3	83
Maxey	Elem.	6,472	3	3	100%	3	75
Roper	Elem.	6,740	3	3	100%	3	79
Minimum		*6,472*	*3*	*3*	*100%*	*3*	*75*
Maximum		*6,740*	*3*	*3*	*100%*	*3*	*83*
Average		*6,606*	*3*	*3*	*100%*	*3*	*78*
Std. deviation		*154*	*0*	*0*	*0%*	*0*	*4*

Group B: Air-Cooled Chiller and Gas-Fired Hot Water Boiler

School	School Type	Total Floor Area (m^2)	Age of School (yrs)	Age of Primary Cooling System (yrs)	Fraction of Total Floor Area Cooled (%)	Age of Primary Heating System (yrs)	Number of Units Serviced
Belmont	Elem.	9,729	75	5	87%	5	98
Humann	Elem.	8,317	8	8	79%	8	53
Minimum		*8,317*	*8*	*5*	*79%*	*5*	*53*
Maximum		*9,729*	*75*	*8*	*87%*	*8*	*98*
Average		*9,023*	*42*	*7*	*83%*	*7*	*76*
Std. deviation		*999*	*47*	*2*	*6%*	*2*	*32*

Group C: Water-Cooled Chiller and Gas-Fired Steam Boiler

School	School Type	Total Floor Area (m^2)	Age of School (yrs)	Age of Primary Cooling System (yrs)	Fraction of Total Floor Area Cooled (%)	Age of Primary Heating System (yrs)	Number of Units Serviced
East	H.S.	34,171	31	2	85%	31	83
West Lincoln	Elem.	6,221	42	21	69%	42	92
Minimum		*6,221*	*31*	*2*	*69%*	*31*	*83*

TABLE 2a (Continued)
Building and Heating and Cooling System Characteristics for 20 Schools in Lincoln, Nebraska (I-P Units)

School	School Type	Total Floor Area (ft^2)	Age of School (yrs)	Age of Primary Cooling System (yrs)	Fraction of Total Floor Area Cooled (%)	Age of Primary Heating System (yrs)	Number of Units Serviced
Maximum		*34,171*	*42*	*21*	*85%*	*42*	*92*
Average		*20,196*	*37*	*12*	*77%*	*37*	*88*
Std. deviation		*19,764*	*8*	*13*	*11%*	*8*	*6*

Group D: Water-Cooled Chiller and Gas-Fired Hot Water Boiler

School	School Type	Total Floor Area (m^2)	Age of School (yrs)	Age of Primary Cooling System (yrs)	Fraction of Total Floor Area Cooled (%)	Age of Primary Heating System (yrs)	Number of Units Serviced
Zeman	Elem.	4,890	24	24	96%	24	40
Everett	Elem.	8,469	70	6	83%	70	40
Fredstrom	Elem.	5,642	15	15	73%	15	28
Goodrich	M.S.	11,021	29	8	90%	29	120
Hill	Elem.	5,204	22	22	86%	22	38
Kahoa	Elem.	5,043	26	26	89%	26	45
McPhee	Elem.	4,439	33	3	100%	33	40
Morley	Elem.	5,239	37	23	78%	37	59
Park	M.S.	17,751	72	8	92%	8	46
Pyrtle	Elem.	4,113	34	32	100%	3	61
Rousseau	Elem.	6,788	34	2	91%	34	49
Bryan	H.S.	2,058	42	26	100%	42	31
Minimum		*2,058*	*15*	*2*	*73%*	*3*	*28*
Maximum		*17,751*	*72*	*32*	*100%*	*70*	*120*
Average		*6,721*	*37*	*16*	*90%*	*29*	*50*
Std. deviation		*4,143*	*18*	*10*	*9%*	*17*	*24*

mobilization/demobilization allowances. Labor rates have been normalized to reflect national in-house rates for common laborers and skilled workers and include base rate, fringes, workman's compensation, and fixed overhead (Means 1998a, 1998b). Four crafts were identified: custodial, HVAC specialist and technicians, building crafts, and building maintenance. Custodial, building crafts, and building maintenance rates are $21.15 per hour, while the more skilled HVAC trades cost $36.85 per hour. Mobilization and demobilization allowances are included in aggregated PM tasks listed in Means; however, they are not adequately represented when only a few tasks are chosen by the user (Mossman 1999). Adjustments have been made to labor efforts to include mobilization and demobilization requirements and are based on the original PM task identified by Lincoln, as well as equipment type, size, and location.

Lincoln performs an overwhelming majority of the maintenance work using in-house resources. The only contracted HVAC task identified was that for cooling tower chemical treatment. The contract is worth $22,000. PM costs for this task were allocated to schools utilizing cooling towers, based on the capacity of the cooling systems installed in each.

SUMMARY OF RESULTS

The number of annual PM requests, labor costs, material costs, and total PM costs per typical unit of equipment are identified in Table 3 for each school studied. Units are identified by equipment type and serial number and may represent, for example, GHPs, pumps, air-handlers, exhaust fans, unit ventilators and/or heaters, chillers, boilers, cooling towers, air-cooled condensers, or air compressors. On a per unit basis, average annual PM requirements or requests, per unit of equipment, are lowest for GHP schools at 4.8 and highest for WCC/GSB schools at 7.5. Similarly, average labor costs per GHP component are lowest at $32, followed by ACC/GHWB at $45, WCC/GSB at $57, and WCC/GHWB at $65. Average material costs, however, are lowest at $31 per unit for the ACC/GHWB schools and highest for

TABLE 3
Number of Annual PM Requests, Annual Labor Costs, Annual Material Costs, and Total Annual PM Costs per Equipment Unit

Group A: Geothermal Heat Pumps (Vertical-Bore)

School	Annual PM Requests per Unit	Labor Costs per Unit ($)	Material Costs per Unit ($)	Total PM Costs per Unit ($)
Campbell	4.4	30	35	65
Cavett	5.2	34	29	63
Maxey	4.7	32	38	70
Roper	4.8	32	29	61
Minimum	*4.4*	*30*	*29*	*61*
Maximum	*5.2*	*34*	*38*	*70*
Average	*4.8*	*32*	*33*	*65*
Std. deviation	*0.3*	*1*	*4*	*4*

Group B: Air-Cooled Chiller and Gas-Fired Hot Water Boiler

School	Annual PM Requests per Unit	Labor Costs per Unit ($)	Material Costs per Unit ($)	Total PM Costs per Unit ($)
Belmont	4.9	34	44	78
Humann	7.8	56	18	75
Minimum	*4.9*	*34*	*18*	*75*
Maximum	*7.8*	*56*	*44*	*78*
Average	*6.3*	*45*	*31*	*76*
Std. deviation	*2.1*	*16*	*18*	*3*

Group C: Water-Cooled Chiller and Gas-Fired Steam Boiler

School	Annual PM Requests per Unit	Labor Costs per Unit ($)	Material Costs per Unit ($)	Total PM Costs per Unit ($)
East	6.8	49	67	116
West Lincoln	8.2	65	39	104
Minimum	*6.8*	*49*	*39*	*104*
Maximum	*8.2*	*65*	*67*	*116*
Average	*7.5*	*57*	*53*	*110*
Std. deviation	*1.0*	*12*	*20*	*8*

Group D: Water-Cooled Chiller and Gas-Fired Hot Water Boiler

School	Annual PM Requests per Unit	Labor Costs per Unit ($)	Material Costs per Unit ($)	Total PM Costs per Unit ($)
Zeman	3.5	27	37	64
Everett	5.2	55	109	165
Fredstrom	6.1	60	100	160
Goodrich	9.8	82	67	150
Hill	4.0	29	15	45
Kahoa	6.4	54	51	105
McPhee	9.3	87	95	182
Morley	9.8	88	79	166
Park	6.3	62	149	211
Pyrtle	9.1	79	50	128

TABLE 3 (Continued)
Number of Annual PM Requests, Annual Labor Costs, Annual Material Costs, and Total Annual PM Costs per Equipment Unit

School	Annual PM Requests per Unit	Labor Costs per Unit ($)	Material Costs per Unit ($)	Total PM Costs per Unit ($)
Rousseau	9.7	89	68	157
Bryan	8.9	71	50	122
Minimum	*3.5*	*27*	*15*	*45*
Maximum	*9.8*	*89*	*149*	*211*
Average	*7.4*	*65*	*73*	*138*
Std. deviation	*2.4*	*21*	*36*	*48*

the WCC/GHWB schools at $73. Overall PM costs, on a per unit basis, are lowest for the GHP schools at $65 and highest for the WCC/GHWB schools at $138. Annually, the GHP schools exhibit lower average total PM costs than the schools utilizing the conventional HVAC systems (Table 4). Itemized components of total PM costs include labor costs, material costs, and contracted PM costs for cooling tower water treatment. The variation in average total PM costs is due to the size of the school and the number of HVAC units requiring PM, as well as the particular PM needs of the components of the HVAC system. From this perspective, the GHP schools have the lowest average annual PM costs of $5,074, followed by ACC/GHWB at $5,808, WCC/GHWB at $8,255, and WCC/GSB at $13,075. It is interesting to note that the standard deviation for the GHP schools is relatively small, at $225. The reasoning for this is that the GHP schools all have the same mechanical design. The variation does not seem to be impacted by manufacturer of GHP units, as Campbell and Maxey utilize equipment from a different manufacturer than Roper and Cavett (Hennings 1998).

Area-normalized average annual preventive maintenance costs are provided in Table 5, along with repair, service, and corrective action costs from the first study and the total annual maintenance costs reported by Lincoln databases. Average annual PM costs are lowest for the ACC/GHWB schools at 5.87 ¢/yr·ft^2 (63.14 ¢/yr·m^2); however, the standard deviation is large (2.05 ¢/yr·ft^2) (22.12 ¢/yr·m^2) as Belmont annual PM costs outweigh Humann's by nearly 3 ¢/yr·ft^2 (31 ¢/yr·m^2). GHP PM costs are second lowest at an average of 7.14 ¢/yr·ft^2 (76.86 ¢/yr·m^2), followed by WCC/GSB at 9.82 ¢/yr·ft^2 (105.39 ¢/yr·m^2) and WCC/GHWB at 12.65 ¢/yr·ft^2 (136.30 ¢/yr·m^2). Again, standard deviations are large for the other conventional systems, WCC/GSB and WCC/GHWB, at 7.77 ¢/yr·ft^2 (83.92 ¢/yr·m^2) and 5.30 ¢/yr·ft^2 (57.23 ¢/yr·m^2), respectively.

Total annual average maintenance costs, normalized to total floor area, were determined by combining the results of the PM analysis with those of the previous study of repair, service, and corrective actions. GHP systems report total average annual maintenance costs of 9.27 ¢/yr·ft^2 (99.76 ¢/yr·m^2), which corresponds well to the in-house averages of 9.3 ¢/yr·ft^2 (100.11 ¢/yr·m^2) reported in the recent ASHRAE study (Cane et al. 1998). ACC/GHWB systems reported the lowest average annual total maintenance cost of 8.75 ¢/yr·ft^2 (94.20 ¢/yr·m^2), outperforming GHP by only 0.52 ¢/yr·ft^2 (5.6 ¢/yr·m^2) with equipment that is just slightly older than the GHP equipment. Average WCC/GHWB costs were highest at 18.71 ¢/yr·ft^2 (201.61 ¢/yr·m^2).

TABLE 4
Number of Annual PM Requests, Annual Labor Effort, Annual Labor Costs, Annual Material Costs, Annual Contracted PM Costs, and Total Annual PM Costs

Group A: Geothermal Heat Pumps (Vertical-Bore)

School	PM Requests per Year	Labor Effort per Year (hours)	Labor Costs per Year ($)	Material Costs per Year ($)	Contracted PM Costs per Year ($)	Total PM Costs per Year ($)
Campbell	334	109	2,307	2,651	0	4,958
Cavett	429	132	2,792	2,447	0	5,239
Maxey	349	114	2,417	2,867	0	5,285
Roper	381	120	2,540	2,276	0	4,816
Minimum	*334*	*109*	*2,307*	*2,276*	*0*	*4,816*
Maximum	*429*	*132*	*2,792*	*2,867*	*0*	*5,285*
Average	*373*	*119*	*2,514*	*2,560*	*0*	*5,074*
Std. deviation	*42*	*10*	*208*	*256*	*0*	*225*

TABLE 4 (Continued)
Number of Annual PM Requests, Annual Labor Effort, Annual Labor Costs, Annual Material Costs, Annual Contracted PM Costs, and Total Annual PM Costs

Group B: Air-Cooled Chiller and Gas-Fired Hot Water Boiler

School	PM Requests per Year	Labor Effort per Year (hours)	Labor Costs per Year ($)	Material Costs per Year ($)	Contracted PM Costs per Year ($)	Total PM Costs per Year ($)
Belmont	477	156	3,362	4,302	0	7,664
Humann	413	136	2,991	960	0	3,951
Minimum	*413*	*136*	*2,991*	*960*	*0*	*3,951*
Maximum	*477*	*156*	*3,362*	*4,302*	*0*	*7,664*
Average	*445*	*146*	*3,177*	*2,631*	*0*	*5,808*
Std. deviation	*45*	*14*	*263*	*2,363*	*0*	*2,626*

Group C: Water-Cooled Chiller and Gas-Fired Steam Boiler

School	PM Requests per Year	Labor Effort per Year (hours)	Labor Costs per Year ($)	Material Costs per Year ($)	Contracted PM Costs per Year ($)	Total PM Costs per Year ($)
East	563	181	4,053	5,590	6,253	15,895
West Lincoln	757	266	5,991	3,594	670	10,225
Minimum	*563*	*181*	*4,053*	*3,594*	*670*	*10,225*
Maximum	*757*	*266*	*5,991*	*5,590*	*6,253*	*15,895*
Average	*660*	*224*	*5,022*	*4,592*	*3,461*	*13,075*
Std. deviation	*137*	*60*	*1,371*	*1,411*	*3,948*	*3,988*

Group D: Water-Cooled Chiller and Gas-Fired Hot Water Boiler

School	PM Requests per Year	Labor Effort per Year (hours)	Labor Costs per Year ($)	Material Costs per Year ($)	Contracted PM Costs per Year ($)	Total PM Costs per Year ($)
Zeman	139	51	1,084	1,474	1,263	3,822
Everett	207	88	2,212	4,377	912	7,501
Fredstrom	171	68	1,672	2,808	1,093	5,573
Goodrich	1,178	450	9,885	8,080	1,305	19,270
Hill	152	52	1,118	585	1,456	3,160
Kahoa	289	102	2,430	2,308	1,520	6,259
McPhee	373	150	3,462	3,809	669	7,940
Morley	580	231	5,163	4,656	789	10,609
Park	291	118	2,850	6,873	2,866	12,590
Pyrtle	556	211	4,789	3,037	1,018	8,884
Rousseau	476	193	4,383	3,326	1,534	9,244
Bryan	277	94	2,207	1,560	487	4,254
Minimum	*139*	*51*	*1,084*	*585*	*487*	*3,160*
Maximum	*1,178*	*450*	*9,885*	*8,080*	*2,866*	*19,270*
Average	*391*	*151*	*3,438*	*3,574*	*1,243*	*8,255*
Std. deviation	*290*	*112*	*2,444*	*2,195*	*613*	*4,477*

TABLE 5
Annual Preventative Maintenance Costs, Repair, Annual Service, and Corrective Action Costs, and Total Annual Maintenance Costs per Square Meter (I-P Units)

Group A: Geothermal Heat Pumps (Vertical-Bore)

School	Preventative Maintenance Costs per Year per ·ft^2 (¢/yr·ft^2)	Repair, Service, and Corrective Action Costs per Year per ft^2 (¢/yr·ft^2)	Total Maintenance Costs per Year per ft^2 (¢/yr·ft^2)	Total Maintenance Costs per Year per Cooling ft^2 (¢/yr·cool ft^2)
Campbell	7.12	2.38	9.50	9.50
Cavett	7.22	2.35	9.57	9.57
Maxey	7.59	2.45	10.04	10.04
Roper	6.64	1.33	7.97	7.97
Minimum	*6.64*	*1.33*	*7.97*	*7.97*
Maximum	*7.59*	*2.45*	*10.04*	*10.04*
Average	*7.14*	*2.13*	*9.27*	*9.27*
Std. deviation	*0.39*	*0.53*	*0.90*	*0.90*

Group B: Air-Cooled Chiller and Gas-Fired Hot Water Boiler

School	Preventative Maintenance Costs per Year per ft^2 (¢/yr·ft^2)	Repair, Service, and Corrective Action Costs per Year per ft^2 (¢/yr·ft^2)	Total Maintenance Costs per Year per ft^2 (¢/yr·ft^2)	Total Maintenance Costs per Year per Cooling ft^2 (¢/yr·cool ft^2)
Belmont	7.32	3.79	11.11	12.77
Humann	4.41	1.98	6.39	8.09
Minimum	*4.41*	*1.98*	*6.39*	*8.09*
Maximum	*7.32*	*3.79*	*11.11*	*12.77*
Average	*5.87*	*2.89*	*8.75*	*10.43*
Std. deviation	*2.05*	*1.28*	*3.33*	*3.31*

Group C: Water-Cooled Chiller and Gas-Fired Steam Boiler

School	Preventative Maintenance Costs per Year per ft^2 (¢/yr·ft^2)	Repair, Service, and Corrective Action Costs per Year per ft^2 (¢/yr·ft^2)	Total Maintenance Costs per Year per ft^2 (¢/yr·ft^2)	Total Maintenance Costs per Year per Cooling ft^2 (¢/yr·cool ft^2)
East	4.32	2.65	6.97	8.20
West Lincoln	15.31	4.80	20.11	29.15
Minimum	*4.32*	*2.65*	*6.97*	*8.20*
Maximum	*15.31*	*4.80*	*20.11*	*29.15*
Average	*9.82*	*3.73*	*13.54*	*18.68*
Std. deviation	*7.77*	*1.52*	*9.29*	*14.81*

Group D: Water-Cooled Chiller and Gas-Fired Hot Water Boiler

School	Preventative Maintenance Costs per Year per ft^2 (¢/yr·ft^2)	Repair, Service, and Corrective Action Costs per Year per ft^2 (¢/yr·ft^2)	Total Maintenance Costs per Year per ft^2 (¢/yr·ft^2)	Total Maintenance Costs per Year per Cooling ft^2 (¢/yr·cool ft^2)
Zeman	7.26	6.09	13.35	13.91
Everett	8.23	0.74	8.97	10.80
Fredstrom	9.18	0.93	10.11	13.85
Goodrich	16.24	3.09	19.33	21.48

TABLE 5 (Continued)
Annual Preventative Maintenance Costs, Repair, Annual Service, and Corrective Action Costs, and Total Annual Maintenance Costs per Square Meter (I-P Units)

School	Preventative Maintenance Costs per Year per ft^2 (¢/yr·ft^2)	Repair, Service, and Corrective Action Costs per Year per ft^2 (¢/yr·ft^2)	Total Maintenance Costs per Year per ft^2 (¢/yr·ft^2)	Total Maintenance Costs per Year per Cooling ft^2 (¢/yr·cool ft^2)
Hill	5.64	4.79	10.43	12.13
Kahoa	11.53	4.60	16.13	18.12
McPhee	16.62	2.32	18.94	18.94
Morley	18.65	16.27	34.92	44.77
Park	6.59	1.03	7.62	8.28
Pyrtle	19.98	22.38	42.36	42.36
Rousseau	12.65	2.37	15.02	16.51
Bryan	19.21	8.19	27.40	27.40
Minimum	*5.64*	*0.74*	*7.62*	*8.28*
Maximum	*19.98*	*22.38*	*42.36*	*44.77*
Average	*12.65*	*6.07*	*18.71*	*20.71*
Std. deviation	*5.30*	*6.71*	*10.90*	*11.83*

TABLE 5a
Annual Preventative Maintenance Costs, Repair, Annual Service, and Corrective Action Costs, and Total Annual Maintenance Costs per Square Foot (S-I Units)

Group A: Geothermal Heat Pumps (Vertical-Bore)

School	Preventive Maintenance Costs per Year per m^2 (¢/yr·m^2)	Repair, Service, and Corrective Action Costs per Year per m^2 (¢/yr·m^2)	Total Maintenance Costs per Year per m^2 (¢/yr·m^2)	Total Maintenance Costs per Year per Cooling m^2 (¢/yr·cool m^2)
Campbell	76.60	25.62	102.22	102.22
Cavett	77.73	25.30	103.03	103.03
Maxey	81.65	26.37	108.02	108.02
Roper	71.46	14.32	85.77	85.77
Minimum	*71.46*	*14.32*	*85.77*	*85.77*
Maximum	*81.65*	*26.37*	*108.02*	*108.02*
Average	*76.86*	*22.90*	*99.76*	*99.76*
Std. deviation	*4.2*	*5.74*	*9.67*	*9.67*

Group B: Air-Cooled Chiller and Gas-Fired Hot Water Boiler

School	Preventive Maintenance Costs per Year per m^2 (¢/yr·m^2)	Repair, Service, and Corrective Action Costs per Year per m^2 (¢/yr·m^2)	Total Maintenance Costs per Year per m^2 (¢/yr·m^2)	Total Maintenance Costs per Year per Cooling m^2 (¢/yr·cool m^2)
Belmont	78.78	40.80	119.58	137.44
Humann	47.50	21.31	68.82	87.11
Minimum	*47.50*	*21.31*	*68.82*	*87.11*
Maximum	*78.78*	*40.80*	*119.58*	*137.44*
Average	*63.14*	*31.05*	*94.20*	*112.28*
Std. deviation	*22.12*	*13.78*	*35.89*	*35.59*

TABLE 5a (Continued)
Annual Preventative Maintenance Costs, Repair, Annual Service, and Corrective Action Costs, and Total Annual Maintenance Costs per Square Foot (S-I Units)

Group C: Water-Cooled Chiller and Gas-Fired Steam Boiler

School	Preventive Maintenance Costs per Year per m^2 (¢/yr·m^2)	Repair, Service, and Corrective Action Costs per Year per m^2 (¢/yr·m^2)	Total Maintenance Costs per Year per m^2 (¢/yr·m^2)	Total Maintenance Costs per Year per Cooling m^2 (¢/yr·cool m^2)
East	46.05	28.53	74.58	87.74
West Lincoln	164.73	51.67	216.40	313.62
Minimum	*46.05*	*28.53*	*74.58*	*87.74*
Maximum	*164.73*	*51.67*	*216.40*	*313.62*
Average	*105.39*	*40.10*	*145.49*	*200.68*
Std. deviation	*83.92*	*16.36*	*100.28*	*159.72*

Group D: Water-Cooled Chiller and Gas-Fired Hot Water Boiler

School	Preventive Maintenance Costs per Year per m^2 (¢/yr·m^2)	Repair, Service, and Corrective Action Costs per Year per m^2 (¢/yr·m^2)	Total Maintenance Costs per Year per m^2 (¢/yr·m^2)	Total Maintenance Costs per Year per Cooling m^2 (¢/yr·cool m^2)
Zeman	78.05	65.55	143.61	149.59
Everett	88.75	7.97	96.72	116.53
Fredstrom	98.55	10.01	108.56	148.71
Goodrich	175.03	33.26	208.29	231.43
Hill	60.74	51.56	112.30	130.59
Kahoa	124.18	49.52	173.70	195.17
McPhee	178.63	24.97	203.60	203.60
Morley	202.11	175.13	377.24	483.64
Park	70.97	11.09	82.06	89.19
Pyrtle	214.90	240.90	455.80	455.80
Rousseau	136.51	25.51	162.03	178.05
Bryan	207.20	88.16	295.36	295.36
Minimum	*60.70*	*7.97*	*82.06*	*89.19*
Maximum	*214.90*	*240.90*	*455.80*	*483.64*
Average	*136.30*	*65.30*	*201.61*	*223.14*
Std. deviation	*57.23*	*72.22*	*117.53*	*127.67*

TABLE 5b
Summary of Annual Preventive Maintenance Costs, Repair, Annual Service, and Corrective Action Costs, and Total Annual Maintenance Costs per Square Foot (I-P Units)

Average PM Costs, Repair, Service, and Corrective Action Costs, and Total Maintenance Costs				
School	**Preventive Maintenance Costs per Year per ft^2 (¢/yr·ft^2)**	**Repair, Service, and Corrective Action Costs per Year per ft^2 (¢/yr·ft^2)**	**Total Maintenance Costs per Year per ft^2 (¢/yr·ft^2)**	**Total Maintenance Costs per Year per Cooling ft^2 (¢/yr·cool ft^2)**
Geothermal Heat Pumps (vertical bore)	7.14	2.13	9.27	9.27
Air-Cooled Chiller and Gas-Fired Hot Water Boiler	5.87	2.88	8.75	10.43
Water-Cooled Chiller and Gas-Fired Steam Boiler	9.82	3.73	13.54	18.68
Water-Cooled Chiller and Gas-Fired Hot Water Boiler	12.65	6.07	18.71	20.71

TABLE 5c
Summary of Annual Preventive Maintenance Costs, Repair, Annual Service, and Corrective Action Costs, and Total Annual Maintenance Costs per Square Meter (S-I Units)

Average PM Costs, Repair, Service, and Corrective Action Costs, and Total Maintenance Costs				
School	**Preventive Maintenance Costs per Year per m^2 (¢/yr·m^2)**	**Repair, Service, and Corrective Action Costs per Year per m^2 (¢/yr·m^2)**	**Total Maintenance Costs per Year per m^2 (¢/yr·m^2)**	**Total Maintenance Costs per Year per Cooling m^2 (¢/yr·cool m^2)**
Geothermal Heat Pumps (vertical bore)	76.86	22.90	99.76	99.76
Air-Cooled Chiller and Gas-Fired Hot Water Boiler	63.14	31.05	94.20	112.28
Water-Cooled Chiller and Gas-Fired Steam Boiler	105.39	40.10	145.49	200.68
Water-Cooled Chiller and Gas-Fired Hot Water Boiler	136.30	65.30	201.61	223.14

Considering that most of the schools are not completely cooled, the total annual maintenance costs per cooled floorspace were developed for comparison. The average annual total maintenance costs per cooled square foot are lowest for the GHP schools, at 9.27 ¢/yr per cooled ft^2 (99.76 ¢/yr per cooled m^2), with a standard deviation of 0.9 ¢/yr per cooled ft^2 (9.67 ¢/yr per cooled m^2). ACC/GHWB costs are second lowest at an average of 10.43 ¢/yr per cooled ft^2 (112.28 ¢/yr per cooled m^2), followed by WCC/GSB at 18.68 ¢/yr per cooled ft^2 (200.68 ¢/yr per cooled m^2) and WCC/GHWB at 20.71 ¢/yr per cooled ft^2 (223.14 ¢/yr per m^2). The standard deviations for the other conventional systems, are 3.31, 14.81, and 11.83 ¢/yr per cooled ft^2 (35.59, 159.72, and 127.67 ¢/yr per cooled m^2), respectively.

A list of the most frequent work codes cited for each system type is presented in Table 6. Filter replacement, lubrication of motors and pumps, and belt checks are the PM activities most often implemented for both GHP and conventional systems. It is interesting to note, in the case of the GHP systems, that the manufacturer recommends the following activities: keep air out of water coils, maintain positive loop pressure, periodically check water coils for scaling, inspect filters (and replace) every two to three months, inspect (and clean) condensate pans and drains twice a year, and inspect (and clean) air coils once a year (Water Furnace 1996). In comparison, the Lincoln PM database issues requests for filter inspection (and replacement) every three months, belt inspection every three months, and motor and pump lubrication every two or six months. While this practice is less than ideal, it is not uncommon for organizations to address only what they have the capacity to handle on a regular basis. Under these conditions, neglected PM activities eventually surface as repair, service, or corrective actions. This was the case in reviewing the repair, service, and corrective action database for the Lincoln GHP schools, as it was apparent that the omitted PM task of inspecting condensate pans and drains was actually resulting in leakage problems for some GHPs.

TABLE 6
Most Frequent Work Codes Cited for Preventive Maintenance Activities

Group A: Geothermal Heat Pumps (Vertical-Bore)

Work Code	Total Calls Per Year (4 Schools)	Calls per Year per School
Filter Replacements	1,336	334.0
Lubrication of Motors and Pumps	81	20.3
Filter Replacement and Belt Check	56	14.0
Total	*1,473*	*368.3*
Total PM Calls	*1,493*	
% of Total PM Calls	*99%*	

Group B: Air-Cooled Chiller and Gas-Fired Hot Water Boiler

Work Code	Total Calls Per Year (2 Schools)	Calls per Year per School
Filter Replacements and Coil Vacuuming	236	118.0
Filter Replacements	200	100.0
Filter Replacements and Belt Check	182	91.0
Belt Check	96	48.0
Lubrication of Motors and Pumps	92	46.0
Total	*806*	*403.0*
Total PM Calls	*890*	
% of Total PM Calls	*91%*	

Group C: Water-Cooled Chiller and Gas-Fired Steam Boiler

Work Code	Total Calls Per Year (2 Schools)	Calls per Year per School
Filter Replacements	789	394.5
Filter Replacements and Lubrication	213	106.5
Lubrication and Belt Check	76	38.0
Lubrication of Motors and Pumps	59	29.5
Heating Plant Burner Check	32	16.0
Total	*1,169*	*584.5*
Total PM Calls	*1,247*	
% of Total PM Calls	*94%*	

Group D: Water-Cooled Chiller and Gas-Fired Hot Water Boiler

Work Code	Total Calls Per Year (12 Schools)	Calls per Year per School
Filter Replacements	2,779	231.6
Filter Replacements and Lubrication	483	40.3
Filter Replacements, Lubrication and Belt Check	269	22.4
Filter Replacements and Belt Check	130	10.8
Lubrication of Motors and Pumps	118	9.8
Total	*3,779*	*314.9*
Total PM Calls	*4,689*	
% of Total PM Calls	*81%*	

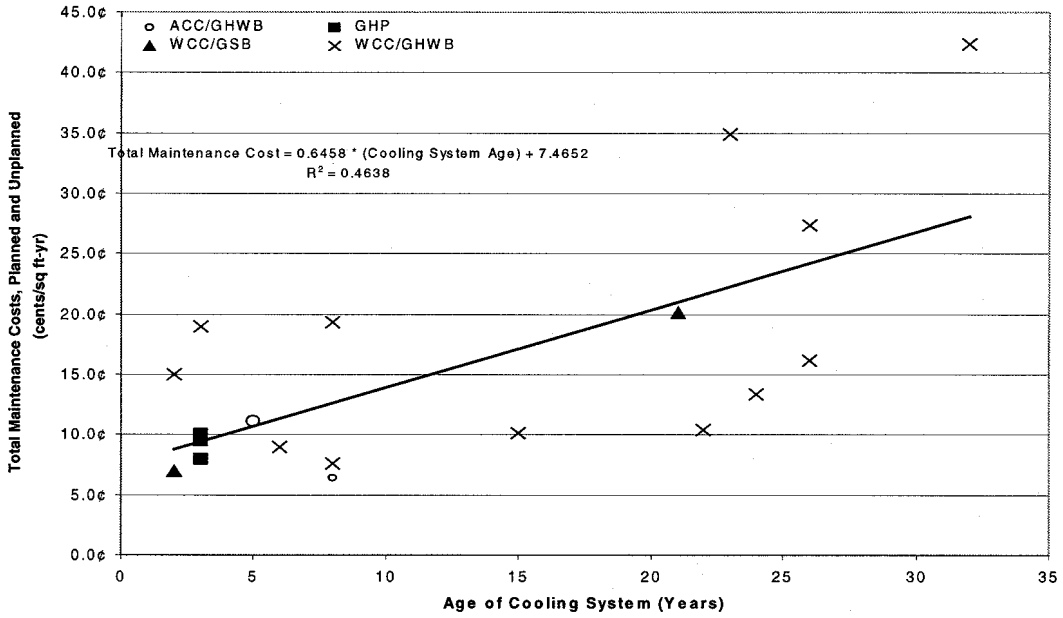

Figure 1 *Relationship between total maintenance costs (planned and unplanned) and cooling system age (I-P units).*

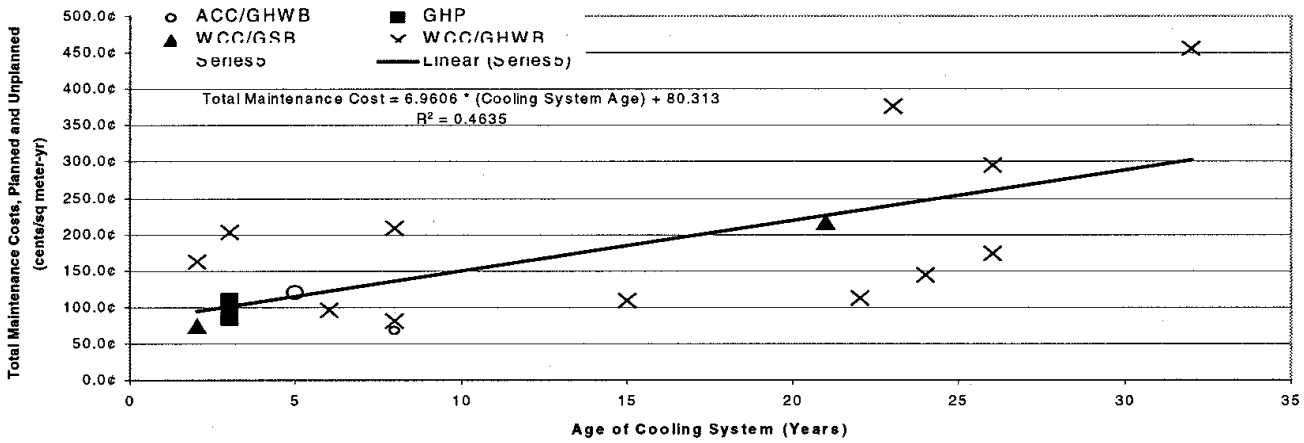

Figure 1a *Relationship between total maintenance costs (planned and unplanned) and cooling system age (S-I units).*

The previous study on unplanned maintenance actions uncovered a linear relationship (R^2 = 0.51) between annual costs for unplanned maintenance and the age of the schools' cooling systems. A similar analysis of PM costs determined that a statistically significant, weak linear relationship (R^2 = 0.269, $p < 0.05$) exists between annual PM costs and age of cooling system. Again, no linear relationship between PM costs and heating system age was identified. When PM costs are combined with the unplanned costs for repair, service, and corrective actions, a linear relationship with cooling system age is retained ($R^2 = 0.464$, $p < 0.05$), as is illustrated in Figure 1. The relationship between these total maintenance costs and cooling system age seem to be dominated by the unplanned maintenance actions.

CONCLUSIONS

Annual costs for planned preventive maintenance activities were estimated and then combined with annual costs for repair, service, and corrective actions to develop an estimate of total annual maintenance costs for 20 schools located in Lincoln, Nebraska. Preventive maintenance costs were estimated using a database of PM work orders maintained by the

school district. Annual PM costs, normalized to total floor area, were 5.87 ¢/yr·ft^2 (63.14 ¢/yr·m^2) for ACC/GHWB schools, followed by 7.14 ¢/yr·ft^2 (76.86 ¢/yr·m^2) for GHP, 9.82 ¢/yr·ft^2 (105.39 ¢/yr·m^2) for WCC/GSB, and 12.65 ¢/yr·ft^2 (136.30 ¢/yr·m^2) for WCC/GHWB. Total annual maintenance costs were 8.75 ¢/yr·ft^2 (94.20 ¢/yr·m^2) for ACC/GHWB schools, followed by 9.27 ¢/yr·ft^2 (99.76 ¢/yr·m^2) for GHP, 13.54 ¢/yr·ft^2 (145.49 ¢/yr·m^2) for WCC/GSB, and 18.71 ¢/yr·ft^2 (201.61 ¢/yr·m^2) for WCC/GHWB. A linear relationship ($R^2 = 0.464$, $p < 0.05$) between total annual maintenance costs and cooling system age was evident. It should be noted that these costs represent only the trends seen in the maintenance database of the Lincoln School District. Because of differences in the number of schools using each system type, varying equipment age, and the small total number of schools included in the study, the maintenance costs presented here may not be representative of the maintenance costs seen for similar equipment in other locations.

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