

MEASURED PERFORMANCE OF FIVE RESIDENTIAL GEOTHERMAL SYSTEMS

Prepared for

Geothermal Heat Pump Consortium
701 Pennsylvania Avenue, NW
Third Floor
Washington, DC 20004

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401

Prepared by

NAHB Research Center, Inc.
400 Prince George's Boulevard
Upper Marlboro, MD 20774-8731

November 22, 1999

MEASURED PERFORMANCE OF FIVE RESIDENTIAL GEOTHERMAL SYSTEMS

Prepared for

Geothermal Heat Pump Consortium
701 Pennsylvania Ave., NW, 3rd Floor
Washington, DC 20004

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401

by

NAHB Research Center, Inc.
400 Prince George's Boulevard
Upper Marlboro, MD 20774-8731

November 22, 1999

ACKNOWLEDGMENTS

This report was prepared by the NAHB Research Center, Inc., with support from the National Renewable Energy Laboratory and the U.S. Department of Energy under the Residential Energy Efficiency Program (REEP), and from the Geothermal Heat Pump Consortium. Dan Cautley and Joe Wiehagen are the principal authors of this report. Tom Kenney was the project reviewer.

Disclaimer

This report was prepared by the NAHB Research Center, Inc., as an account of work sponsored by the National Renewable Energy Laboratory and the Department of Energy, and the Geothermal Heat Pump Consortium. This report presents findings and conclusions by the staff of the Research Center and may be released or copied only with the permission of the Clients.

ABOUT THE NAHB RESEARCH CENTER

The NAHB Research Center is a not-for-profit subsidiary of the National Association of Home Builders (NAHB). The NAHB has 190,000 members, including 50,000 builders who build more than 80 percent of American homes. The Research Center conducts research, analysis, and demonstration programs in all areas relating to home building; carries out extensive programs of information dissemination and interchange among members of the industry, and between the industry and the public.

NAHB Research Center, Inc.
400 Prince George's Boulevard
Upper Marlboro, MD 20774-8731
☎ (301) 249-4000 or (800) 638-8556
Fax (301) 249-0305
www.nahbrc.org

TABLE OF CONTENTS

EXECUTIVE SUMMARY	1
INTRODUCTION	3
Sites	3
METHODOLOGY	4
Data Acquisition	4
Analysis.....	5
HEATING PERFORMANCE	6
Typical Heating Operation	6
System Output and Performance in Heating.....	9
Seasonal Performance Trends in Heating.....	12
COOLING PERFORMANCE	18
Typical Cooling Operation	18
System Output and Performance in Cooling	21
Seasonal Performance Trends in Cooling.....	22
SYSTEM SIZING	26
Characterizing Heating Loads.....	27
Characterizing Cooling Loads	31
Design Load Estimation	34
Installed Capacity.....	36
SYSTEM CYCLING	37
DOMESTIC WATER HEATING	40
Analysis Methods.....	40
Failure of a Desuperheater.....	40
Water Heating Performance.....	41
CONCLUSIONS	47
APPENDIX A - Consumer Verification of Desuperheater Operation	A-1
APPENDIX B - Simplified Analysis of Desuperheater Performance with Lower Tank	
Element Disabled	B-1

LIST OF TABLES

Table 1: Characteristics of Five Test Homes and Geothermal Systems	4
Table 2: Estimated Error in Measured Parameters, Geothermal Systems Study.....	6
Table 3: 1997-1998 Heating Season Operation of Five Geothermal Systems	10
Table 4: 1998-1999 Partial Heating Season Operation of Five Geothermal Systems	10
Table 5: 1997-1999 Combined Seasonal Heating Performance of Five Geothermal Systems	11
Table 6: 1998 Cooling Season Operation of Five Geothermal Systems.....	21
Table 7: 1998 Cooling Season Performance of Five Geothermal Systems.....	22
Table 8: Heating Characteristics of Five Geothermal Homes, Based on Regression of Heating Output vs. Temperature Difference	30
Table 9: Cooling Characteristics of Five Geothermal Homes, Based on Regression of Cooling Output vs. Temperature Difference and Temperature Rise.....	34
Table 10: Design Heating Loads.....	35
Table 11: Design Cooling Loads	35
Table 12: System Sizing in Heating, Five Geothermal Systems	36
Table 13: System Sizing in Cooling—Five Geothermal Systems	36
Table 14: Measured Water Heating Energy Delivery, Five Residential Geothermal Systems, December 1997–November 1998.....	43
Table 15: Measured Water Heating Performance Indicators, Five Residential Geothermal Systems, December 1997–November 1998.....	44

LIST OF FIGURES

Figure 1: Typical Hourly Heating Operation—Geothermal Unit 1, January 11-14, 1998	7
Figure 2: Typical Hourly Heating Operation—Geothermal Unit 2, January 11-14, 1998	7
Figure 3: Typical Hourly Heating Operation: Geothermal Unit 3, January 11 – 14, 1998	8
Figure 4: Typical Hourly Heating Operation—Geothermal Unit 4, January 11 – 14, 1998.....	8
Figure 5: Typical Hourly Heating Operation—Geothermal Unit 5, January 11-14, 1998	9
Figure 6: 1997-1998 Heating Season Performance Trends—Geothermal Unit 1	13
Figure 7: 1997-1998 Heating Season Performance Trends—Geothermal Unit 2.....	13
Figure 8: 1997-1998 Heating Season Performance Trends—Geothermal Unit 3	14
Figure 9: 1997-1998 Heating Season Performance Trends—Geothermal Unit 4.....	15
Figure 10: 1997-1998 Heating Season Performance Trends—Geothermal Unit 5	15
Figure 11: COP vs. Entering Water Temperature, 5 Geothermal Systems, Combined 1997-1999 Heating Seasons, Daily Average Values.....	17

LIST OF FIGURES (continued)

Figure 12: Typical Hourly Cooling Operation—Geothermal Unit 1, August 8-11 1998.....	18
Figure 13: Typical Hourly Cooling Operation—Geothermal Unit 2, August 8-11, 1998.....	19
Figure 14: Typical Hourly Cooling Operation—Geothermal Unit 3, August 8 – 11, 1998...	19
Figure 15: Typical Hourly Cooling Operation—Geothermal Unit 4, August 8-11, 1998.....	20
Figure 16: Typical Hourly Cooling Operation—Geothermal Unit 5, August 8 – 11, 1998...	20
Figure 17: 1998 Cooling Season Performance Trends—Geothermal Unit 1.....	23
Figure 18: 1998 Cooling Season Performance Trends—Geothermal Unit 2.....	23
Figure 19: 1998 Cooling Season Performance Trends—Geothermal Unit 3.....	24
Figure 20: 1998 Cooling Season Performance Trends—Geothermal Unit 4.....	24
Figure 21: 1998 Cooling Season Performance Trends—Geothermal Unit 5.....	25
Figure 22: COP vs. Entering Water Temperature, Five Geothermal Systems, 1998 Cooling Season, Daily Average Values.....	26
Figure 23: Indoor Temperature vs. Hour of Day, Five Geothermal Systems, December 1, 1997–February 15, 1998.....	28
Figure 24: Hourly Heating Output vs. Temperature Difference—Five Geothermal Systems, Combined Heating Seasons	30
Figure 25: Indoor Temperature vs. Hour of Day, Active Cooling Periods Only, Five Geothermal Systems, May 1 – September 30, 1998	32
Figure 26: Hourly Cooling Output vs. Temperature Difference—Five Geothermal Systems, 1998 Cooling Seasons	33
Figure 27: Operating Cycle Length vs. Duty Cycle—Five Geothermal Systems, 1997-1998 Heating Season Daily Average Values	38
Figure 28: Operating Cycle Length vs. Duty Cycle—Five Geothermal Systems, 1998 Cooling Season, Daily Average Values	39
Figure 29: Measured Domestic Hot Water Energy Delivery—5 Geothermal Systems, December 1997—November 1998	42
Figure 30: Ratio of Purchased Energy to Hot Water Load by Month, Five Geothermal Systems, December 1997 – November 1998.....	45
Figure 31: Desuperheater Fraction of Load vs. Desuperheater Operation, Three Geothermal Systems.....	46
Figure 32: Desuperheater Loop Temperatures and Water Draws, Showing Possible Thermosiphoning, Geothermal Unit 5, One Day of Operation	47

EXECUTIVE SUMMARY

NAHB Research Center performed data collection and analysis of the performance of five residential geothermal systems in northeastern Ohio. The objective of the project was to characterize performance of the systems in occupied homes and to compare the measured output at design conditions to standard sizing methods. Data gathered included ground loop temperatures and flow rates, domestic water heating loop temperatures, hot water load flows and temperatures, air temperatures, electrical inputs, environmental temperatures, and operating status of compressors and auxiliary heating. The equipment of three major geothermal manufacturers was represented.

Each of the systems studied was able to meet the heating loads imposed with very little use of auxiliary heat. Two of the five systems used no auxiliary heat during the period of study, and the highest value for any system was about 4 percent of total heating energy consumption. Low use of auxiliary heat is explained in part by compressor capacities that exceed manufacturers' ratings. In one system, the auxiliary heat was normally left disabled. Measured seasonal Coefficient of Performance (COP) values in heating ranged from 2.9 to 3.3, and compared well with manufacturers' ratings. The maximum measured system output, not including auxiliary heating, was larger than manufacturers' ratings in four of five cases. Loop temperature trends in heating showed some signs of undersized loops in two of the five systems, emphasizing the importance of proper loop sizing and installation. COP was shown to correlate with loop operating temperature.

The cooling load on each system was much smaller than the heating load, and cooling loads in the homes studied was driven by occupant demand in addition to indoor-outdoor temperature difference. Measured seasonal COP values ranged from 3.5 to 4.5, and the maximum measured system output in cooling ranged from 81 to 112 percent of rated capacity.

Heating and cooling loads at design conditions were estimated from the measured data for each home and compared to Air Conditioning Contractors of America (ACCA) Manual J calculated design loads. In heating, Manual J predicted design loads higher than measured values by a median of 17 percent, providing confidence in the use of Manual J for sizing in this climate. In cooling, Manual J predicted loads that varied widely compared to measured values. Geothermal systems sized for heating loads in cold climates will generally provide adequate cooling capacity.

Compressor capacity ratings in heating ranged from 71 to 109 percent of the estimated design heating load, with four of the five systems sized under 100 percent of the load. Sizing of compressor output to less than 100 percent of heating design appears to be an appropriate way to limit system cost, and, as shown here, does not necessarily lead to high use of auxiliary heat. In cooling, rated capacities ranged from 1.2 to 3.2 times projected design load, an expected result in a heating dominated climate.

The systems equipped with desuperheaters for domestic water heating provided 9 to 47 percent of the water heating load, with higher performance explained by long system

operating hours and reduced hot water tank temperature. The failure of one desuperheater system due to pipe blockage was identified from data collected during the study, suggesting the need for system design improvements and for a means of periodically verifying operation. In the absence of optimizing the desuperheater design, the value of desuperheaters is questionable. The two systems equipped with dedicated water heating provided 100 percent of the load from geothermal system operation. However, the thermal losses in these two systems was larger by a factor of over 2.5 compared to the average thermal losses of the desuperheater systems, due to the use of long piping loops and continuous or intermittent pump operation to allow water temperature sampling.

INTRODUCTION

The NAHB Research Center worked under the sponsorship of the National Renewable Energy Laboratory, U.S. Department of Energy, and the Geothermal Heat Pump Consortium to monitor the performance of several residential geothermal heating and cooling systems. First Energy (formerly Ohio Edison) provided field support for the project. The goal of the project was to provide potential users of geothermal systems with information that increases confidence in sizing methods and system performance. Specific objectives of the project include: comparison of measured system heating and cooling output at design conditions to standardized design calculations, and measurement of system operating coefficient of performance (COP) under varying heating and cooling conditions. This report summarizes results of the project.

Sites

Five recently built homes in the greater Cleveland, Ohio area were monitored from May 1997 through January 1999. Each home had a geothermal system designed to provide space heating, cooling, and domestic water heating. The geothermal systems included the products of three manufacturers. Two of the systems used a horizontal ground loop configuration, while the other three used vertical heat exchange loops. Characteristics of the systems are summarized in Table 1.

Table 1: Characteristics of Five Test Homes and Geothermal Systems

Item	House 1	House 2	House 3	House 4	House 5
Year of Construction	1996	1996	Occupied June 1997	1996	1994
No. of Occupants	2	3	3	3	4
Foundation Type	Slab	Slab	Basement	Basement/ crawl space	Basement
No. of Levels Above Grade	1	1	2	1	1
Finished Floor Area, sq. ft.	1,847	2,305	2,882	1,940	2,221
Basement Floor Area, sq. ft.	--	--	1,541	1,940 Includes crawl space	2,221
Air Handler Fan Type	3 Speed, AC motor	ECM, variable speed	ECM, variable speed	selectable, single speed AC motor	ECM, variable speed
Nominal System Size, tons	3	4	5	3 ½	4
Loop Type	Vertical	Vertical	Vertical	Horizontal	Horizontal slinky
DHW System Type	On-demand	On-demand	Desuper- heater	Desuper- Heater	Desuper- heater
Supply Duct Type	PVC pipe	PVC pipe	Metal	Metal	Metal
Return Duct Type	Flex	Flex	Metal & flex	Metal	Metal
Supply Duct Location	Under slab	Under slab	Conditioned space	Conditioned space	Conditioned Space
Return Duct Location	Attic	Attic	Attic and conditioned space	Conditioned space	Conditioned space

METHODOLOGY

Data Acquisition

Performance information for the monitored systems was based on measurement of fluid temperatures and flow rates (which allow calculation of energy delivery), electrical inputs, and environmental conditions. The ground loop flow rates were monitored in each system using turbine flow meters in the loops. Air-side flow rates were measured on a one-time basis during equipment setup using several different methods. These methods included calculating air flow from the measured temperature rise while supplying a known electric resistance heat input, using a measured return air-side airflow through a Duct Blaster™ calibrated fan and matching normal operating pressures in the system supply plenum, and matching pressure drop curves for system blowers or filters. Flow rates in the domestic water heating loops were also measured on a one-time basis, using non-invasive, sonic velocity measurements. Temperatures in the air stream, ground loop, and domestic water heating loop were measured at the entry to and exit from the geothermal unit, using semiconductor transducers. Electric power consumption was also monitored, as were domestic water heating draws, delivery temperatures, and current draws of water heating elements. Condensate production was measured using rain gauges providing a pulse output.

The operating status of compressors and blowers was monitored using current switches in most of the systems.

Data loggers installed at each site were set up to measure and record the monitored parameters. Measurement channels were scanned at five second intervals, and data points recorded each minute. Data was transmitted to the NAHB Research Center offices via a modem link several times each day during the study period.

Analysis

The energy values needed for evaluation of system performance include heating energy delivered, cooling energy delivered, domestic water heating energy delivered, and electrical inputs. The heating and cooling energy delivered may be calculated from monitored delivery temperatures (supply and return air temperatures) and the air flow rate. An alternative method is the use of the overall energy balance on the geothermal system: the total energy input from the ground loop plus electrical energy equals the total output in heating, cooling, and/or water heating.

One major obstacle encountered in the use of the loop temperature and flow data in calculating delivered energy was the characteristic response time of the temperature sensors used for ground loop temperature measurement. The external sensors used to measure loop temperatures had a time constant in response to loop fluid temperature changes of one to two minutes. The sensors moved toward room temperature when the systems were not running, and the lag in tracking loop temperatures during startup conditions led to errors in calculating energy output; estimated at 5 to 15 percent. To allow correction of the data, fast-response immersion thermocouple sensors were installed in each monitored system. Four of these installations with the new sensors were performed during the 1997-98 heating season, while the fifth was performed in August 1998.

Several calculation techniques were used to correct for transient errors in loop temperatures. First, for two of the systems (Unit 1 and 2), a detailed analysis of the development of loop temperature differences during operating cycles was performed, and the loop temperature measurements were corrected as a function of time and operating status. For Units 3 and 5, the ratio of hourly energy delivered as measured by the original external sensors to that measured using the immersion sensors was calculated. Then regressions of this ratio were developed against ground loop temperature and total system output. These regressions account for a large portion of the variability in the difference between the two measurements. It should be noted that the loop energy delivery has been calculated directly from the immersion temperature sensor data, starting from the time of installation of these sensors in each system. For Unit 4, energy output calculated by energy balance compares very closely to energy output calculated from air side flow and temperature difference, and the air side measurements are used in this report.

Coefficient of Performance, (COP) is defined here as the total useful delivered energy divided by the electrical operating energy for a period. COP values calculated from field

measurements are expected to vary from Air Conditioning and Refrigeration Institute (ARI) standard ratings, which are performed under fixed, controlled conditions.

In general, in the analyses presented, space heating and space cooling inputs and outputs are reported separate from domestic water heating inputs and outputs for the two systems with dedicated water heating (Units 1 and 2). Similarly, for the systems with desuperheaters, (Units 3, 4, and 5), domestic water heating outputs are reported as separate values. For these three systems, however, we have no technical basis for separating the ground loop inputs or electrical inputs for water heating from those for space heating, and overall system COP values are reported for combined space conditioning and water heating.

Ground loop fluid temperature is reported as a general indicator of the adequacy of ground loop sizing and heat transfer. The temperatures reported are the minimum for each hour of the temperatures recorded during system operation. No loop temperatures are reported for hours when no operation occurred.

The accuracy of the results were estimated using an assumption of normally distributed errors in the key measured parameters, and a root sum square estimation of total error. Table 2 lists the values of estimated errors in measured parameters.

Table 2: Estimated Error in Measured Parameters, Geothermal Systems Study

Parameter	Estimated Measurement Error
Ground Loop Temperature (Thermocouple Sensors)	$\pm 0.2^{\circ}\text{F}$
Ground Loop Flow Rate	$\pm 3\%$
Corrections Applied to Delivered Ground Loop Energy	$\pm 10\%$
Electric Energy	$\pm 6\%$

The estimated errors in calculated energy delivery and COP are approximately ± 7 percent.

HEATING PERFORMANCE

Typical Heating Operation

The typical heating operation of each system has been explored graphically. Figures 1 through 5 show total heating energy delivered, indoor and outdoor temperatures, and temperature difference, on an hourly basis, for January 11 through 14, 1998. This period was selected as representative of one of the coldest parts of the 1997 to 1998 heating season, with a low temperature of about 13°F on January 14.

Figure 1: Typical Hourly Heating Operation—Geothermal Unit 1, January 11-14, 1998

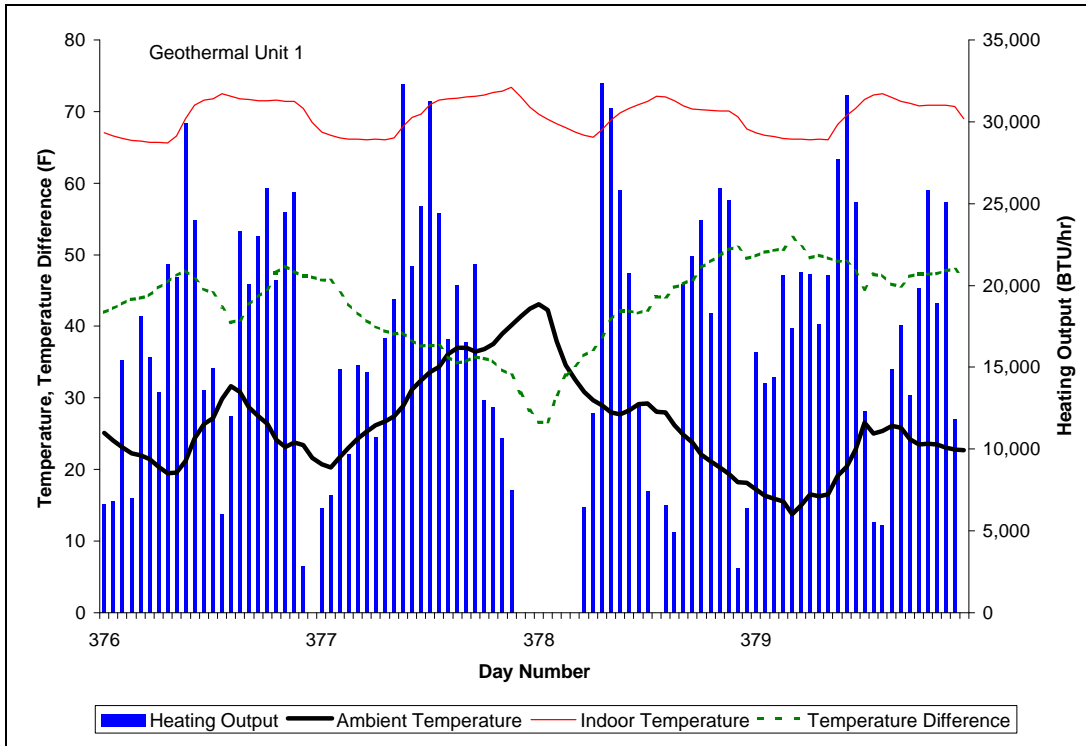


Figure 2: Typical Hourly Heating Operation—Geothermal Unit 2, January 11-14, 1998

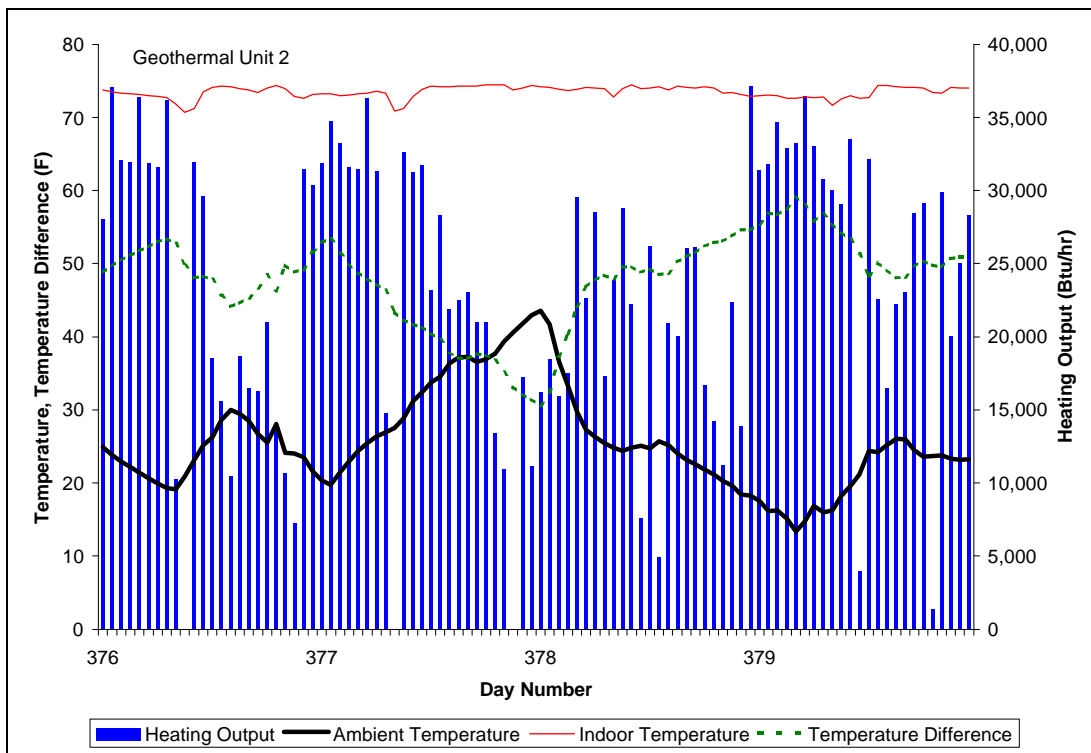


Figure 3: Typical Hourly Heating Operation: Geothermal Unit 3, January 11 – 14, 1998

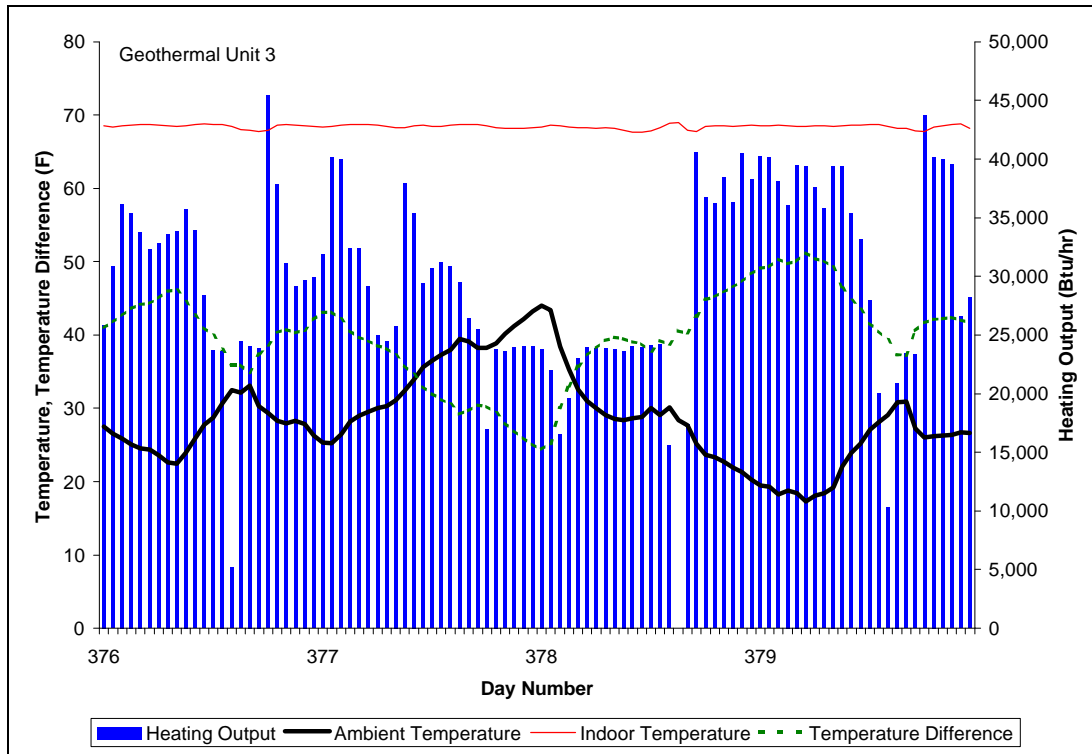


Figure 4: Typical Hourly Heating Operation—Geothermal Unit 4, January 11 – 14, 1998

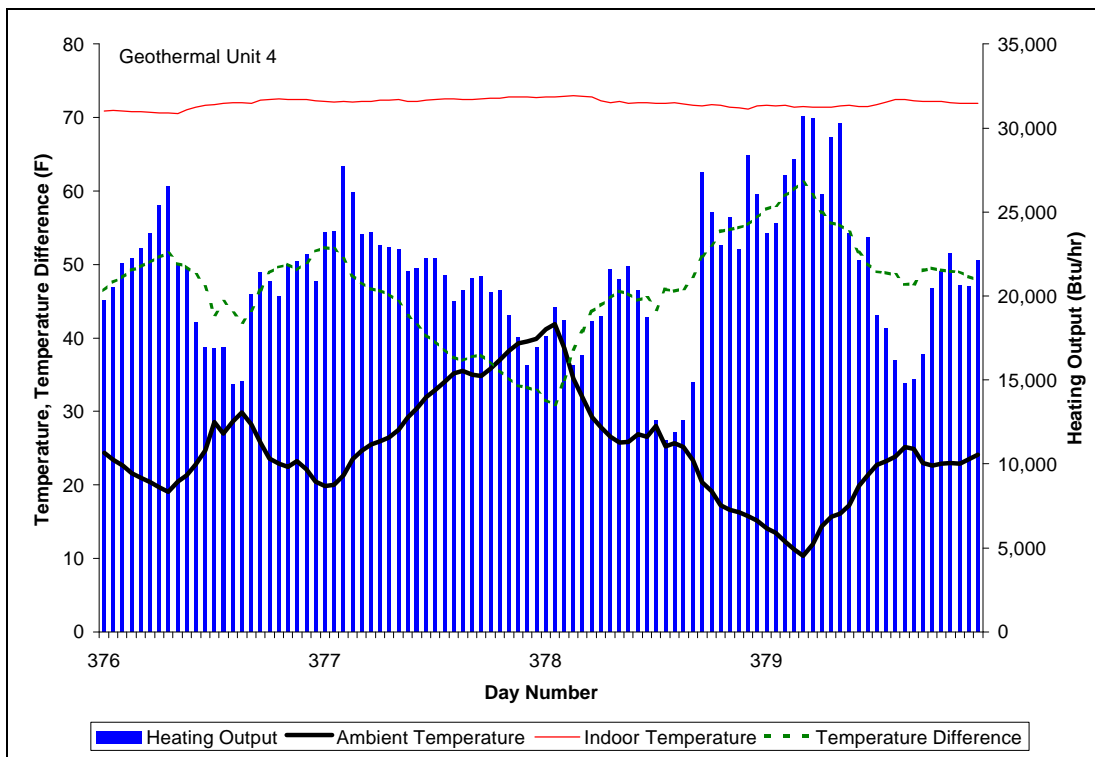


Figure 5: Typical Hourly Heating Operation—Geothermal Unit 5, January 11-14, 1998

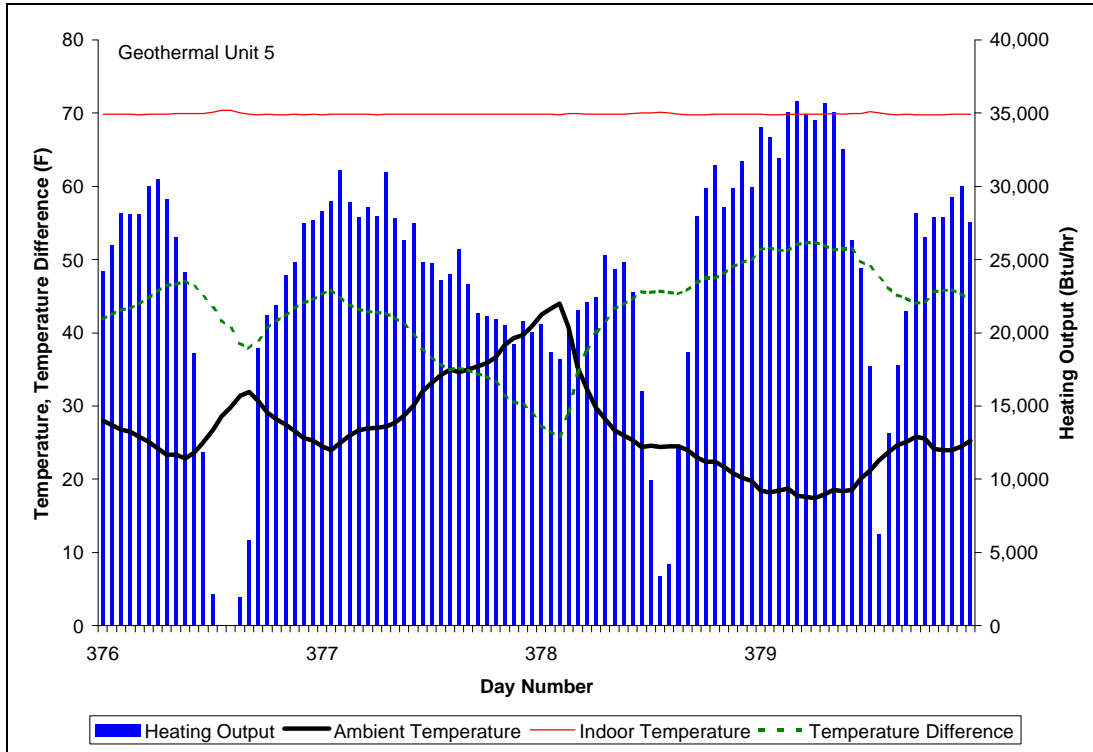


Figure 1 shows the signature of thermostat night setback. The indoor temperature resides at 70°F or higher during daytime hours, and is allowed to decline to about 66°F at night. Little heating energy is used during the setback period. Setback significantly affects the relationship between temperature difference and heating requirements, and must be considered in the investigation of system output at design conditions, discussed later in this report.

In general, Units 2 through 5 show a pattern of heating energy use driven by temperature difference. Figure 2 shows some signs of thermostat manipulation, with a drop in temperature occurring during mid-morning hours on at least the first two days shown. The low heating output of Unit 5 during early afternoon hours is probably the result of passive solar gains in the home.

System Output and Performance In Heating

Heating performance data was evaluated for the 1997 – 1998 heating season (September 1997 through May 1998) and for part of the following season, from September 1998 through January 1999.

The overall heating season performance for each unit is summarized in Table 3 (for the 1997 – 98 season) and Table 4 (for the 1998 – 99 partial season). The number of days with heating output greater than 25,000 Btu provides a comparative indicator of the heating use intensity of each home. Coincident domestic water heating is the water heating output of the

geothermal unit during space heating cycles. This value applies only to Units 3, 4, and 5, which have desuperheaters.

Electrical input, for Units 1 and 2, includes all electric energy used for space heating, and excludes energy used for water heating (hot water loop pump operation at any time, and compressor, loop pump and controls during hot water heating cycles). Electric input for Units 3, 4, and 5 includes all electric input during the heating season, with the exception of energy used during occasional cooling episodes. Water heating is integrated with space heating in these systems, and the energy inputs cannot be differentiated. Heating load to area ratio is the amount of space heating delivered per finished square foot of floor area.

Table 3: 1997-1998 Heating Season Operation of Five Geothermal Systems

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Number of Days with >25,000 Btu Heating Output	192	253	220	211	211
Stage 1 Operating Time, Hours	1043	1214	2901	1896	2335
Stage 2 Operating Time, Hours	-	5.9	734	-	1101
Total Blower Operating Time, Sep - May	1048	4722	3778	1931	3714
Seasonal Measured Heating Output, 10 ⁶ Btu	44.0	76.4	101.0	58.8	84.4
Seasonal Total Electric Resistance Heating, 10 ⁶ Btu	0.0	0.0	0.55	0.12	0.64
Seasonal Coincident DHW Output, Desuperheaters Only 10 ⁶ Btu	-	-	4.9	2.0	2.3
Seasonal Electrical Input, 10 ⁶ Btu	13.4	25.6	35.3	22.5	27.0
Heating/Area Ratio, Btu/sq ft	23,800	33,100	35,000	30,300	30,300

Note: Average measured degree days across site was 5,249 °F-Days at a 65°F base.

Table 4: 1998-1999 Partial Heating Season Operation of Five Geothermal Systems

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Number of Days with >25,000 Btu Heating Output	106	143	124	114	121
Stage 1 Operating Time, Hours	848	1552	1337	1115	1061
Stage 2 Operating Time, Hours			590		699
Total Blower Operating Time, Sep – Jan	848	1992	1997	1119	1897
Measured Heating Output, 10 ⁶ Btu	26.4	42.4	62.1	40.1	44.2
Seasonal Total Electric Resistance Heating, 10 ⁶ Btu	0.0	0.0	2.59	0.10	1.93
Seasonal Coincident DHW Output, Desuperheaters Only 10 ⁶ Btu			2.2	1.1	3.1
Total Electrical Input, 10 ⁶ Btu	8.0	13.5	23.2	12.7	16.1
Heating/Area Ratio, Btu/sq ft	14,300	18,400	21,500	20,700	19,900

Note: Partial season, September – January only. Average measured degree days across site was 3,159°F-Days at a 65°F base.

The total heating load on Unit 1 is the least of the five systems, and is explained by the smaller size of the home, thermostat setback strategy, and an indoor temperature lower than most of the other homes during active heating. The same factors explain the lower heating energy use per square foot for the Unit 1 home. The load on Unit 3 is the largest of the group, explained by the larger size of the home, through decreased influence of internal gains, and an increased influence of glazing area.. The Unit 3 and Unit 5 homes also compete for the largest heating use per square foot.

Each of the five systems easily satisfies the space heating load of the home. The very small amount of auxiliary electric heating used is likely due in part to system oversizing, but also demonstrates the ability of geothermal systems to maintain output at design temperatures. The relatively larger auxiliary heating use in the 1998 – 99 partial season is a result of lower extreme temperatures: the lowest temperature reached during the 1997 – 98 season was about 13 °F, while 1998 – 99 partial season temperatures reached -1°F. The winter design temperature for northeastern Ohio is 5 °F. Although the occupants of the Unit 1 home practice a daily thermostat setback, no backup electric resistance heating is used during recovery periods. This is due to the intentional disabling of the auxiliary heating when the system is in normal operating mode.

Table 5 provides a summary of performance based on both heating seasons. COP values are calculated directly from combined seasonal input and output values reported in the table. COP values for Units 1 and 2 are for heating only, while the values for Units 3, 4, and 5 include domestic water heating. Entering water temperature refers to the temperature of fluid returning from the ground loop to the geothermal unit.

Table 5: 1997-1999 Combined Seasonal Heating Performance of Five Geothermal Systems

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Maximum Hourly Heating Output (Compressor only)	35,950	37,480	43,250	34,410	28,739
Compressor Operating Time during Maximum Heating Output Hour (min)	60	60 (Stage 2)	60	60	60 (Stage 2)
Minimum Entering Water Temperature during Operation, °F	32.6	33.0	27.0	31.9	29.7
Typical Ground Loop Flow Rate, Stage 1 (gal/min)	9.1	12.0	8.2	11.1	6.6
Typical Ground Loop Flow Rate, Stage 2 (gal/min)	N/A	*	11.5	N/A	9.2
Operating COP (Heating Only)	3.30	3.04	-	-	-
Operating COP (Heating + Water Heating)	-	-	2.91	3.14	3.18
Rated Compressor Heating Capacity (per ARI 330), Btu/hr	29,000	32,500	42,000	31,000	33,000
Resistance Heating Capacity, Btu/hr	34,000	49,000	67,000	49,000	34,000
Rated Ground Loop Flow (gpm) (St1/St2)	9.0	5.0/10.0	8.0/14.0	8.0	6.0/12.0
Rated COP per ARI 330	3.1	3.2	3.0	3.2	3.1

* No data available

Note: ARI 330 ratings are based on an entering water temperature of 32°F and an air temperature of 70°F.

The maximum measured output exceeds the rated output in four of the five cases. Contributing factors may include differences in entering water temperature and return air temperature between standard rating conditions and operating conditions when the maximum output was measured. In the case of Unit 5, domestic water heating energy output of about 3,000 Btu was recorded in addition to the space heating output.

The measured COPs are generally near manufacturers' ratings. However, the manufacturers' ratings are for the highest level of output (Stage 2 in 2-stage systems), and Stage 1 operation should offer higher COPs. The COP of Unit 2 is affected by fan operation and by the ground loop pump. The owners of Unit 2 choose to keep the fan operating full time, and the system draws about 85 Watts in the fan-only operating mode. This power draw reduces system COP by about 3 percent. The ground loop flow rate in Unit 2 is typically about 12 gpm, while the manufacturer's ratings call for only 5 gpm in Stage 1 operation. Operation at the higher flow rate increases power consumption, and, while it may have modest heat transfer benefits, it probably has a negative effect on COP.

The minimum entering water temperatures (EWT), recorded in Units 3 and 5 both drop below freezing, a possible indication of loop undersizing. Both these systems would be expected to operate at higher seasonal COPs if the loop temperatures were higher.

Seasonal Performance Trends in Heating

Seasonal trends in ground loop temperature and COP can be used as indicators of design and performance problems such as ground loop undersizing. Figure 6 through Figure 10 present 1997 – 98 heating season trends for each unit, including output, outdoor ambient temperature, entering water temperature, and COP using daily average values.

Figure 6: 1997-1998 Heating Season Performance Trends—Geothermal Unit 1

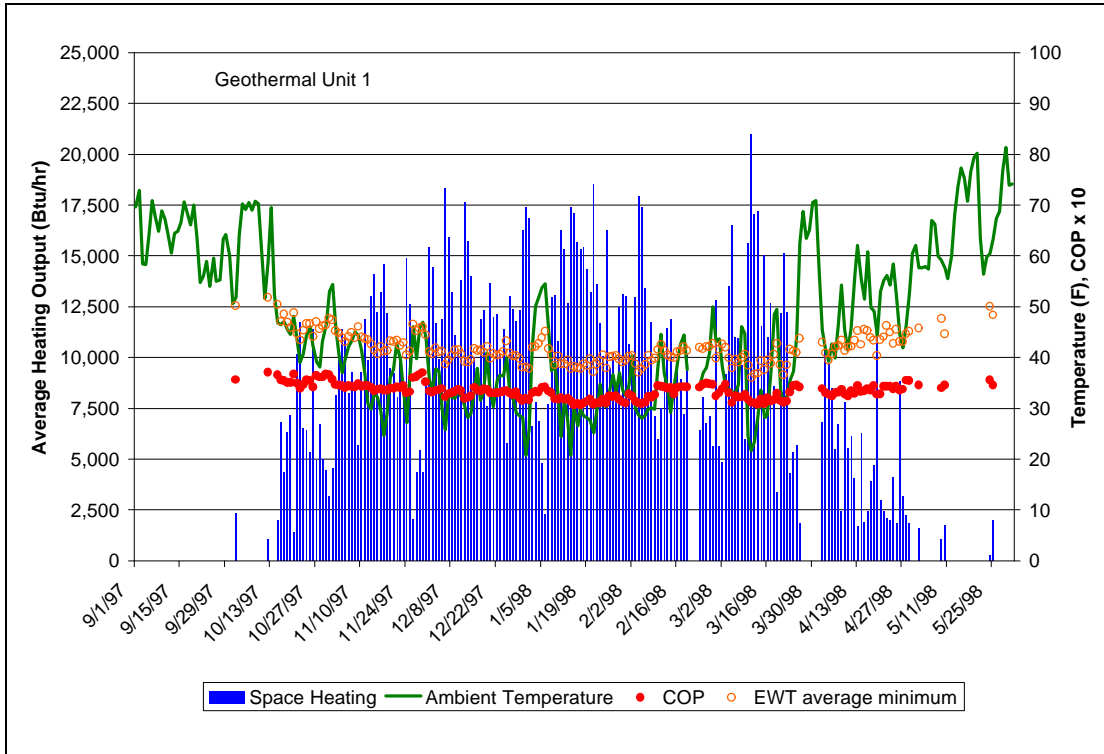


Figure 7: 1997-1998 Heating Season Performance Trends—Geothermal Unit 2

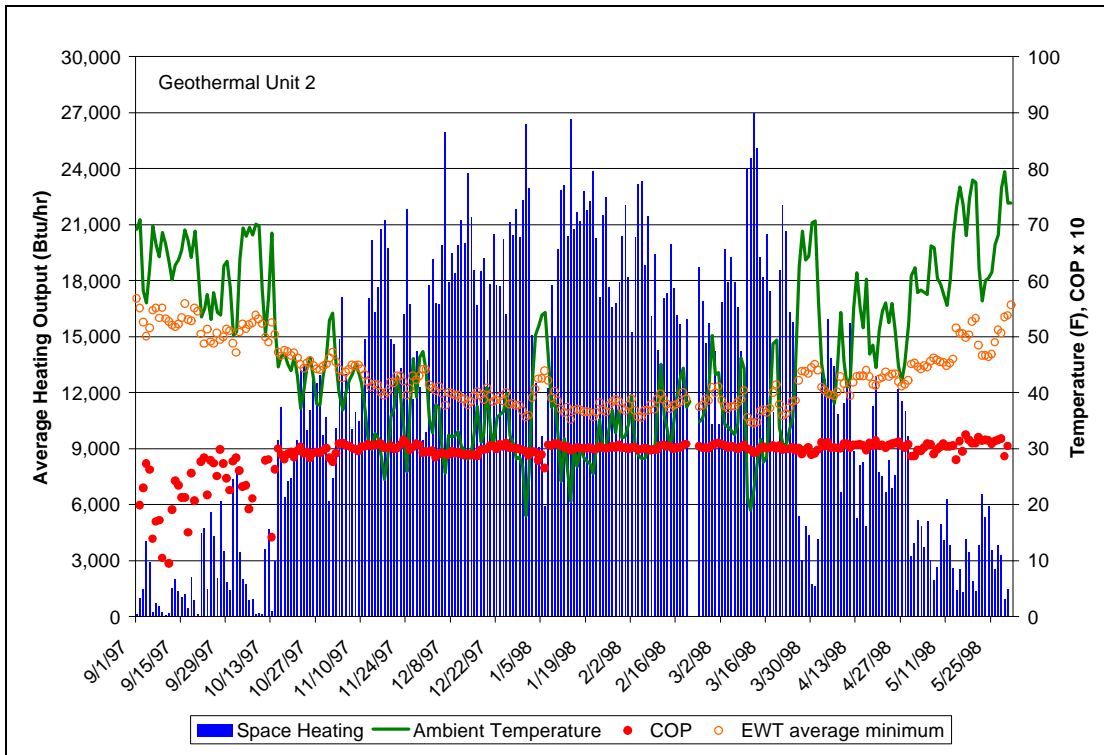


Figure 8: 1997-1998 Heating Season Performance Trends—Geothermal Unit 3

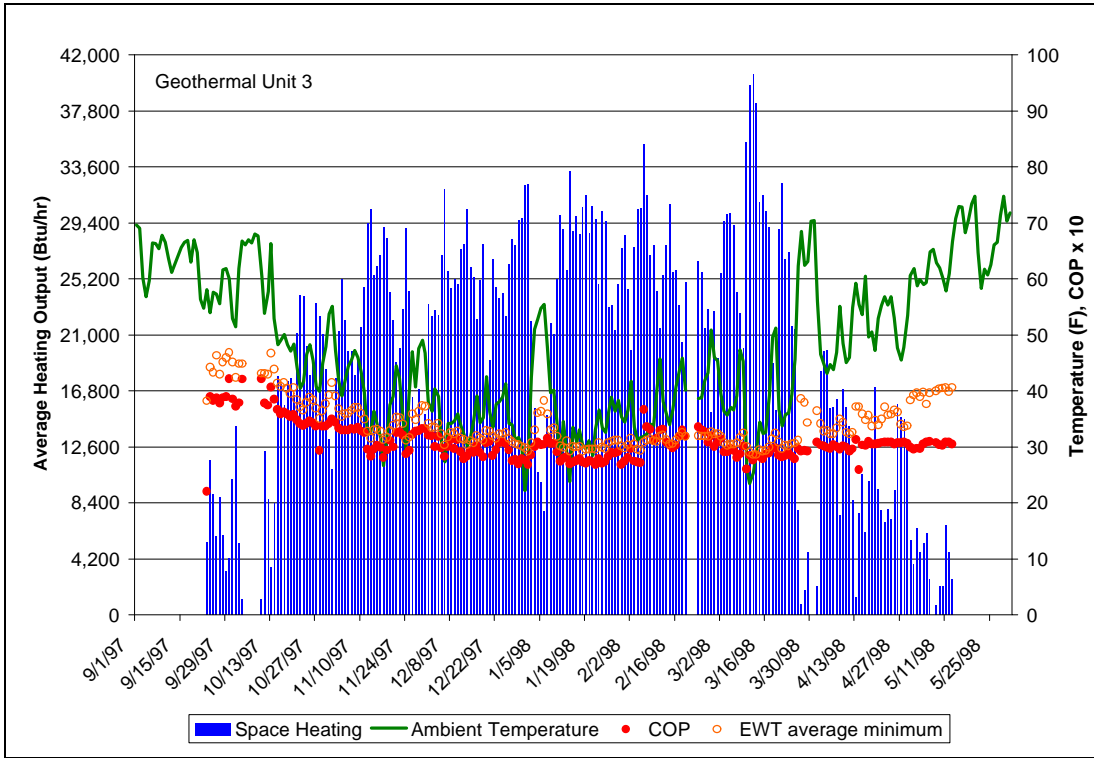


Figure 9: 1997-1998 Heating Season Performance Trends—Geothermal Unit 4

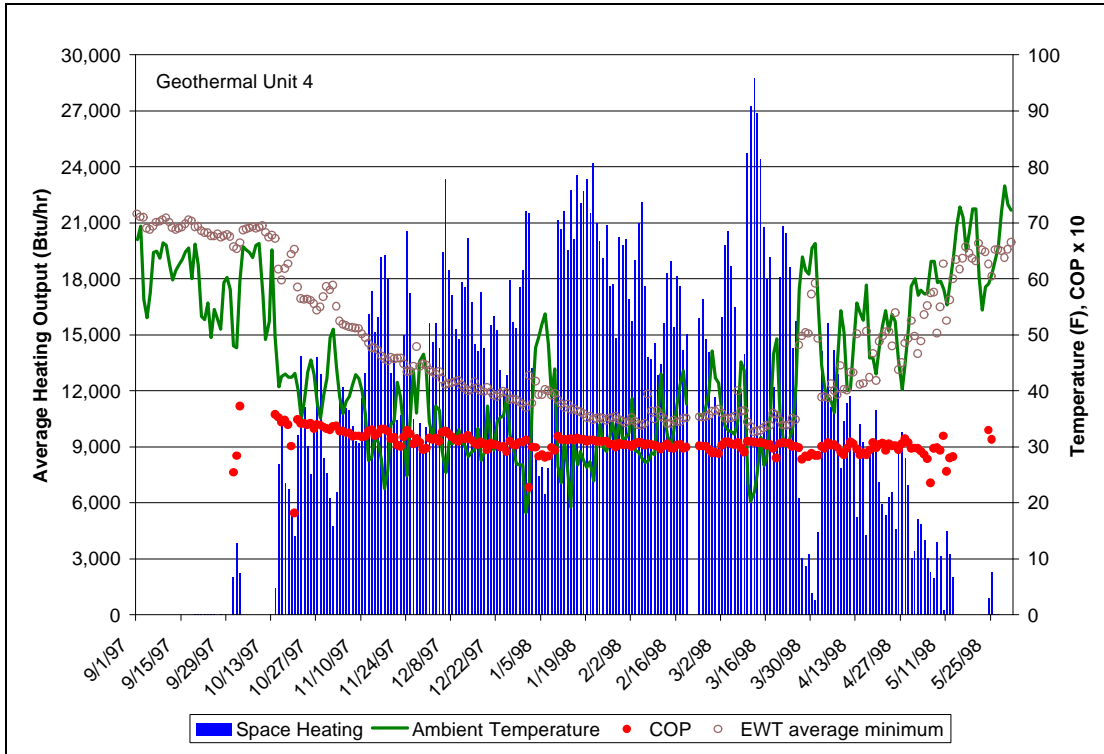
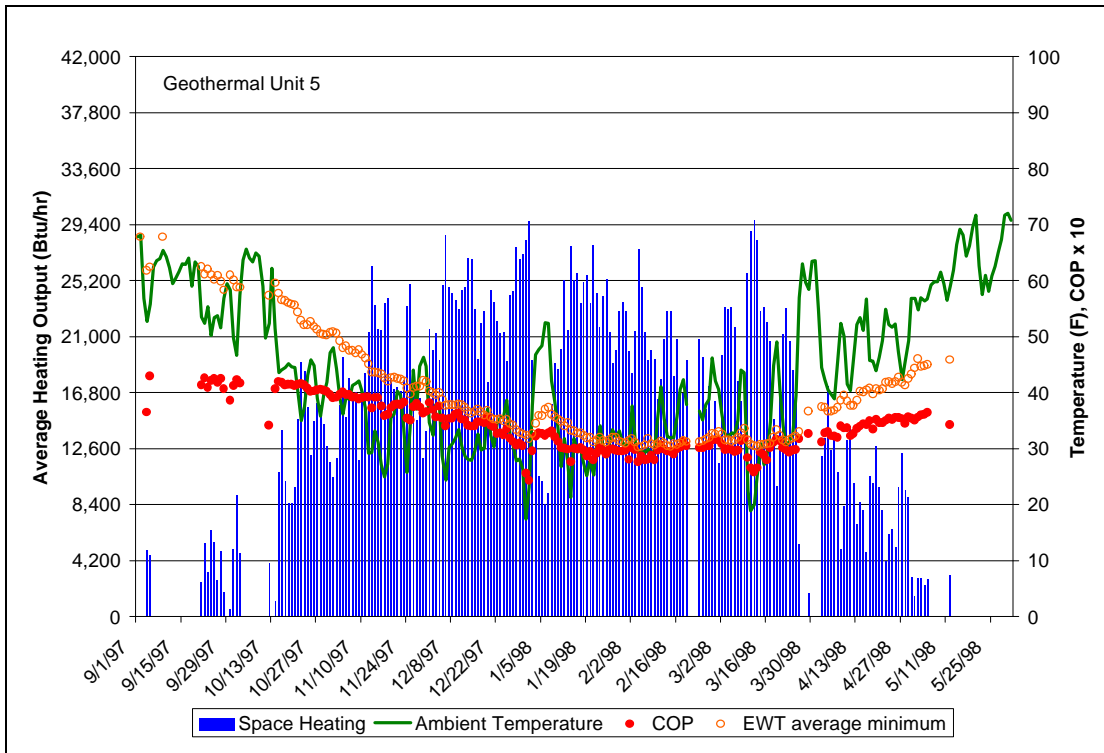


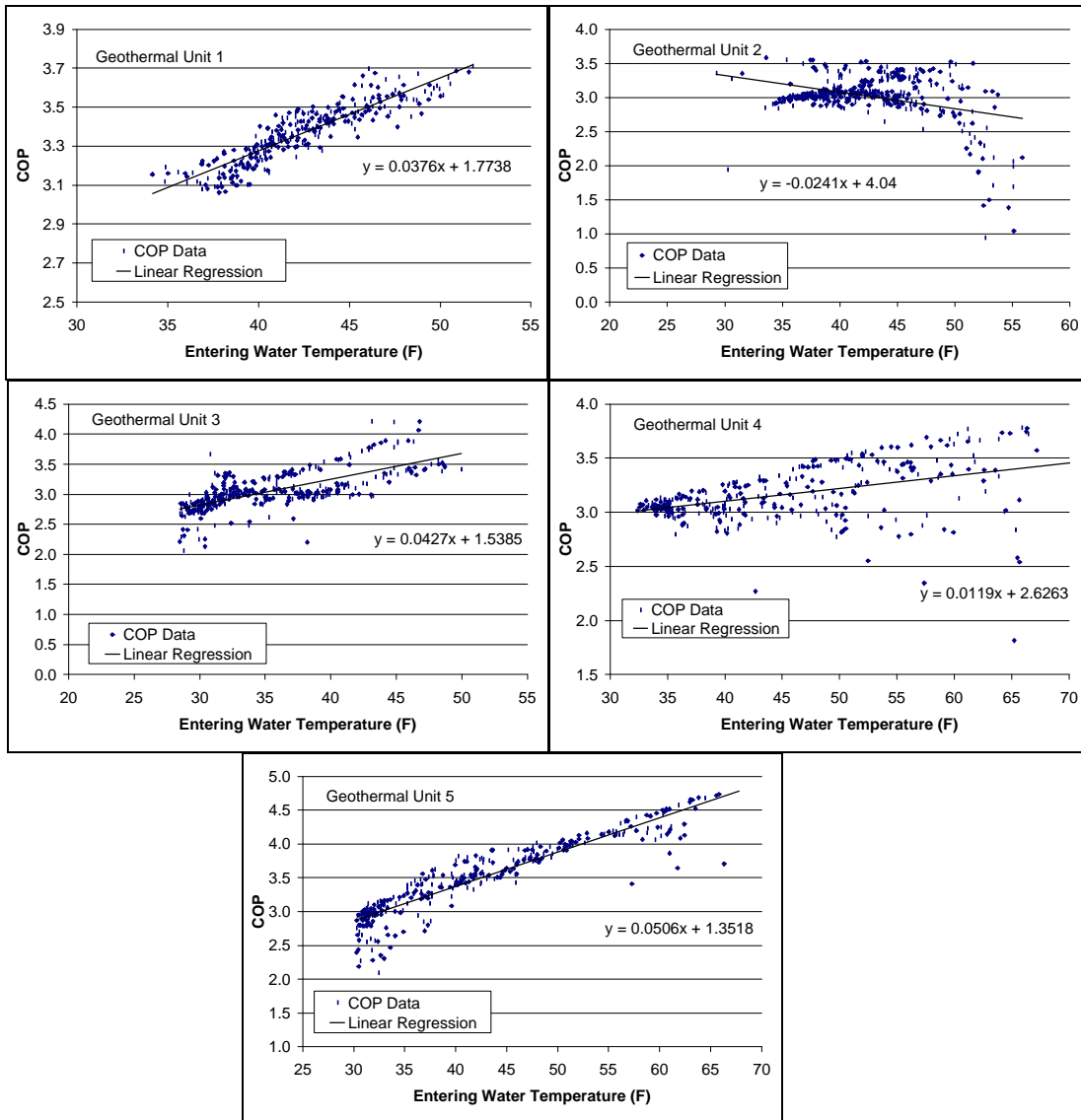
Figure 10: 1997-1998 Heating Season Performance Trends—Geothermal Unit 5



Units 1 and 2 show ground loop temperatures that remain well above 32°F throughout the heating season, and COP values that remain relatively flat, both indicating adequate ground loop sizing. The COP for Unit 2 is very low early in the season, as a result of continuous fan operation combined with a small load. Unit 3 shows a loop temperature that drops below 30°F, and significantly depressed mid-season COP values, probable indications of a somewhat undersized ground loop. (An undersized ground loop in this context may be too short, or may suffer from poor thermal conductivity of the grout or surrounding soils). Units 4 and 5 show greater seasonal swings in loop temperature, a characteristic of horizontal loops installed closer to the surface. Unit 4 shows a pattern of adequate loop sizing, with loop temperatures consistently above 32°F. Unit 5 displays lower loop temperatures, and may have a slightly undersized loop.

The relationship between loop temperature and operating COP was explored using daily average values for both heating seasons. Figure 11 shows the relationships graphically.

Figure 11: COP vs. Entering Water Temperature, 5 Geothermal Systems, Combined 1997-1999 Heating Seasons, Daily Average Values



In general, the systems show the expected trend of increasing heating COP with increasing ground loop temperature. The trend for Unit 2 is distorted by the low COP values resulting from full time fan operation early in the season, when loop temperatures are relatively high. The two apparent branches of the data for Unit 3 represent Stage 1 and Stage 2 operation. The reason for the large amount of scatter in the Unit 4 data is unknown. Among the three systems showing a distinct positive correlation of COP and entering water temperature, the average slope of the regressions is 0.044, representing a change in COP value of 0.4 with a 10°F change in loop temperature.

COOLING PERFORMANCE

Typical Cooling Operation

Typical operation of the systems in cooling is displayed in Figures 12 through 16. Each graph indicates a positive correlation between outdoor temperature and cooling output. Unit 1 and 2, however, experience sharp changes in indoor temperature, and unit output drops to zero during some periods of high outdoor temperature. This provides evidence of changes in thermostat setting. Unit 4 shows less pronounced evidence of thermostat changes. Units 3 and 5 show stable indoor temperatures and system output matching the outdoor temperature trend, and more continuous operation than the other systems. The indoor temperature setpoint varies among the homes, with Units 1 and 2 set at about 77°F during cooling operation, Units 3, 4 and 5 set between 73°F and 76°F. Units 3, 4 and 5 also demonstrate short-term increases in entering water temperature associated with high cooling output.

Figure 12: Typical Hourly Cooling Operation—Geothermal Unit 1, August 8-11 1998

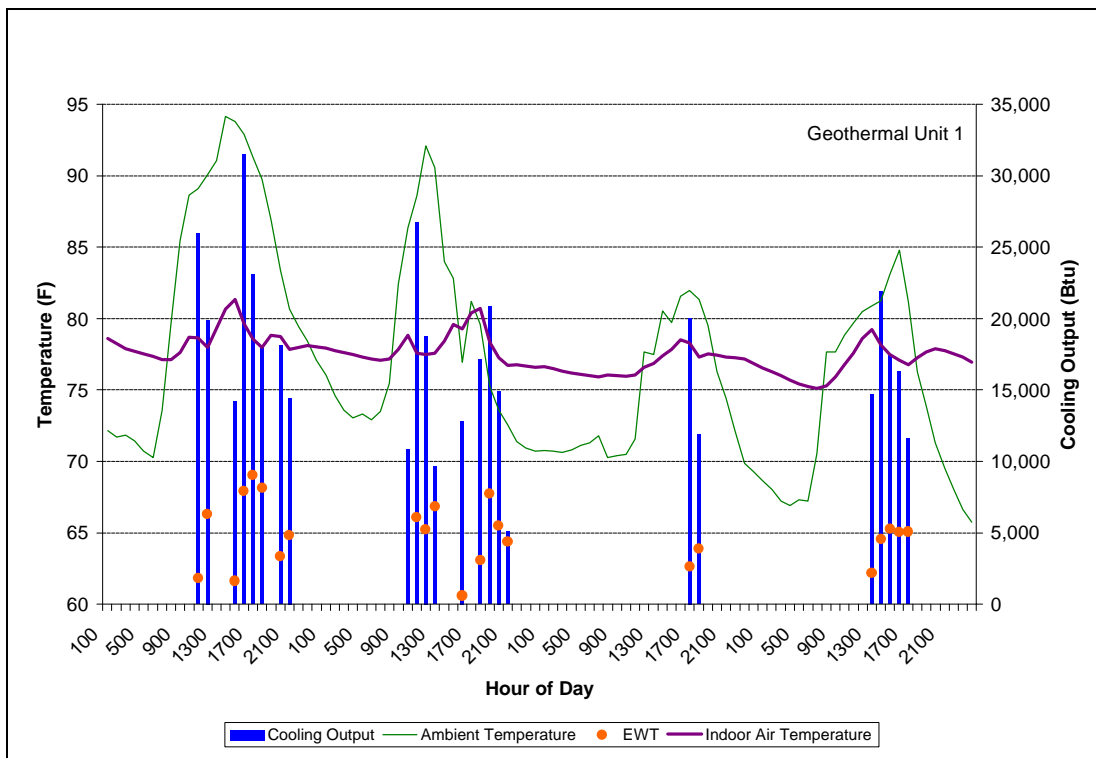


Figure 13: Typical Hourly Cooling Operation—Geothermal Unit 2, August 8-11, 1998

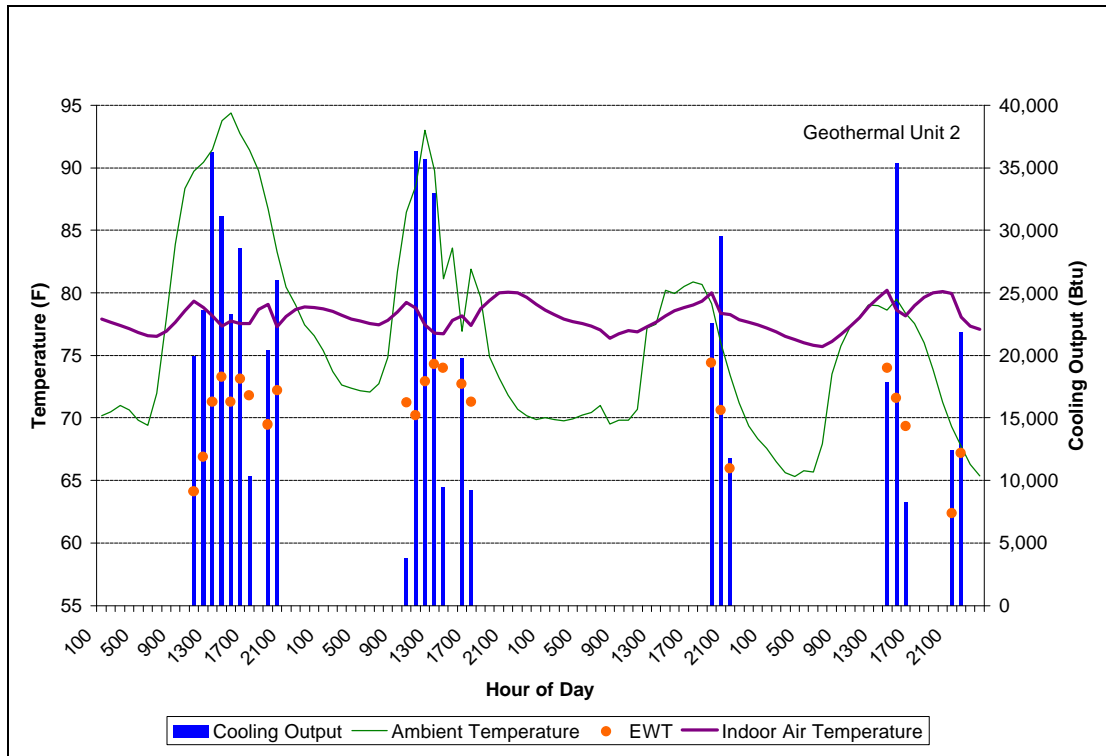


Figure 14: Typical Hourly Cooling Operation—Geothermal Unit 3, August 8 – 11, 1998

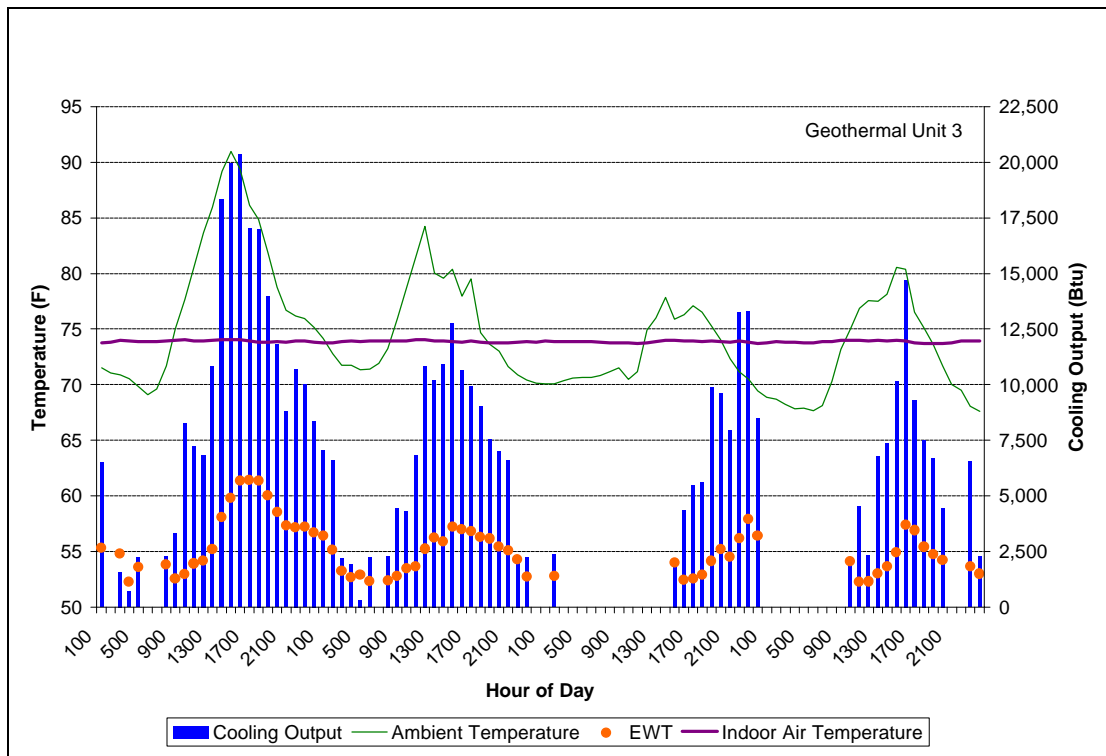


Figure 15: Typical Hourly Cooling Operation—Geothermal Unit 4, August 8-11, 1998

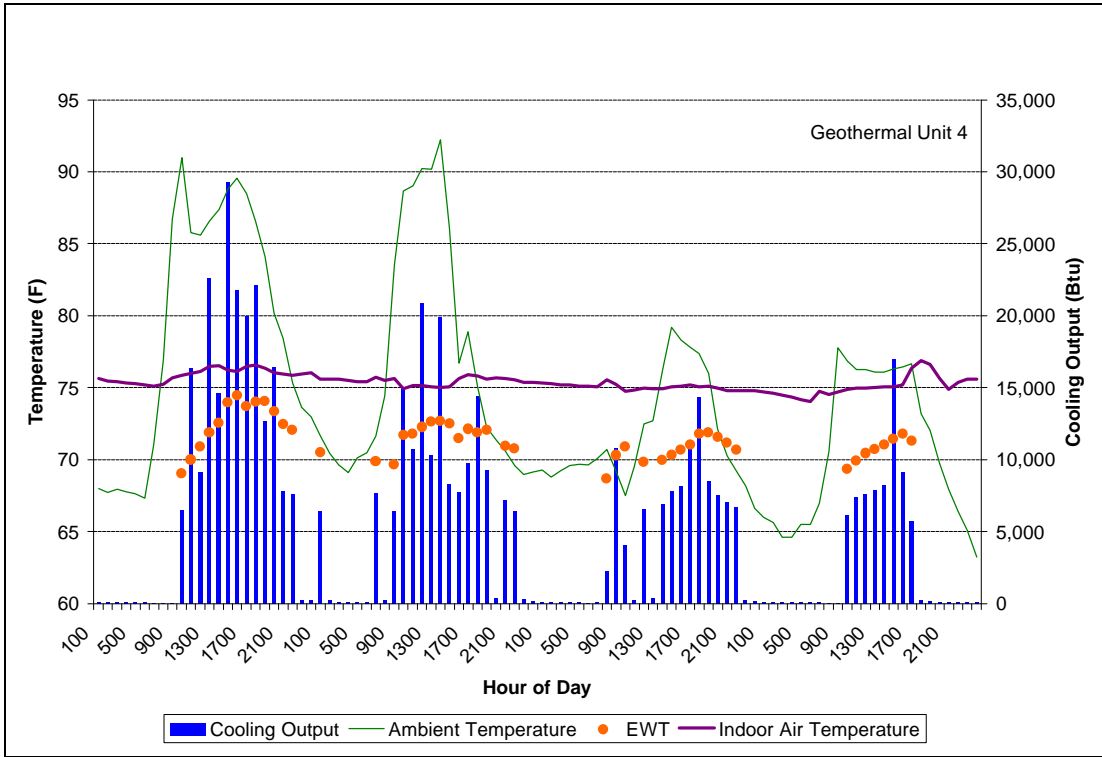
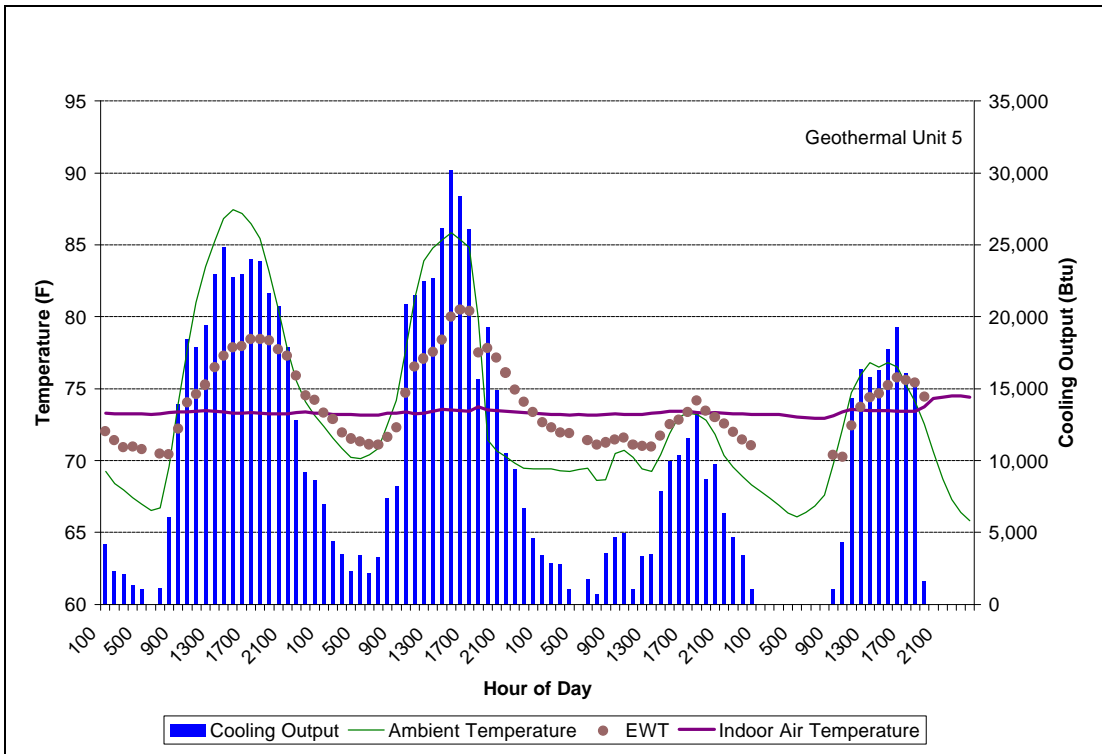


Figure 16: Typical Hourly Cooling Operation—Geothermal Unit 5, August 8 – 11, 1998



System Output and Performance in Cooling

Cooling season performance for the five systems is summarized in Table 6. The number of days with average cooling output > 25,000 Btu/hr provides comparison of the intensity with which each system is used. Total cooling output is the total output (sensible and latent) for the cooling season, while Cooling Load/Area Ratio is the amount of cooling delivered per finished square foot of area.

Table 6: 1998 Cooling Season Operation of Five Geothermal Systems

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Number of Days with Cooling Output > 25,000 Btu	31	111	77	79	65
Stage 1 Operation (hr)	127.8	216.3	203.6	250.4	459.6
Stage 2 Operation	N/A	195.1	1.1	N/A	112.3
Blower Operation (hr)	91.6	744.6	237.0	251.2	647.1
Total Cooling Output, 10 ⁶ Btu	3.007	13.445	7.275	9.908	13.926
Latent Output, 10 ⁶ Btu	0.6	2.1	1.3	2.2	1.6
Latent Fraction of Total Cooling (%)	19.5	15.8	17.1	22.1	11.3
DHW Output – Desuperheaters Only, 10 ⁶ Btu	N/A	N/A	0.221	0.213	0.099
Domestic Hot Water Pump Operation (hr)	N/A	N/A	202.0	178.4	618.7
Loop Input, 10 ⁶ Btu	3.799	17.345	8.705	12.599	17.797
Electric Input, 10 ⁶ Btu	0.792	3.899	1.652	2.904	3.971
Compressor Run Time (hr)	127.8	411.3	204.7	250.4	571.9
Compressor Seasonal Duty Cycle	0.054	0.122	0.064	0.076	0.182
Cooling/Area Ratio, Btu/sq ft	1,650	5,850	2,500	5,100	6,250

Note: Average measured cooling degree days across sites was 402 °F-Days at a 74 °F base.

The load on unit 2 is much greater than that on Unit 1, a home of similar construction, simply because the occupants choose to cool the home more frequently. Units 3, 4, and 5 are similar to one another in the intensity of cooling use, and are not operated as many days as Unit 2.

The Unit 1 and Unit 3 homes use the least total cooling and least cooling per square foot. However, the primary reason that Unit 1 is little used is the occupant pattern of control, in activating the system only sparingly. Unit 3 is set to keep the home at about 74°F throughout the season, however, this home site is heavily wooded. It is the only site with significant shading. The shading probably accounts for the lower cooling requirement. The Cooling Load/Area Ratio for Unit 2 is more than three times the value for the similarly constructed Unit 1, indicating the dominant effect that occupant control habits can have on cooling requirements.

Units 2, 3, and 5 have two stages of cooling available. Unit 2 shows a relatively high number of hours in Stage 2 operation. This is probably a function of frequent thermostat changes. By contrast, Unit 5 shows a much smaller fraction of hours in Stage 2, and Unit 3 shows almost none. The operation of Unit 3 is probably influenced by the shading of the site,

limiting the maximum cooling loads. Table 7 summarizes cooling performance of the five systems.

Table 7: 1998 Cooling Season Performance of Five Geothermal Systems

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Maximum Hourly Cooling Output, Btu/hr	36,400	41,710	49,390	46,930	41,580
Compressor Operation during Maximum Cooling Hour, min	60	60 (Stage 1)	7 (St 1) 52 (St 2)	60	60 (Stage 2)
COP – Cooling Only	3.80	3.45			
COP – Cooling + Domestic Hot Water			4.54	3.49	3.53
<i>Rated Cooling Capacity per ARI 330, Btu/hr</i>	<i>36,600</i>	<i>47,800</i>	<i>61,000</i>	<i>42,000</i>	<i>50,000</i>
<i>Rated EER (COP)</i>	<i>12.7</i> <i>(3.7)</i>	<i>15.0</i> <i>(4.4)</i>	<i>12.6</i> <i>(3.7)</i>	<i>13.2</i> <i>(3.9)</i>	<i>14.0</i> <i>(4.1)</i>

Note: ARI rating conditions for cooling are 77°F entering water temperature and 80°F entering air temperature.

The maximum measured cooling output of several systems is lower than rated values. This is explained, in the case of Unit 2 and 3, partly by the fact that the systems did not operate a full hour using Stage 2. Unit 5 has a loop flow rate below the manufacturer’s rated value, as mentioned earlier, which may reduce its effective capacity.

The measured COP values vary significantly from rated values in some cases. This may be due in part to the effect of relatively low loads and short operating cycles. Unit 3 in particular operates in very short cycles in cooling, discussed in a later section. Unit 2 has a high loop flow rate, implying high loop power consumption, and uses full-time fan operation at most times, reducing COP. Unit 5 is the only system that shows any evidence of loop capacity problems in cooling, covered in the following section.

Seasonal Performance Trends in Cooling

Figures 17 through 21 present 1998 cooling seasonal performance trends for the five systems studied, using daily average values.

Figure 17: 1998 Cooling Season Performance Trends—Geothermal Unit 1

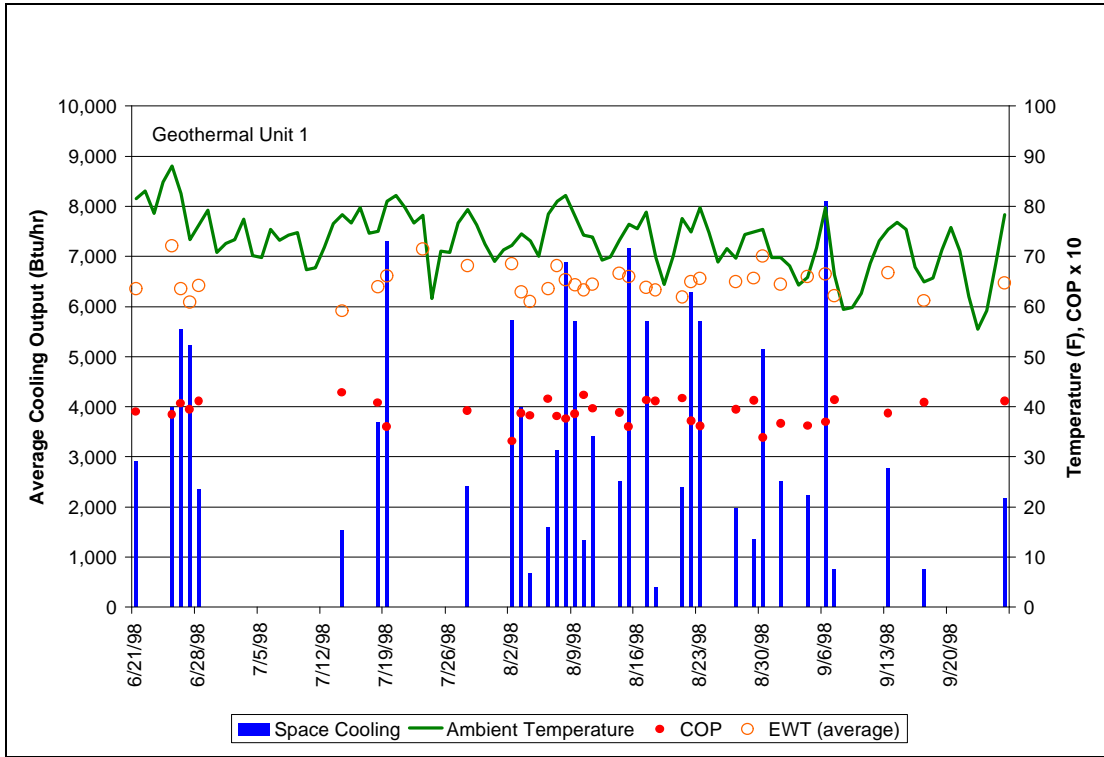


Figure 18: 1998 Cooling Season Performance Trends—Geothermal Unit 2

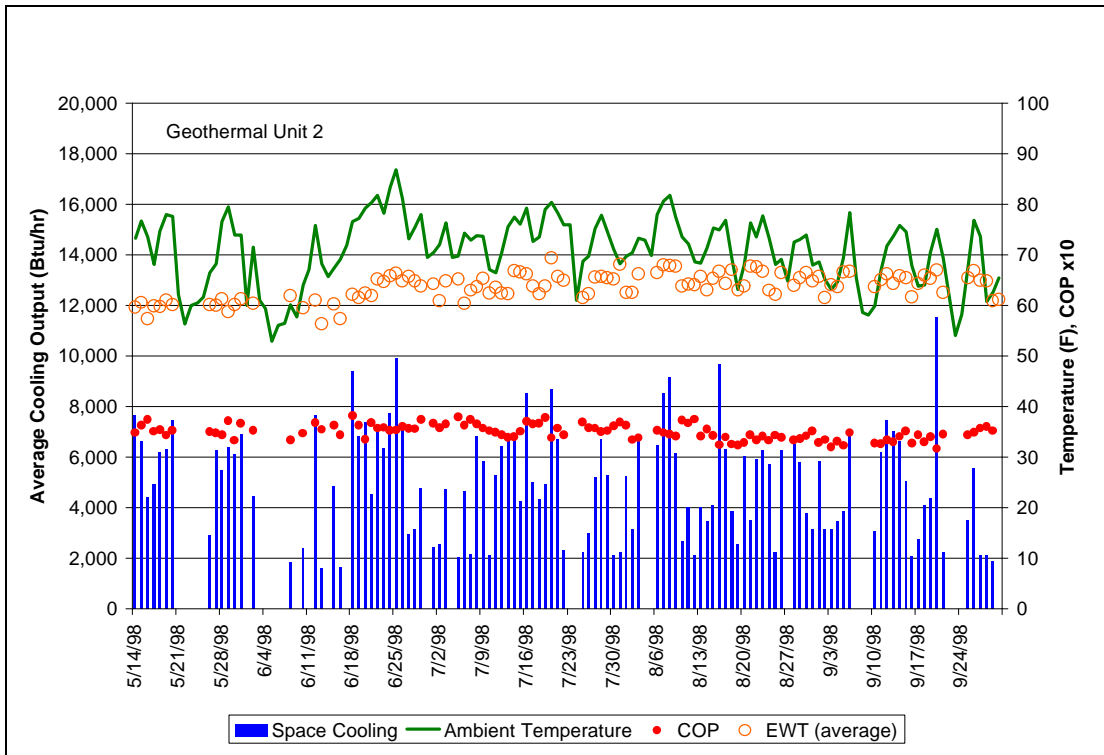


Figure 19: 1998 Cooling Season Performance Trends—Geothermal Unit 3

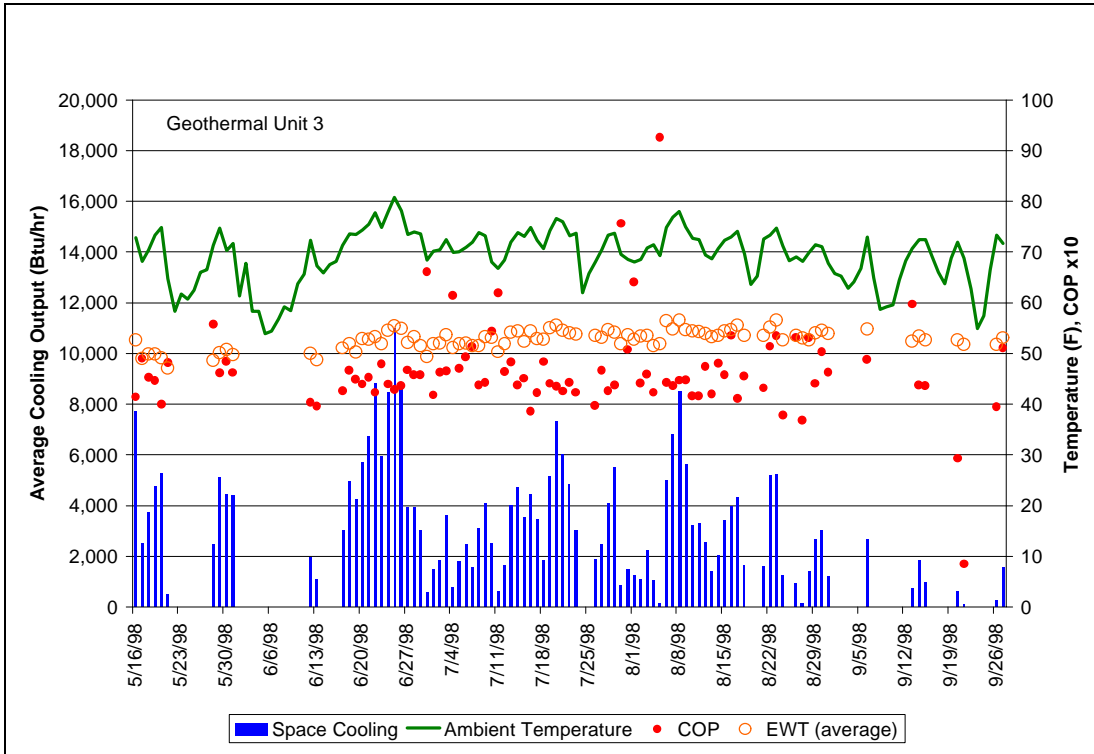


Figure 20: 1998 Cooling Season Performance Trends—Geothermal Unit 4

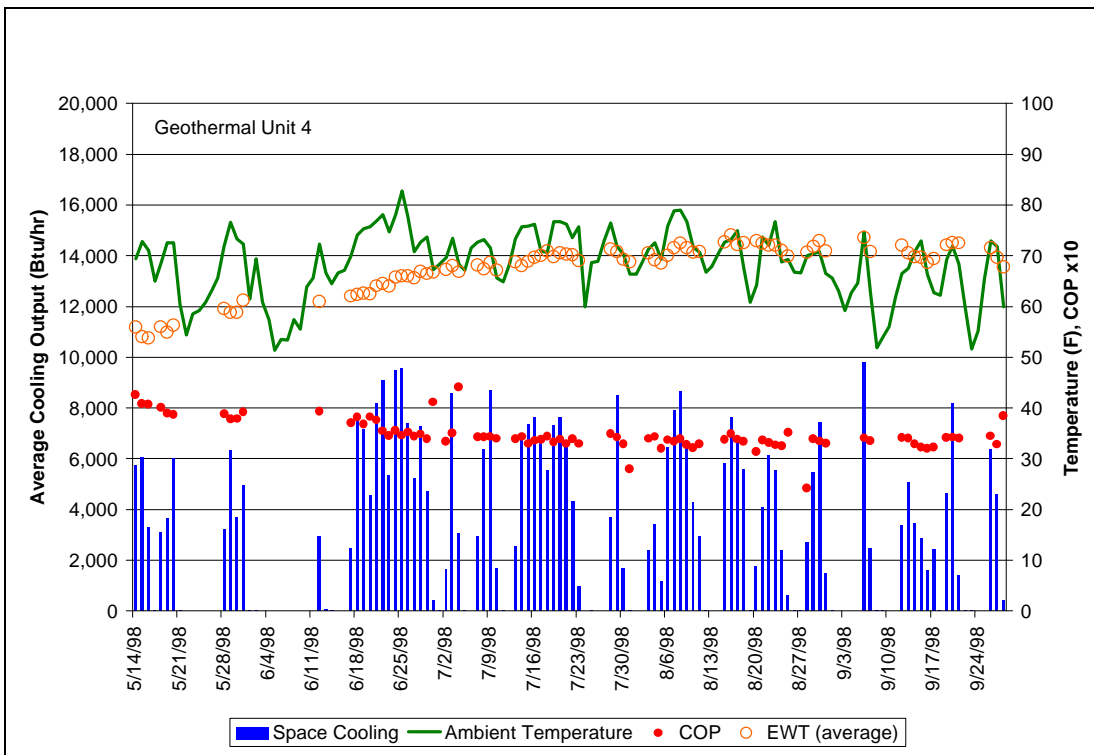
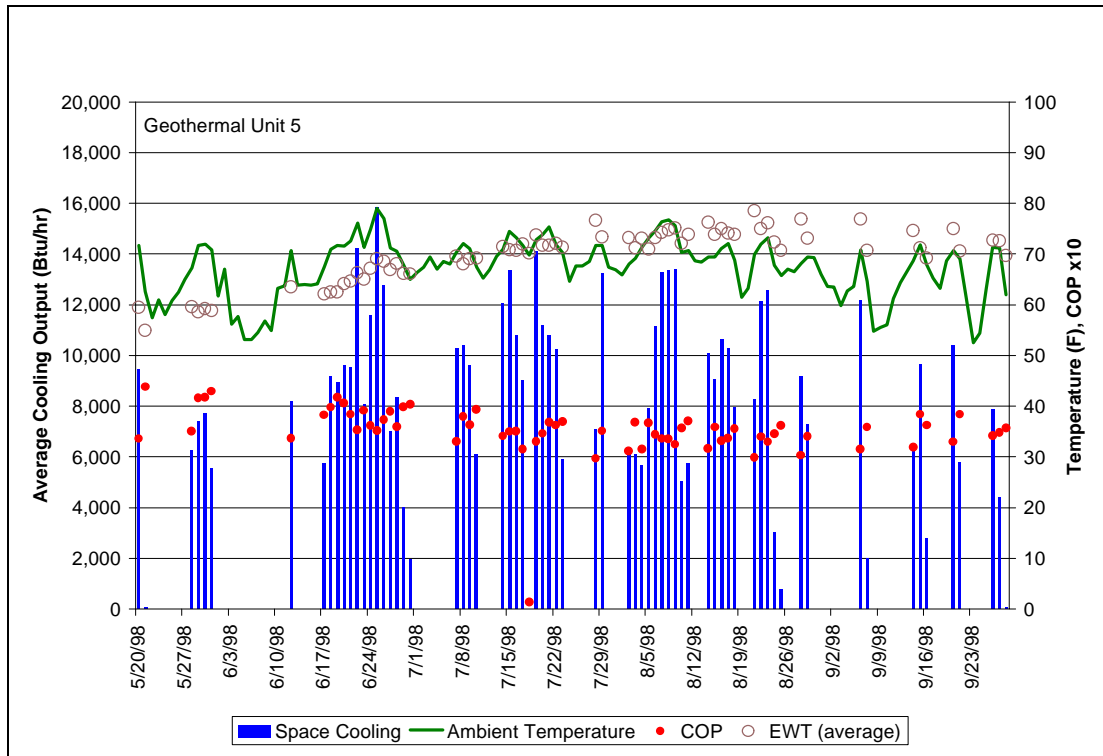


Figure 21: 1998 Cooling Season Performance Trends—Geothermal Unit 5



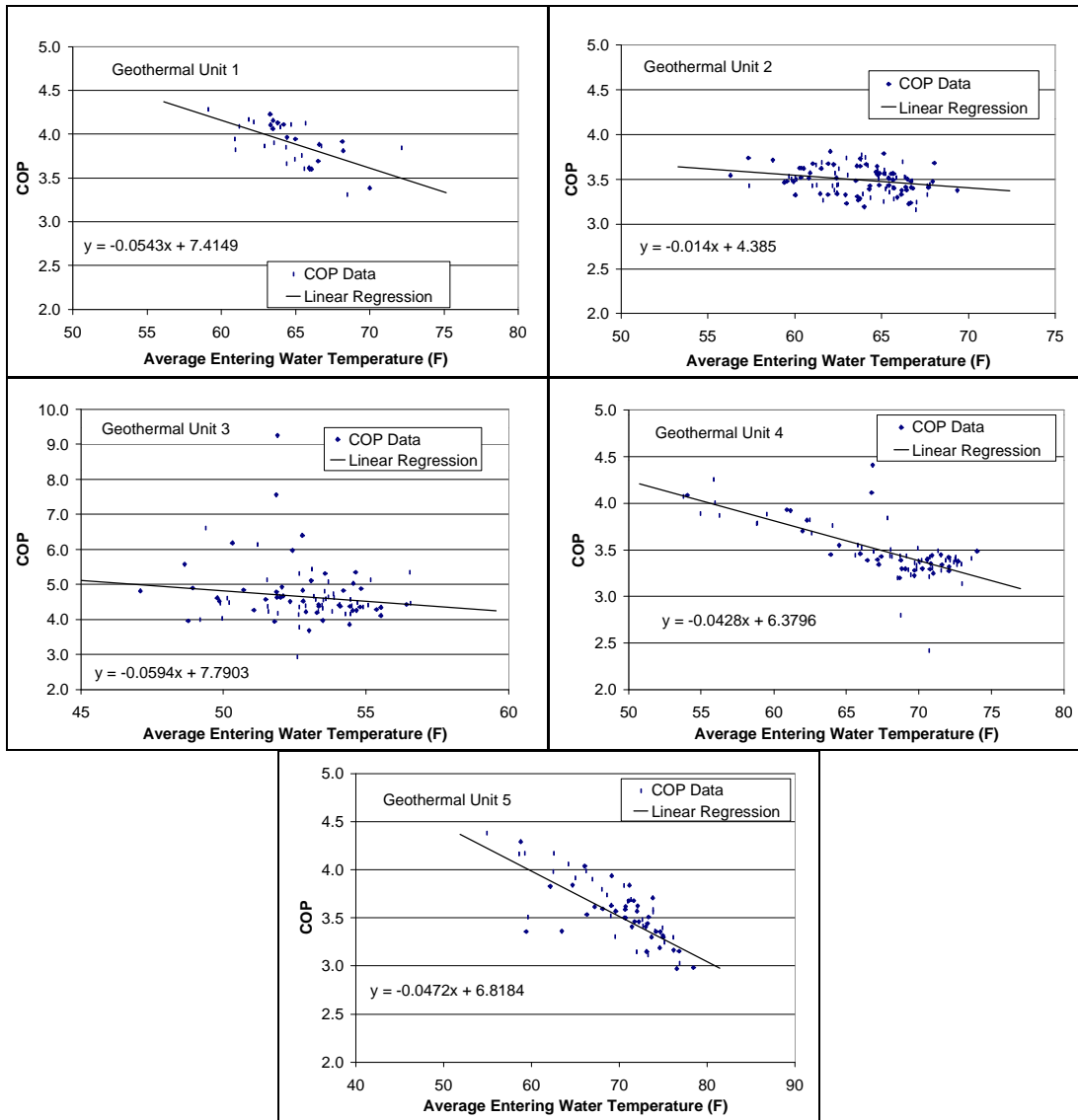
Each system shows intermittent operation; there are a number of days within the cooling season when the systems do not operate. The effect of occupant control in limiting use of cooling is apparent in the graph for Unit 1. The trend in entering water temperature and operating COP for Units 1, 2, and 3 is fairly flat, and temperatures remain moderate. This indicates that the ground loops are adequately sized for the cooling loads imposed. The behavior of the Unit 3 ground loop in cooling may be contrasted with that in heating, when the loop temperature dropped to the lowest of the five systems. The 1998 seasonal cooling load on Unit 3, however, was about 12 percent of the 1997 – 98 seasonal heating load, and the loop appears to be quite adequate for cooling. The scatter in COP values for Unit 3 is the result of error terms in the estimated desuperheater output, which is calculated independently from an energy balance around the water heater, in conjunction with small measured cooling output.

Entering water temperatures for Units 4 and 5 experience a greater rise during the season, characteristic of horizontal ground loop installation. While the Unit 4 data shows temperatures that climb to just over 70°F on a daily basis, Unit 5 loop temperatures approach 80°F. Hourly data for Unit 5 also shows sharp increases in loop temperatures during cooling operation, providing evidence of loop undersizing or low heat transfer.

The relationship of Coefficient of Performance to entering water temperature is explored in Figure 22. Four of the five systems exhibit similar slopes in the relationship, with an average slope of -0.051 . This implies a COP reduction of 0.5 with a loop temperature drop of 10°F.

The reason that the COP vs. entering water temperature relationship for Unit 2 shows a much lower slope is not known.

Figure 22: COP vs. Entering Water Temperature, Five Geothermal Systems, 1998 Cooling Season, Daily Average Values



SYSTEM SIZING

One objective of the study is the comparison of the measured output of the systems at design conditions to the calculated heating requirements at design conditions. The importance of installing systems with adequate capacity to meet heating (and cooling) loads at design conditions is obvious in allowing maintenance of a comfortable temperature under severe conditions. System oversizing may additionally permit faster recovery from temperature setback, encouraging the use of this fundamental energy savings strategy. Significant

oversizing, however, also may have significant negative consequences, related to increased cycling rates and to cost. Oversizing is generally expected to result in increased rates of cycling, as a shorter period of operation is required to satisfy the thermostat. In both heating and cooling, such cycling may increase wear and tear on the compressor and other moving components. In cooling operation, dehumidification increases as the coil temperature decreases, and short cycling can lead to inadequate dehumidification. Increased sizing also implies increased system cost. This is particularly true of geothermal systems, due to the cost of placing ground loops which adds an average of about \$ 850 per ton (12,000 Btu/hr) of capacity.

Characterizing Heating Loads

A simplified method for experimentally finding the rate of heat loss of a building at design conditions would be the measurement of system output at design conditions. This method is limited in its reliance on a small amount of data, which makes the method susceptible to short term deviations from typical performance, and to scatter in the data. Instead, a common model was used to explain heating and cooling energy use.

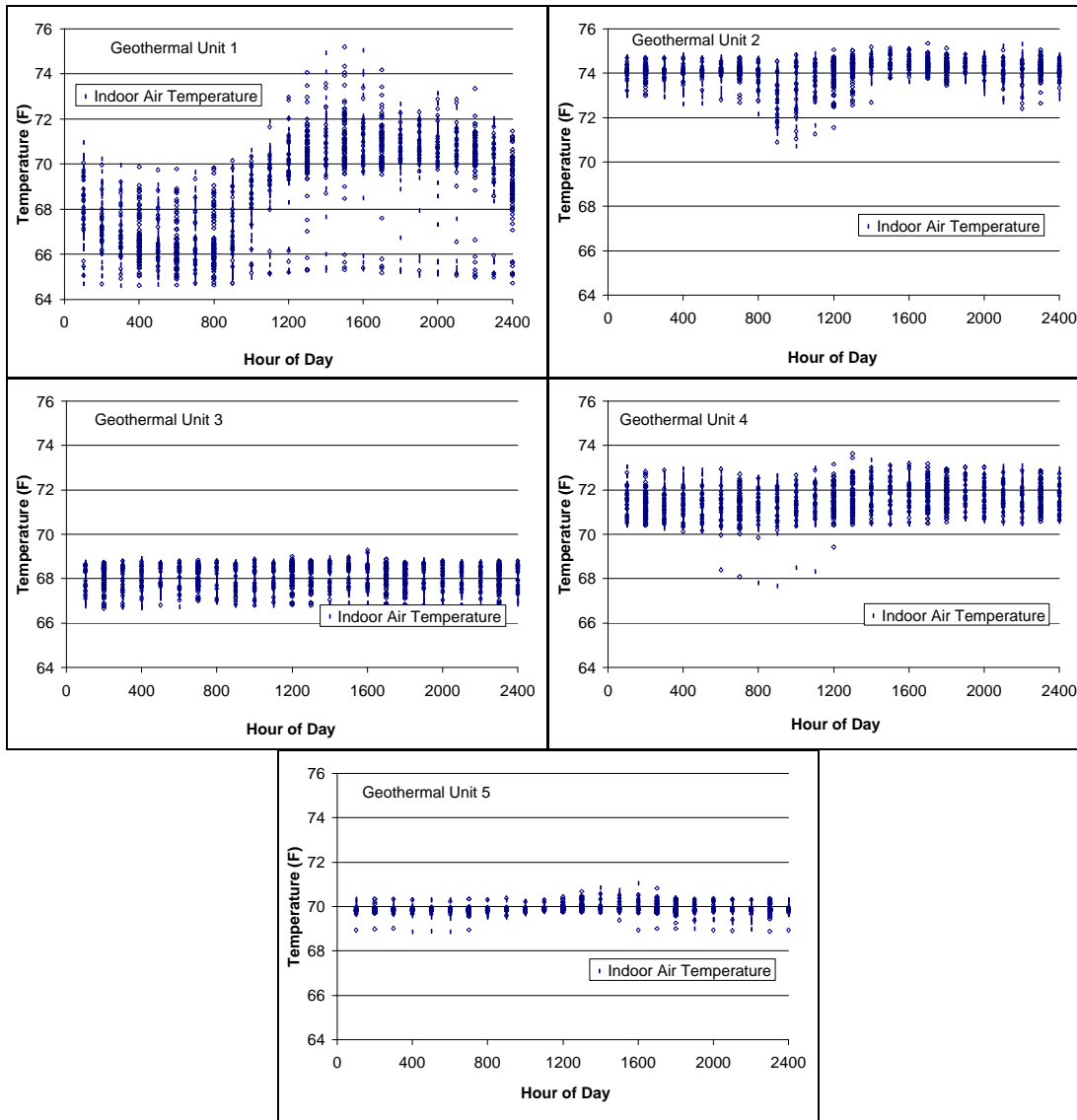
The steady state heating requirement for homes is often modeled as a linear function of the indoor-outdoor temperature difference, less the average rate of internal heat gains (including miscellaneous indoor electric loads, occupants, and solar gains):

$$\text{Heat Required} = (\text{Heat Loss Coefficient} \times \text{Temperature Difference}) - \text{Internal Gains}$$

This relationship assumes steady state conditions and a purely linear relationship between heat loss and temperature difference.

Values of Heat Loss Coefficient and Internal Gains can be estimated from a regression of measured heating output against temperature difference. Before performing this regression, the stability of the indoor temperature was evaluated in each home during the heating season. Changes in thermostat setting cause sudden changes in system output, violating the assumption of steady state performance and reducing the accuracy of the regression analysis. For the period of December 1, 1997 through February 15, 1998, indoor temperature was plotted against hour of the day for each of the five systems, to identify cases of regular thermostat setback or other patterns that repeat on a daily cycle. Figure 23 displays these results.

Figure 23: Indoor Temperature vs. Hour of Day, Five Geothermal Systems, December 1, 1997–February 15, 1998



The Unit 1 home shows a distinct and very regular pattern of thermostat night setback, with temperatures falling off between 2100 and 0600 hours, and increasing between 0800 and about 1400 hours. Unit 2 shows some signs of a short-term setback during mid-morning hours, but generally stable temperatures otherwise. The remaining systems show stable temperatures during heating.

In developing the relationship between temperature difference and heating requirements, we explored the use of variable averaging times for both heating output and temperature difference. Shorter averaging periods would tend to include partial cycles of system operation, yielding highly variable heating output values. Longer averaging periods have the advantage of stabilizing the heating output, but reduces the precision of the results. Longer

averaging periods for temperature difference values may improve the results if the home has a dominant heating time constant much longer than one hour. The results showed that changing averaging times has little effect on the estimated heat loss coefficients and design loads, and we have used one-hour averaging for Units 2, 3, 4, and 5. We have used data for nighttime periods (2100 to 0600 hours) in performing the analysis. The use of nighttime data is expected to eliminate the effect of solar gains and reduce the effect and variation of internal gains from appliance use

To overcome the effect of the diurnal thermostat setback in Unit 1, daily average heating output and temperature difference was used for analysis of this system. The use of 24 hour periods means that daytime solar gains, and internal gains from all periods of occupant activity, are reflected in the results.

Figure 24 shows the relationship of measured heating output to indoor-outdoor temperature difference for the five systems. In addition to performing regressions were performed of heating output against temperature difference, multiple regressions of heating output against both temperature difference and temperature rise from the previous hour, in order to allow for changes in heating output driven by changes in thermostat setting. The use of the multiple regression led to only minor changes in the results, and is not presented here, although the technique was used in analysis of cooling data.

Figure 24: Hourly Heating Output vs. Temperature Difference—Five Geothermal Systems, Combined Heating Seasons

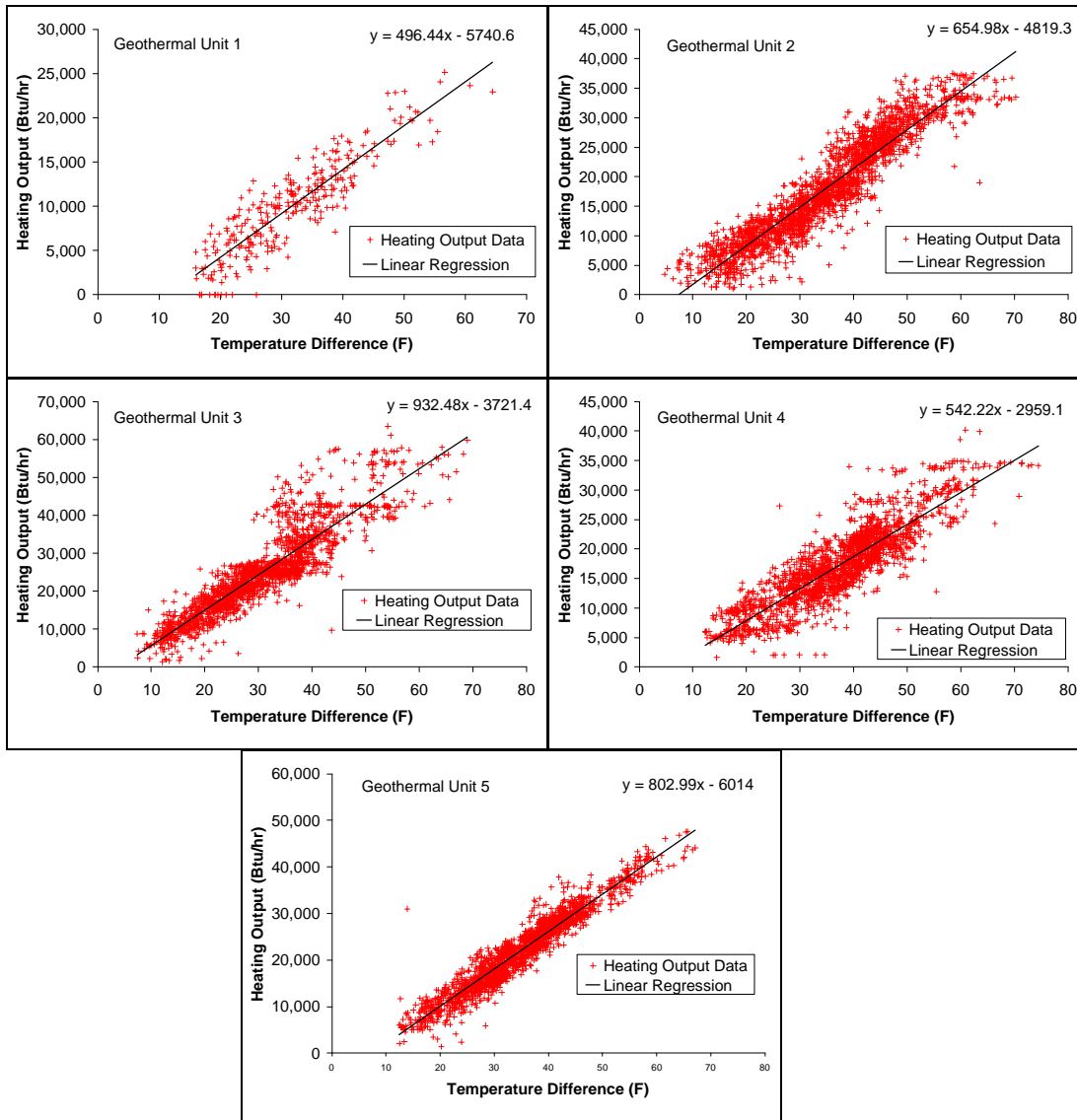


Table 8: Heating Characteristics of Five Geothermal Homes, Based on Regression of Heating Output vs. Temperature Difference

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Estimated Heat Loss Coefficient (Slope), Btu/°F hr	496	655	932	542	803
Estimated Average Internal Gains (Intercept), Btu/hr	5740	4820	3720	2960	6010
R ² of estimate	.81	.88	.80	.76	.92

Note: Unit 1 based on daily data, other units based on hourly data.

Characterizing Cooling Loads

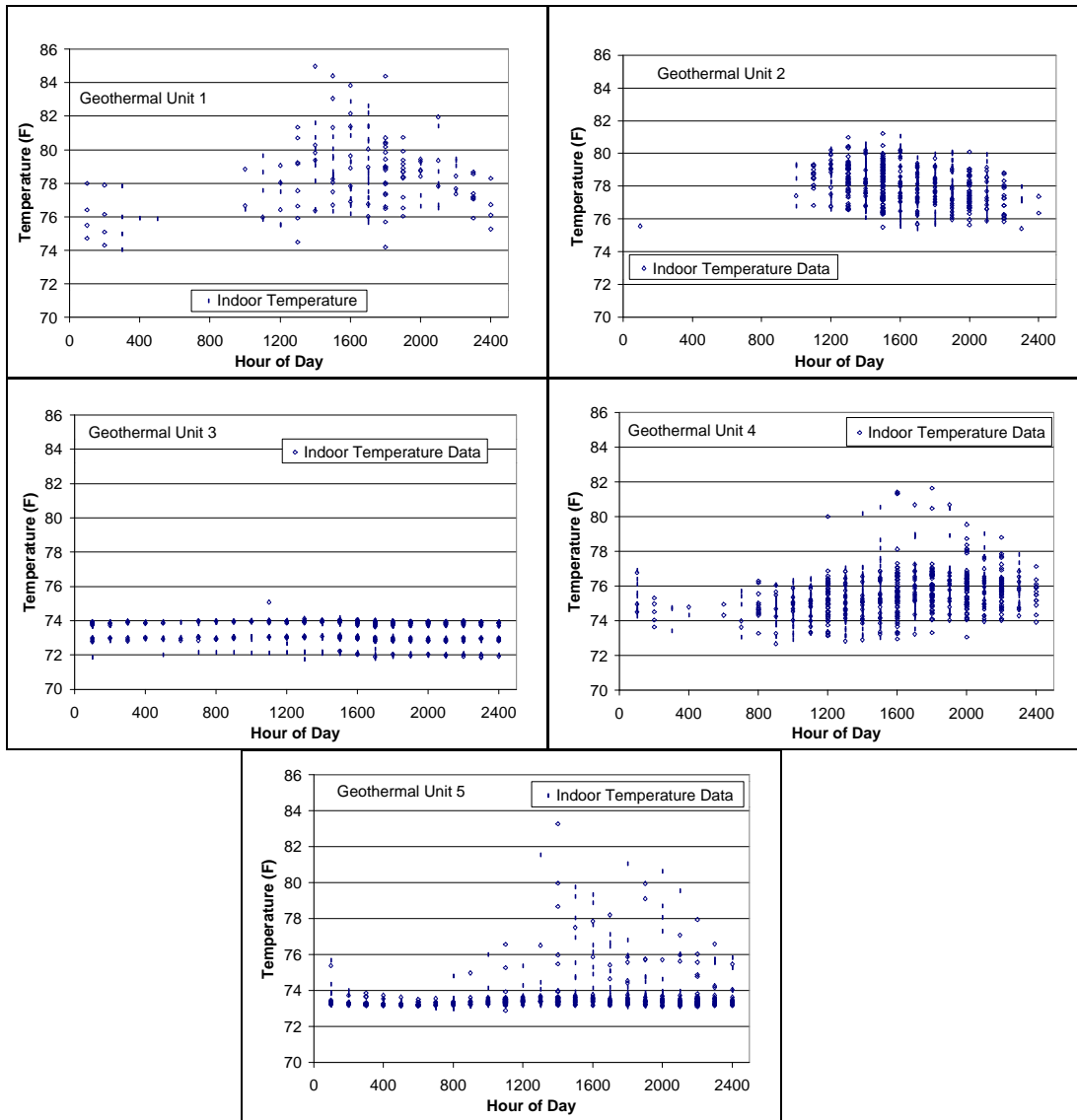
The relationship between cooling and temperature difference is assumed to be similar to that in heating, with the exception that internal gains increase rather than decrease the load. The relationship can be expressed as follows:

$$\text{Cooling Required} = (\text{Heat Gain Coefficient} \times \text{Temperature Difference}) + \text{Internal Gains}$$

It is generally recognized that cooling loads are more significantly driven by factors other than temperature difference, including solar gains, and that cooling loads include latent or dehumidification loads, however, this simple relationship remains useful in predicting required output under specific conditions.

As in the case of heating, we have evaluated internal temperature as a check on the assumption of steady state conditions. (See Figure 25) These plots are for hours with cooling system operation only.

Figure 25: Indoor Temperature vs. Hour of Day, Active Cooling Periods Only, Five Geothermal Systems, May 1 – September 30, 1998



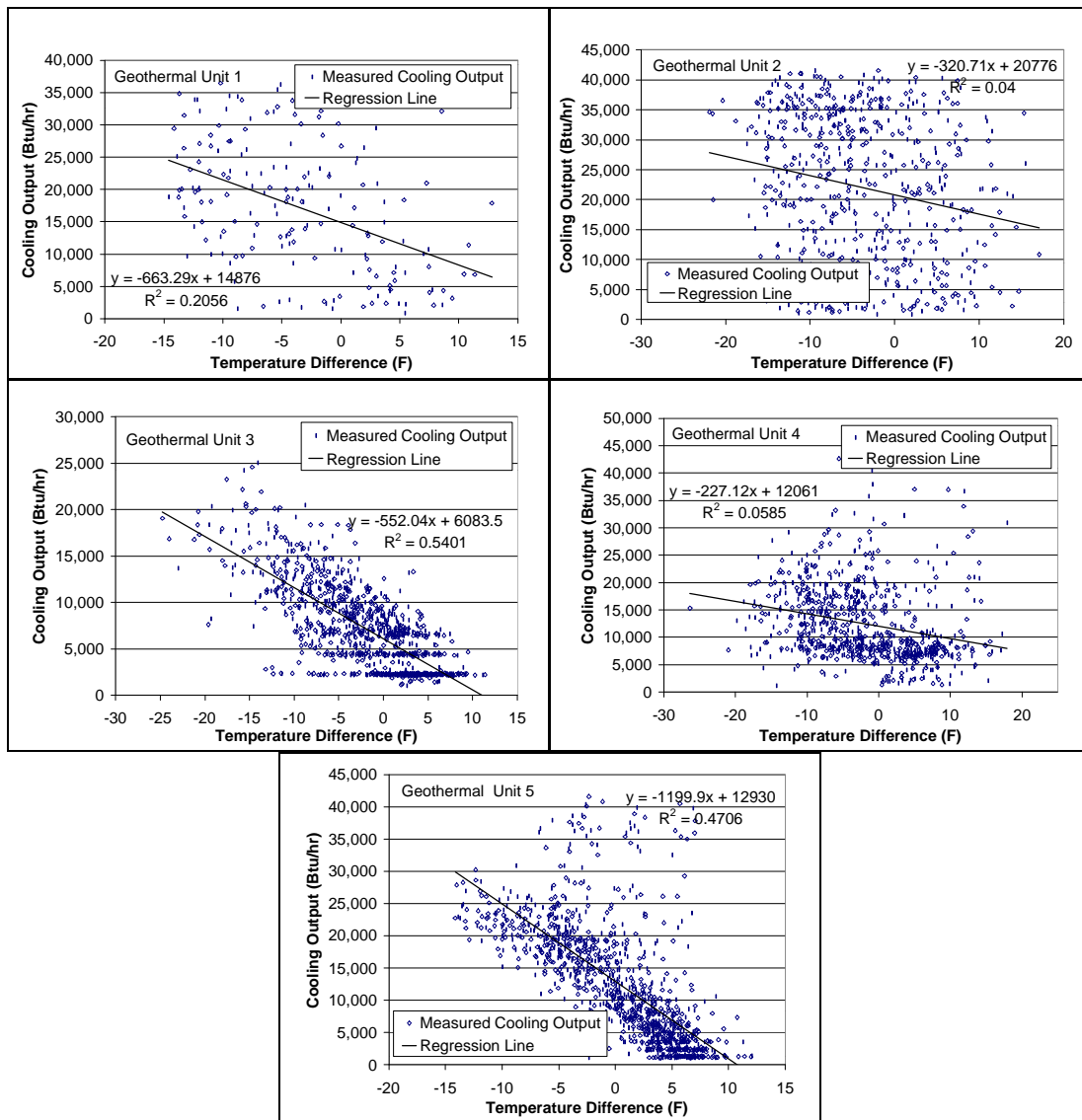
The graphs show that the indoor temperature is inconsistently controlled in Units 1, 2, 4, and 5. With some exceptions, Unit 3 is controlled by a stable thermostat setpoint. In units 1 and 2, there is a pronounced indication of the effects of thermal mass which decreases system operation in the early morning hours.

The analysis of heating characteristics presented above was based on nighttime data, with the advantages of stable temperature setpoint and reduced internal gains. In contrast, design cooling loads are expected to occur during daytime hours, with solar and internal gains contributing significantly. Daytime periods of operation for the systems studied also include changes in thermostat setting. To accommodate daytime data with changes in thermostat setting, regressions were performed of the cooling output of each system against both

temperature difference and temperature rise of the current hour compared to the previous hour. In all cases, the analysis was limited to hours with more than 1000 Btu of measured cooling output.

Figure 26 shows the relationship of measured cooling output to indoor-outdoor temperature difference for the five systems. The single highest hourly value of cooling output for Unit 3 is not shown on the graph for reasons of clarity.

Figure 26: Hourly Cooling Output vs. Temperature Difference—Five Geothermal Systems, 1998 Cooling Seasons



The graphs and regression lines show considerable scatter in the relationship of cooling output to temperature difference. Table 9 shows the results of the regression of cooling output against temperature difference, and the multiple regression of cooling output against

temperature difference and temperature rise from the previous hour. The estimated temperature change coefficient is the amount of cooling output associated with a temperature change of one degree from the previous hour.

Table 9: Cooling Characteristics of Five Geothermal Homes, Based on Regression of Cooling Output vs. Temperature Difference and Temperature Rise

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Using Temperature Difference Only					
Estimated Heat Gain Coefficient (Slope), Btu/°F hr	-663	-323	-558	-227	-1,200
Estimated Gains during Cooling (Intercept), Btu/hr	14,876	20,799	6,108	12,060	12,930
R ² of estimate	0.21	0.04	0.51	0.06	0.47
Using Temperature Difference and Temperature Rise from Previous Hour					
Estimated Heat Gain Coefficient (Slope) , Btu/°F hr	-686	-412	-572	-447	-1,188
Estimated Gains during Cooling (Intercept) , Btu/hr	10,858	18,332	6,096	10,690	11,778
Estimated Temperature Change Coefficient, Btu/°F	-6,285	-5,798	11,176	-8,918	-14,980
R ² of estimate	0.56	0.26	0.63	0.39	0.77

The multiple regression results improve the R² of the estimates, and are used in the analysis of design loads. However, the low R² values are evidence that cooling loads cannot be accurately predicted using indoor-outdoor temperature difference as the sole driving force.

Design Load Estimation

Using the measured heating characteristics of each home, the required heating output of each system was estimated at design conditions. This estimate is derived from the derived heat loss coefficient multiplied by the heating design temperature difference, less the estimated internal gains. We have used a winter design temperature difference for northeastern Ohio of 65°F (see Table 10).

Table 10 also includes design heating loads calculated according to Air Conditioning Contractors of America (ACCA) Manual J, and design load estimates made by system installers, when available.

Table 10: Design Heating Loads

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Design Heating Requirement as Estimated from Data, Btu/hr	26,500	37,760	56,860	32,270	46,190
Manual J Design Load, Btu/hr	39,376	45,607	63,969	37,730	47,461
Design Load Estimate by System Installer, Btu/hr	34,730	40,510	N/A	N/A	62,140
Ratio, Manual J/Estimated from Data	1.49	1.21	1.13	1.17	1.03

Note: Unit 1 based on daily data due to “set back” operation, other units based on hourly data.

The ratio of the design loads calculated per Manual J to the estimated design heating requirement based on field data ranges from 1.03 to 1.49. The high value for Unit 1 is probably influenced by the use of daily values for estimation of the building heating characteristics. These daily values include solar effects and other internal gains, and are expected to underpredict heating requirements.

The ratios for the other four systems, ranging from 1.03 to 1.21, indicate good agreement between Manual J and heating needs.

Similar estimates were made of cooling required at design conditions, based on field data. This estimate is derived from the measured heat gain coefficient multiplied by the cooling design temperature difference, plus the estimated internal gains. A cooling design temperature difference of 13 °F was used in these calculations. (See Table 11).

Table 11: Design Cooling Loads

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Design Cooling Requirement as Estimated from Data, Btu/hr	19,780	23,690	13,540	16,500	27,220
Manual J Design Load	19,133	21,628	31,683	28,066	27,959
Design Load Estimate by System Installer, Btu/hr	N/A	N/A	N/A	N/A	N/A
Ratio, Manual J/Estimated from Data	0.97	0.91	2.34	1.70	1.03

Manual J predictions compare closely to the cooling output at design conditions estimated from the field data for Units 1 and 5. Both the Unit 1 and Unit 2 homes have return air systems in unconditioned attics, and were shown to have significant leakage which would draw unconditioned air into the system and increase required output to the conditioned space. Such leakage is not explicitly considered in Manual J analysis, and may account for the ratios below 1.0. The large ratio for Unit 3 is explained by the shading of much of the roof and window areas of the home by mature trees. The reason for the high ratio in the case of Unit 4 is unknown.

Manual J appears to provide useful predictions of design heating load in this heating dominated climate. The prediction of design cooling loads does not appear to be as reliable, and Manual J estimates may simply fail to consider occupant demand for cooling as driven by temperature setpoint changes. In a heating dominated climate such as northeastern Ohio, when integrated heating/cooling systems are sized according to heating loads, cooling output will generally be adequate to meet homeowner needs. Manual J is appropriate for use in this situation. When using Manual J to size cooling equipment only, consideration should be given to the potential for slight undersizing of the unit.

Installed Capacity

The output capacity of the systems as installed was composed to the estimated heating and cooling requirements at design conditions. (See Tables 12 and 13).

Table 12: System Sizing in Heating, Five Geothermal Systems

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Compressor Heating Capacity (ARI Standard 330), Btu/hr	29,000	32,500	43,000	31,000	33,000
Installed Resistance Heating Capacity, Btu/hr	34,000	49,000	67,000	49,000	34,000
Total Capacity	63,000	81,500	110,000	80,000	67,000
Design Heating Requirement as Estimated from Data, Btu/hr	26,500	37,760	56,860	32,270	46,190
System Compressor Capacity/Projected Output, Ratio	1.09	0.86	0.76	0.96	0.71
System Total Capacity/Design Requirement, Ratio	2.10	1.97	2.19	2.76	1.47

Table 13: System Sizing in Cooling—Five Geothermal Systems

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Cooling Capacity (ARI Standard 330), Btu/hr	29,000	32,500	43,000	31,000	33,000
Design Cooling Requirement as Estimated from Data, Btu/hr	19,780	23,690	13,540	16,500	27,220
System Capacity/Projected Output Ratio	1.47	1.37	3.18	1.88	1.21

The rated compressor capacity of the systems in heating is lower than the estimated design load for four of the five systems, ranging from 0.71 to 1.09. This form of undersizing of the compressor is commonly done in heating dominated areas to reduce installed system costs. The heating load in excess of compressor capacity is provided by auxiliary heating. Given the undersizing of compressors as measured here, the low use of auxiliary heating measured is surprising. In part, the low use of auxiliary heating may be explained by the fact that four of the five systems produced maximum measured output greater than their rated output, as discussed earlier. This result lends support to the concept of sizing compressors to between

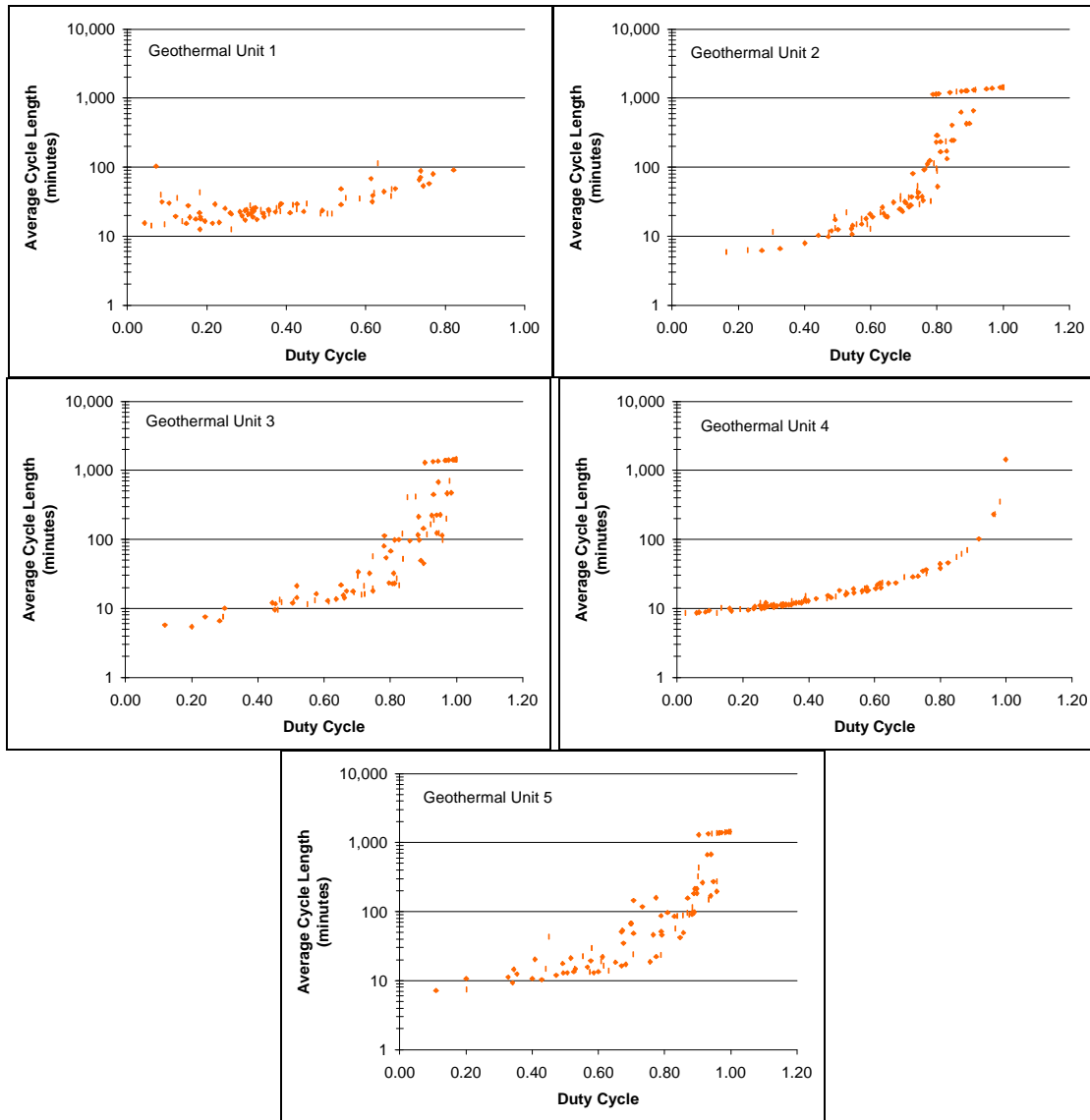
75 and 90 percent of the heating design load in cold climates. The total capacity, including auxiliary heating, should be large enough to satisfy loads somewhat above design loads.

Relative to cooling design loads, the systems are oversized by 10 to 52 percent. In a heating dominated climate, sizing of compressors for heating will generally provide adequate capacity for cooling. When systems are oversized in cooling, the selection of 2-stage equipment may be beneficial in improving COP and dehumidification. Dehumidification performance was not studied in the five Ohio systems.

SYSTEM CYCLING

In evaluating heating and cooling data from the five systems, some episodes of frequent cycling were formed. Cycling of each of the five systems in heating has been characterized by considering the relationship of average cycle length to the overall duty cycle. Duty cycle is the fraction of time during the day that the system compressor operates, in any stage of heating or cooling. (See Figure 27).

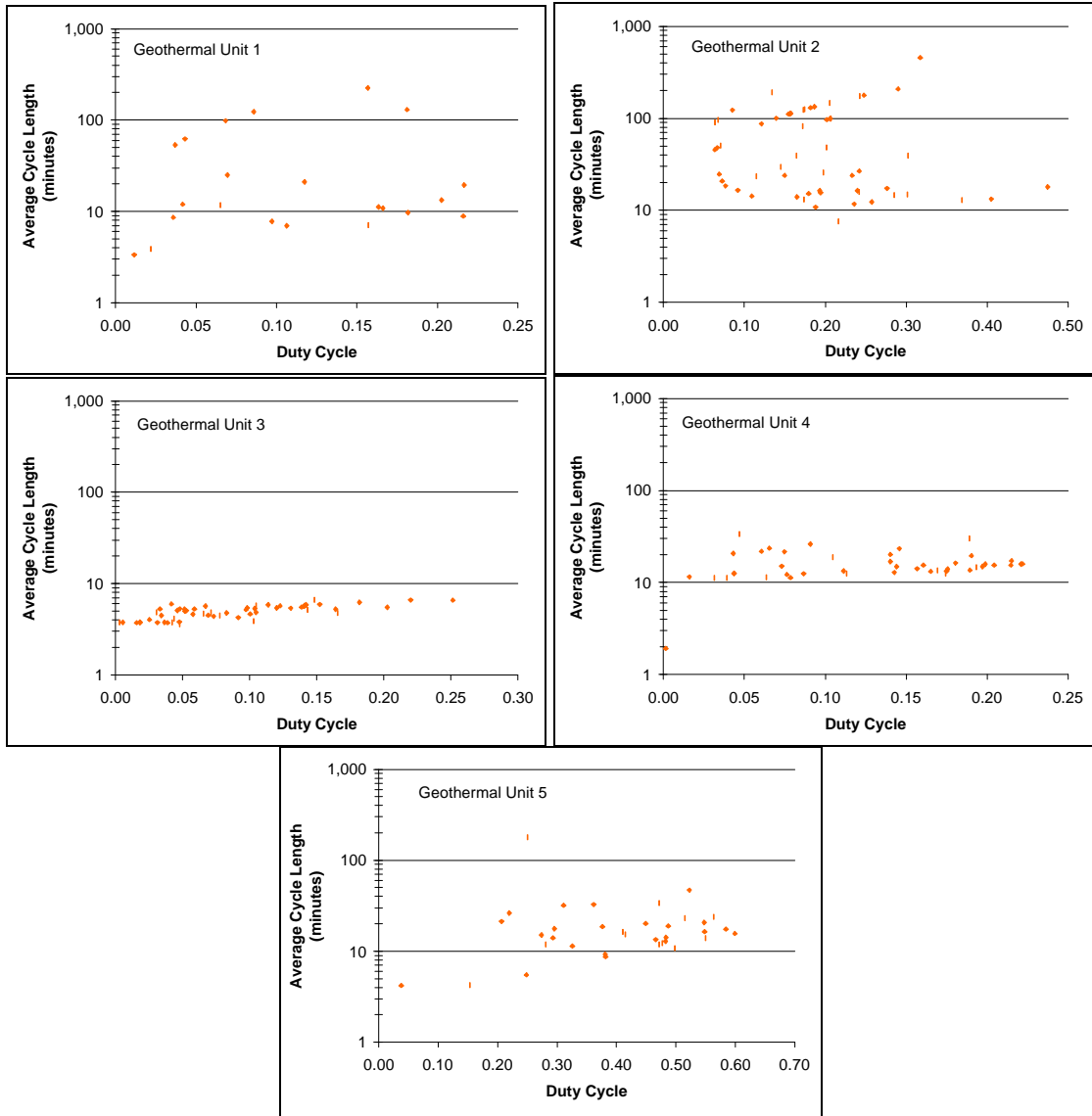
Figure 27: Operating Cycle Length vs. Duty Cycle—Five Geothermal Systems, 1997-1998 Heating Season Daily Average Values



Four of the five systems (Units 2, 3, 4, and 5) display a similar pattern. In each, average cycle length approaches the limit of 1440 minutes (24 hours) in a day as duty cycle approaches 1.00. The two stage systems (Units 2, 3, and 5) show multiple daily values at or near 1440 minutes, consistent with a part-load operating pattern in which the systems operate continuously, switching between Stage 1 and Stage 2 to meet the load. In general, the distinct trend of increased cycle length with increased duty cycle demonstrates that the systems are not “short-cycling” (cycling too quickly) at high duty cycles or load fractions. At the low end, average cycle length dips below 10 minutes for each of the systems, a relatively short operating time. Since these systems take several minutes to reach near-equilibrium operation, short cycle length implies slightly lowered performance.

The cycle length pattern for Unit 1 is quite different. The use of a daily thermostat setback probably increases the average run time throughout the season, increasing the minimum average cycle length compared to the other systems. A similar analysis of cooling season operation is included in Figure 28.

Figure 28: Operating Cycle Length vs. Duty Cycle—Five Geothermal Systems, 1998 Cooling Season, Daily Average Values



Patterns in the cycle length vs. duty cycle relationship are much less distinct in cooling than in heating, however Unit 3 shows an upward trend in cycle length with duty cycle. The average cycle length for Unit 3 is very short, consistently less than 10 minutes. This short cycle length may be evidence of inappropriate setup of system controls, and likely has a detrimental effect on operating COP and dehumidification performance.

DOMESTIC WATER HEATING

Analysis Methods

Estimation of the domestic hot water energy production of the five subject systems was performed indirectly, using an energy balance calculation around the water heater, solving for energy input from the geothermal systems as a function of the measured energy delivered to the load, estimated standby losses, and electric inputs. Load energy was calculated from measured flow and hot and cold water temperatures. The temperatures were corrected for lags in sensor response occurring during the first minute of flow. Tank heat loss coefficients for each system were derived using data for periods with low loads and low geothermal inputs. Losses were estimated on a daily basis, using measured temperatures of hot water and the tank environment. In performing daily energy balance calculations, a loss term that was not predicted by the tank loss calculation appeared for several of the systems. This term is called Other Losses. These additional losses maybe due in part to thermosiphoning between the water tank and the geothermal unit, and also include any errors in the energy balance calculations that accrue as loss values.

Geothermal Units 1 and 2 were equipped with dedicated water heating capability, and operated in water heating mode on call of a domestic hot water temperature sensor. The water heating output of these two systems using was calculated ground loop and electric energy inputs, analogous to the calculation of heating and cooling outputs.

COPs were calculated in water heating mode for Unit 1 & 2. For the three systems equipped with desuperheaters, operating COPs for space conditioning and water heating appear earlier in this report. The ratio of total purchased (electrical) energy used to the water heating energy delivered is also presented. This ratio provides a performance figure for comparing dedicated water heaters to desuperheaters. For the desuperheater systems, the purchased energy includes DHW loop pump energy and electric resistance inputs, but ignores geothermal ground loop pump and compressor inputs. Including this value would change the results noticeably only during periods when the fraction of water heating from geothermal is high.

At the start of the monitoring project, Units 1 and 2 were both configured to circulate water from the water heating tank to the geothermal unit full time. This strategy allows monitoring of DHW temperatures within the geothermal unit. Early analysis of operating data showed that pump power leads to a significant reduction in COP in these systems. In response, the manufacturer modified the circulator control in Unit 2, to operate the loop pump for one minute at five minute intervals, allowing temperature sampling with reduced pump energy use. The results presented for Unit 2 include about one month of operation using the original strategy, during December 1997.

Failure of a Desuperheater

When measuring the flow rate in the desuperheater loop at Unit 5 in August, 1997, project staff realized that there was very low or no flow through the desuperheater loop. Flushing of

the water heater tank and desuperheater loop connector resolved the problem, and the lap flow rate was measured. The loop flow dropped off again over the following weeks, which was evidenced in operating data by desuperheater loop temperatures that remained relatively constant for prolonged periods of pump operation.

In December, 1997, project staff met on-site with representatives of the geothermal system manufacturer and installer, and disassembled the desuperheater loop. The loop was heavily clogged with both a solid mineral precipitate, and with a semi-solid, largely transparent material with a somewhat slimy texture. The desuperheater loop flow path appeared to be plugged nearly completely at the concentric fitting connecting the piping to the water heater, and significant amounts of both materials were removed from the remainder of the loop. Both materials appeared to originate in the water heater.

Testing of the water at the site indicated high hardness in the water from the city utility. The installed water conditioning system was shown to reduce mineral concentrations in the water supply, however, it may have allowed minerals to pass through intermittently, leading to precipitation in the tank. The slimy material in the system was tentatively identified as a bacteria.

In response to the two known episodes of plugging, a recommendation was made to install a pair of shutoff valves and drains in the desuperheater loop. This valving permits the flushing, under pressure, of the entire desuperheater loop. At the end of project data collection, the home owner reported using the flushing valves, and the desuperheater appeared to be operating correctly.

This form of system failure is probably made much more likely when the drain valve at the bottom of water heating tank is used as a connection for drawing water to go to the desuperheater. The use of this connection allows precipitates in the lower few inches of the tank to be drawn into the desuperheater loop. Additionally, the use of concentric fittings for desuperheater supply and return, or any fitting with passages smaller than the basic loop tubing size, may increase the likelihood of loop blockage.

The home owner had not been aware of the desuperheater failure until it was uncovered during system testing. This demonstrates the value of equipment or procedures that would allow system owners to verify operation. Appendix A includes several suggested options for doing this.

Water Heating Performance

Measured performance of the five systems is summarized in Figure 29 and in Table 14. Energy outputs from the water heating system, including hot water energy delivered, tank losses, and other losses, are given positive values. Energy inputs, including electric element inputs, water loop pumping energy, and geothermal inputs, are assigned negative values. Geothermal input is the estimated thermal energy provided by the desuperheater or dedicated water heating function of the system, and does not differentiate between energy from the ground loop and the compressor electric input. Pump energy refers to the DHW loop pump, between the geothermal unit and water tank.

The COP for Units 1 and 2 is presented both as measured, including all DHW loop pumping energy, and as adjusted based on pumping energy used for water heating but not for temperature sampling.

Figure 29: Measured Domestic Hot Water Energy Delivery—5 Geothermal Systems, December 1997—November 1998

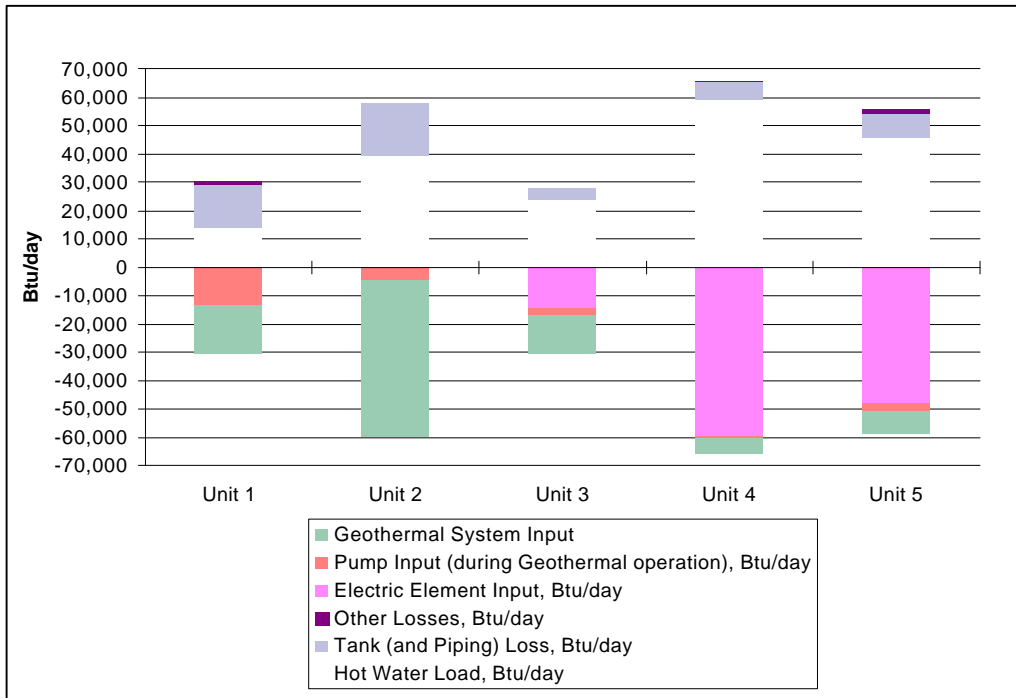


Table 14: Measured Water Heating Energy Delivery, Five Residential Geothermal Systems, December 1997–November 1998

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Water Consumption (gal/day)	29	76	70	108	75
Hot Water Load, Btu/day	13,933	39,007	23,947	59,130	45,674
Tank (and Piping) Loss, Btu/day	14,819	18,579	4,016	5,966	8,707
Other Losses, Btu/day	1,290	0	0	370	1,516
Electric Element Input, Btu/day	0	0	14,684	59,679	48,034
Pump Input (during Geothermal operation), Btu/day	271	2,277	2,317	671	2,712
Pump Input (all other), Btu/day	12,852	2,314	0	0	0
Geothermal System Input to DHW Tank, Btu/day	17,184	55,273	13,279	5,786	7,862
Geothermal Fraction of DHW Load and Losses	1.00	1.00	0.47	0.09	0.14

Large variations in performance across the five systems are evident. Hot water use and loads vary by a factor of about 4 to 1 from high to low. Units 1 and 2 demonstrate the capability of dedicated water heating systems to meet 100 percent of typical water heating loads, while the desuperheater systems rely on electric resistance heating for large fractions of the load. The dedicated water heating systems, however, suffer from a disadvantage in terms of heat loss and pump energy. Tank and piping losses from Unit 1 are 1.7 to 3.7 times as great as the losses of desuperheater systems, and Unit 2 has even higher losses. The high thermal losses are the result of long piping loops in Units 1 and 2, and the fact that the piping is kept continuously heated by the circulation of the pump. Losses from these systems include some losses into the geothermal unit cabinet, where the DHW heat exchanger is heated by the circulating water during off cycles.

The tank losses from Unit 2 are of the same magnitude as those of Unit 1, indicating that the pump operates frequently enough under the revised control strategy to keep the DHW loop temperature fairly high. Pump energy is very high for Unit 1, with full time pump operation, while it is significantly reduced in Unit 2 under the revised control strategy.

The low desuperheater fractions for Units 4 and 5 are the result, in part, of the response time of electric heating elements. In general, when a desuperheater is connected to a single tank with two electric elements, the electric elements will operate according to thermostatic control whenever the tank temperature drops, and will perform most of the heating. When the desuperheater operates, the tank is often hot, and can accept only a limited additional amount of energy.

Greater desuperheater performance can be expected in systems with a dedicated storage volume for water heating. This is demonstrated by the desuperheater performance of Unit 3.

The lower element in the Unit 3 water heater was set at about 90°F, providing a significant thermal storage mass available for desuperheater output (i.e. the desuperheater was not deactivated due to high tank temperature). In addition, the lower average tank temperature increases the heat transfer rate in domestic water heating. Appendix B presents a simplified analysis of the effects of disabling the lower electric element in a single-tank system. The low output of desuperheaters in systems with lower run times and without dedicated storage suggests the need for economic analysis to determine whether the added installation cost is warranted.

Table 15 presents several performance indicators for the geothermal water heating systems.

Table 15: Measured Water Heating Performance Indicators, Five Residential Geothermal Systems, December 1997–November 1998

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Measured COP (includes all measured pump power)	0.86	2.03	N/A	N/A	N/A
COP adjusted for pump operation during DHW heating only	2.39	2.21	N/A	N/A	N/A
Purchased Electric/ DHW Energy to Load	1.44	0.70	0.71	1.02	1.11
Average Water Heating Output during DHW Operation, Btu/hr	34,787	14,689	1,467	2,207	742
Geothermal DHW Output/ Geothermal Total Output, percent	12.4	18.8	4.3	2.7	2.9
Geothermal Operation (space conditioning), hr/day	n/a	n/a	10.0	5.9	10.4
Geothermal Desuperheater Operation, hr/day	n/a	n/a	9.1	2.6	10.6

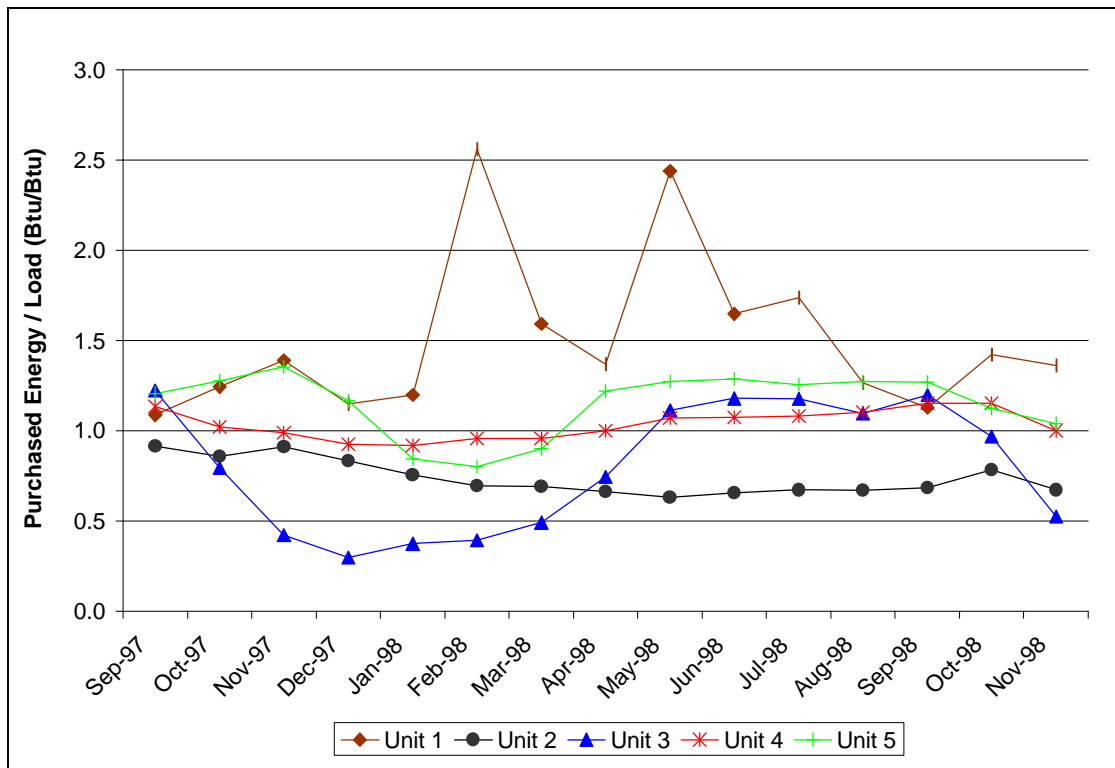
The comparative COP values for Unit 2 show the effect of adopting a control strategy that operates the DHW loop pump only during water heating cycles. This type of control might be accomplished in systems with dedicated water heating by using a field wired thermostat at the hot water tank to replace the thermostat installed on the DHW piping loop. The ratio of purchased energy to DHW load would be about 1.15 to 1.25 for typical electric water heaters. For dedicated geothermal water heaters supplying 100 percent of the load and with low losses, the value should approach 1/COP. The values reported here for Units 1 and 2 are elevated, compared to optimal values, by high losses. The values for Units 4 and 5 show only slight reductions compared to electric water heating, while Unit 3 shows a significant reduction. Since the purchased energy does not include the portion of geothermal compressor or ground loop pumping power attributable to desuperheater output, these values cannot be compared directly to those for Unit 1 and 2.

The average water heating output demonstrates the much higher water heating rate of the dedicated water heating systems. The ratio of geothermal DHW output to geothermal total

output (including heating, cooling, and water heating) additionally emphasizes the capability of the dedicated systems to provide useful water heating output.

The ratio of purchased energy to hot water load by month is presented in Figure 30. The high values for Unit 1 show the effect of very high losses combined with very small loads. By contrast, the reduced pump operation and larger load to loss ratio in Unit 2 yields a ratio consistently less than one, and which would be even lower if the losses were reduced.

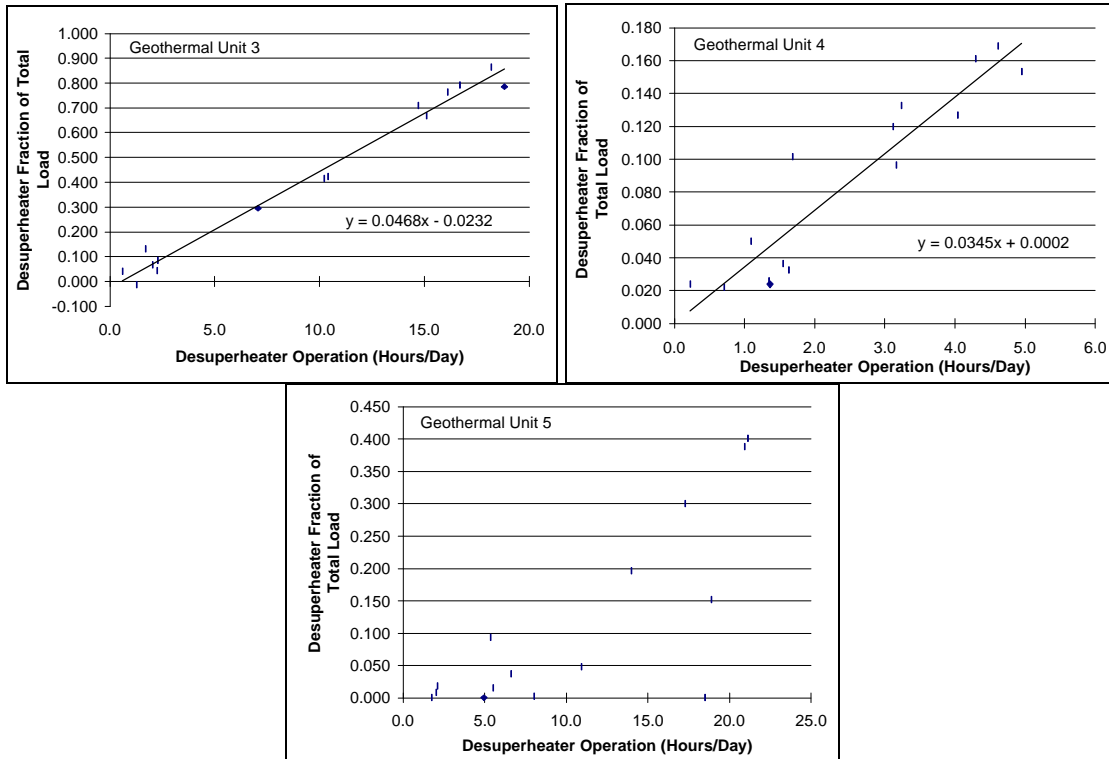
Figure 30: Ratio of Purchased Energy to Hot Water Load by Month, Five Geothermal Systems, December 1997 – November 1998



Unit 3 exhibits a very low ratio for the winter months. This is the result of the low setpoint of the lower tank element, combined with long geothermal system operating hours, yielding a high geothermal fraction. Unit 4 shows lower ratios for winter than the summer months, due to the greater number of operating hours in the winter. Unit 5 also shows higher ratios for winter months, with the exception that September through December 1997 is affected by the loop blockage discussed above.

The relationship between desuperheater output and operating time for Units 3, 4, and 5 was also explored. (See Figure 31).

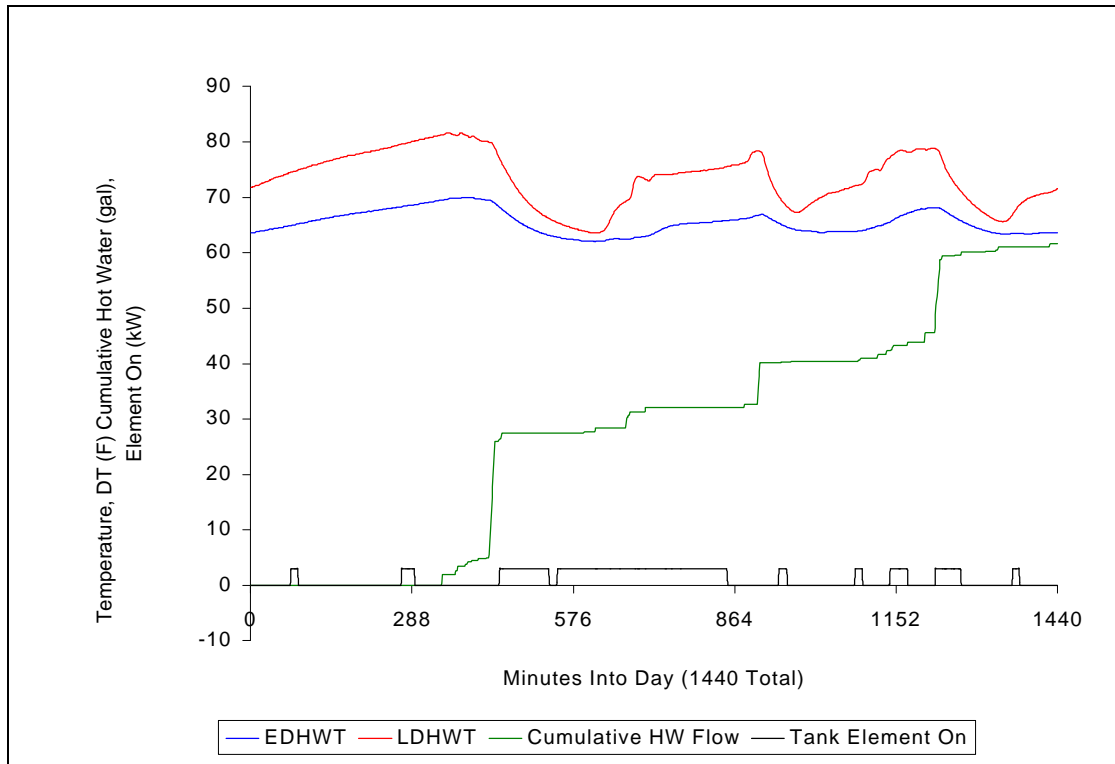
Figure 31: Desuperheater Fraction of Load vs. Desuperheater Operation, Three Geothermal Systems



All three systems show a positive relationship between daily average operating time and desuperheater fraction of output. The higher slope of the regression line for Unit 3 is a result of the lower tank temperature. The data for Unit 5 includes desuperheater fractions of zero for the months when the DHW piping was blocked.

Figure 32 shows a pattern of operation that we suspect is associated with thermosiphoning in the desuperheater loop. The entering and leaving DHW temperatures are close to room temperature throughout the period shown because the desuperheater loop is not operating, and the sensors are influenced by room temperature. The elevated temperatures, however, show that there is some flow through the loop (or flow and conduction from the water heating tank), and the difference in temperature between the entering and leaving water shows that heat loss or gain is occurring. The fact that the pattern varies with hot water draws, which would bring the temperature at the bottom of the tank closer to room temperature, is consistent with thermosiphoning.

Figure 32: Desuperheater Loop Temperatures and Water Draws, Showing Possible Thermosiphoning, Geothermal Unit 5, One Day of Operation



Some geothermal system manufacturers recommend the use of check valves in desuperheater loops to prevent thermosiphoning. However, installers sometimes fail to install the valves, or they may be removed due to unreliability. No check valve was installed on Unit 5. Appendix B suggests a system modification that may effectively prevent thermosiphoning without raising a reliability issue.

CONCLUSIONS

The overall heating and cooling performance of the systems studied was excellent. The measured output of the systems is consistent with manufacturers ratings, and is large enough in each case to provide space heating throughout the winter heating season in northeastern Ohio with very low use of auxiliary electric heating. This demonstrates the capability of geothermal systems to maintain high levels of output throughout the winter, without the degradation in system output characteristics of air source systems operating at low ambient temperatures.

Measured COPs for the systems are consistent with manufacturers' ratings, although the systems that operated primarily in the first stage of two heating or cooling stages might have been expected to perform at a higher average COP. Reasons that operating COPs may differ from manufacturers' values include differences between rating conditions and field

conditions in loop temperatures plenum, air temperatures from, loop flow and temperature rise or fall, loop pumping power, fan power, fan operating time, and measurement errors.

The relationship of COP to entering water (ground loop) temperature establishes the effect that ground loop sizing has on performance, with each system showing a distinct trend toward lower COP when the loop temperature decreases (in heating mode) or increases (in cooling mode). Two of the five systems studied show some evidence of undersizing of ground loops in heating operation. Improved ground loop performance would improve operating COP in these cases. The results emphasize the importance of providing an adequately designed and installed ground loop as part of any geothermal installation.

Heating energy consumption in the homes studied is consistent with the common model of heating explained primarily by temperature difference. Cooling, on the other hand, is driven more significantly by occupant demand, and cooling energy consumption is much better explained by considering both indoor-outdoor temperature difference and indoor temperature change caused by thermostat changes than by temperature difference alone.

Comparison of ACCA Manual J heating design load calculations to heating design loads estimated from field data shows reasonable agreement. Manual J calculations provided results three to 21 percent greater than measured design heating loads in four of the systems studied, and 49 percent in the fifth case. Since HVAC equipment is typically available in size increments of 15 to 20 percent of the design load, sizing to a much greater level of precision may be unwarranted.

A similar comparison in the case of cooling shows much more variability, with the ratio of Manual J to measured design load ranging from 0.91 to 2.34. This appears to be related to the generally poor relationship between temperature difference and cooling load.

The systems studied were sized so that the ratio of compressor output to design heating load is less than 100 percent of the design load in four of five cases, with a range of .71 to 1.09. Sizing ratios of .75 to .90 are appropriate as a means of reducing first cost while maintaining good performance in heating and cooling. Significant oversizing, while it may eliminate almost all use of auxiliary heating, incurs higher installation costs and should not be pursued unless indicated by a complete economic analysis. Significant oversizing may also contribute to short cycling, as was observed in one system in cooling mode.

The water heating performance of the systems studied varied greatly, with the geothermal systems providing as much as 100 percent of water heating load and losses in the systems with dedicated water heating capability, and as little as 9 percent in one system with a desuperheater. Performance of the dedicated water heating systems is marked by high thermal losses, due to the full-time or periodic operation of the DHW circulation pump. Performance of these systems could be improved through implementation of a control strategy that works without relying on periodic water circulation for temperature monitoring.

The fraction of the water heating loads and losses met by the desuperheater systems is correlated to the operating time of the system, with higher operating times and higher

desuperheater energy contributions in winter months. Additionally, a lower average tank temperature in one system appears to have contributed to higher desuperheater output as a fraction of load. Desuperheater systems can benefit from lower storage tank temperatures, which may be achieved by reducing the setpoint of lower tank elements or by providing dedicated storage with no auxiliary heating. In order to meet typical water heating loads when no desuperheater output is available, the use of a large single tank, (e.g. 120 gallons) with a single electric element heating the top portion of the tank might be considered. The low fraction of total geothermal output that goes to water heating in typical desuperheater systems suggests that desuperheaters should be provided with dedicated thermal storage if they are to be used effectively. The use of desuperheaters should be the subject of further life cycle cost analysis.

Proper design, installation and maintenance of desuperheaters may also help assure optimal performance. Systems should be designed to resist the accumulation of mineral precipitates, and should allow for flushing by the system owner. Specifically, the use of concentric fittings that have flow passages smaller than the basic pipe inside diameter should be avoided if possible, and water connections to the water tank should be several inches above the bottom of the tank. Design and installation to prevent thermosiphoning may also improve performance. The industry should consider the use of methods that would allow system owners to verify the operation of desuperheaters.

Appendix A

Consumer Verification of Desuperheater Operation

Desuperheaters associated with geothermal systems and other compression driven systems generally operate as preheaters of domestic hot water, with final heating performed by standard electric or gas energy. The desuperheater energy is most commonly delivered to the bottom of a conventional water heater, with electric elements available to provide the remaining energy required to heat the water.

It is difficult for consumers to verify the operation of desuperheaters configured in this way. Since the water delivery temperature in such a system is generally nearly constant, it does not provide information on the operation of the desuperheater. Utility bills are unlikely to provide useful information, since marginal changes in water heating energy use are likely to be lost in the noise of other changes.

Recognizing the possibility of desuperheater loop blockage, pump failure, and other factors that could reduce desuperheater performance, the availability of some means to verify operation and/or energy production would benefit geothermal system owners. The following is a list of concepts for providing this function.

Manual Check of Desuperheater Loop Temperature

Home owners can check the operation of the desuperheater loop pump by checking the temperature of the loop piping from the geothermal system to the water tank. This test has limitations, in that the loop piping may be hot because of flow of hot water from the water heater, conduction from the water heater, or conduction from the geothermal system. Observation of temperature difference would provide a better indicator, but temperature differences may be small and hard to detect or quantify. Both temperature and temperature difference are meaningful only when the desuperheater is operating, and may not provide clear indication of partial blockage of the loop. To use this technique, thermometers must be installed, and/or owners must know the basic components of their geothermal systems

Flow Indicator in Desuperheater Loop

A simple mechanical indicator of flow on the desuperheater loop would allow verification of pump operation and flow. Desuperheater operation is controlled by temperature, so flow will not always occur when the geothermal system is in operation. As a result, the owner would have to be taught to look for flow at times when the system would be most likely to operate, such as after a large hot water draw. An uncalibrated flow meter would not provide clear indication of a partially blocked loop.

Flow Rate Meter in Desuperheater Loop

A calibrated flow meter in the loop would provide a true measurement of flow adequate for general verification of operation, and would allow identification of partially blocked flow. Flow meters with moving indicators in the flow stream (“rotameters”) may have enough resistance to flow to effectively prevent thermosiphoning in either direction. A flow meter would require understanding of when operation should occur. Such a meter would be installed in the field, external to the geothermal unit.

Monitoring of Temperature Difference across Desuperheater Loop

The sensors and control capability to monitor temperature rise and pump operation could be built into geothermal systems, identifying either proper operation or a fault condition. A signal such as an LED on the unit or thermostat would make the information available to the system owner. This system could be more robust and easier to use than the other options, and would likely be more expensive.

Monitoring of Pump Electrical Characteristics

Some fractional horsepower pump manufacturers provide information on the electrical and flow characteristics of their pumps as a function of flow rate (e.g. relationship between flow rate and operating voltage across capacitor). Control hardware could monitor such characteristics and provide signal of a fault condition when the pump is powered but flow is blocked.

Manual Check on Preheated Water Temperature

In systems using a dedicated preheat tank for the desuperheater, a periodic manual check of the temperature at the preheat tank would provide verification of operation.

Appendix B

Simplified Analysis of Desuperheater Performance with Lower Tank Element Disabled

A simplified hourly simulation model was developed to estimate the performance of a desuperheater delivering energy to a single water heating tank with only a single electric element. The model allows evaluation of the disabling of the lower element in a conventional electric water heater as a means of improving desuperheater performance.

In the model, the desuperheater energy heats the lower portion of the tank as possible, and the electric element adds energy to the top of the tank. The model includes the following adjustable inputs:

- Tank volume
- Heat loss coefficients
- Electric element wattage
- Hot water temperature setpoint
- Temperature limit on desuperheater energy added
- Room temperature

The model calculates standby losses, desuperheater energy inputs, electric energy inputs, and draw energy in hourly time steps. The average temperature of the lower portion and upper portion of the tank are recalculated for the end of each hour. The model allows desuperheater energy to heat only the lower volume of the tank (assumed to be 2/3 of the total volume, though this fraction can be altered), and uses electric heating only in the upper volume. Energy passes from the lower portion of the tank to the upper portion of the tank only through water draws. Standby losses are calculated separately for the lower tank and upper tank, and may be either positive or negative.

The model operates on an hourly data set including hot water draw volume, cold water temperature, and geothermal compressor operating time. We have incorporated a data set from the Unit 4 site in the performance study. The average daily hot water use at this site was 108 gallons per day, and this large usage may affect the results. The use of a single typical value for available desuperheater input is a limitation, since the actual rate varies over time.

The fixed inputs for our analyses were as follows:

Heat loss coefficients	3.6 Btu/hr °F
Hot water temperature setpoint	122 °F
Temperature limit on desuperheater energy added	130 °F
Room temperature	66 °F

The results are shown in Table 1.

Table 1. Desuperheater (DS) Energy Contribution and Delivery Below Hot Water Setpoint

Tank Size, gal	Electric Element Size, Watts	DS Energy Contribution, Btu/day	DS Contribution, percent	Hours with DHW Below Setpoint, Percent
60	2000	13,316	23	14
60	4500	13,316	22	2
80	2000	13,360	23	14
80	4500	13,360	22	1
120	2000	13,390	22	14
120	4500	13,390	22	1

The total amount of desuperheater energy available is about 13,390 Btu/day on average. The model predicts very high utilization of desuperheater energy under all conditions, with only very small amounts left unutilized due to the temperature limit in smaller tanks. The number of hours experiencing hot water delivery below the setpoint appears to be driven almost entirely by the size of the electric element.

The results can be compared to Unit 4 field data, which had the same average rate of energy output from the desuperheater during operation. The data showed 9 percent of the DHW load was provided by the desuperheater, at an average contribution of 5,790 Btu per day. The difference between the model and the field data is probably due in part to the characteristics of the model. However, the model provides an indication that dedicated heat storage for desuperheaters should enable higher levels of performance.