A New Comparison of Vertical Ground Heat Exchanger Design Methods for Residential Applications

John A. Shonder
Member ASHRAE

Van Baxter
Member ASHRAE

Jeff Thornton
Member ASHRAE

Patrick Hughes
Member ASHRAE

ABSTRACT

A previous comparison of vertical ground heat exchanger design methods for geothermal heat pumps in residential applications found large disagreements in the sizes recommended by five commercially-available computer programs, even when consistent information was input to all five. The objective of this work is to repeat the comparison using updated versions of the five programs originally tested, and one new program which was not included in the previous comparison. Simulation models of two sites—one in a cooling dominated climate, and the other in a heating dominated climate—were calibrated to site-collected data and then driven with typical meteorological year data to produce consistent inputs for the six design programs. The results indicate that the programs are now much more consistent with one another. For the cooling dominated site, design lengths vary by about 7%, and for the heating dominated site the design lengths vary by 16%. Compared to the tests performed in 1996, there is now much more consistency among the various design algorithms.

1. INTRODUCTION

In a previous study (Thornton et al. 1997a, 1997b), an energy-use model was developed for a single-family residence at Fort Polk, Louisiana heated and cooled by a geothermal heat pump. The heat pump model was based on the manufacturer's operating data, and Lund University's DST software was used to model the behavior of the vertical heat exchangers. The building model included a detailed, dynamic simulation of the apartment's energy gains and losses due to ambient weather conditions, outdoor air infiltration and internal loads. After calibration with one year of site-collected interval data, the model was used to generate a consistent set of inputs for five commercially-available ground loop heat exchanger design programs.

The results of the comparison were rather unsettling; for a maximum entering water temperature of 95°F, the lengths recommended by the five programs ranged from 160 bore feet per ton to 323 bore feet per ton–a variation of ±27% about the mean recommendation of 233 bore feet per ton. The inconsistency in these results highlighted both the lack of consensus among developers of the heat exchanger design algorithms, and the lack of confidence that engineers, architects and site owners had in the design algorithms that were available as of 1996.

Three years later, new versions have been produced of all of the programs tested. Another design program is also available which was not included in the previous comparison. The objective of this paper is to repeat the comparison using updated versions of the original design programs, using the Fort Polk residence as a test case. Additionally, another set of consistent inputs was developed for a geothermal heat pump residence located in the heating dominated climate of Southern Wisconsin. Given the cooling-dominated climate of Fort Polk, these two sites effectively span the range of

John A. Shonder and **Patrick Hughes** are staff members and **Van Baxter** is group leader at Oak Ridge National Laboratory, Oak Ridge, TN. **Jeff Thornton** is principal of Thermal Energy System Specialists, Madison, WI.

climates in the United States, and provide an excellent test of the capabilities of the software available to design ground loop heat exchangers for residential applications.

2. DESCRIPTION OF SITES AND EQUIPMENT

2.1 Fort Polk, LA

The Fort Polk residence is one of the lower floor apartments in a two-story 5-plex building. A photograph of the building is presented in Figure 1.1. The apartment has a conditioned floor area of 1052 square feet. There is an apartment above and next to the selected unit. The geothermal heat pump has a nominal capacity of 1.5 tons and no backup resistance heat. There are two boreholes at the site separated by 16 feet. Each is 4 1/4 inches in diameter and 258 feet deep and contains a single u-tube of 1 inch diameter polyethylene pipe. The bores are backfilled top-to-bottom with a bentonite-based grout. The heat transfer fluid is pure water with a flowrate of 4.6 gallons per minute. With this flowrate, and at ARI Standard 330 rating conditions (32°F EWT for heating, 77°F EWT for cooling) the manufacturer's performance data indicates that the heating capacity is 12,400 BTU/hr with a COP of 3.7, and the cooling capacity is 18,200 BTU/hr with a cooling EER of 16.4.

Water heating in the Fort Polk apartment is provided by an electric water heater. Although the heat pump does include a desuperheater to supplement the water heater, the desuperheater was disconnected during the data collection period. Additional details on the energy use of the apartment, the operation of the equipment, and the simulation model are given by Hughes and Shonder (1998).

Fort Polk's climate is heavily cooling dominated, with summer design conditions of 95°F DB/77°F WB. A typical year at Fort Polk has 1895 heating degree days and 2442 cooling degree days (both base 65°F).

2.2 Sun Prairie, WI

The Sun Prairie residence is a single-family raised ranch style dwelling with a total of 1370 square feet of living space. A photograph of the residence is presented in Figure 1.2. The geothermal heat pump has a nominal capacity of 2 tons, and includes two stages of electric resistance backup heat (4.8 kW and 7.6 kW). There are two boreholes at the site separated by 15 feet. Each is 6 inches in diameter and 160 feet in length, containing a single u-tube of $\frac{3}{4}$ inch polyethylene pipe. The boreholes were backfilled with soil, and include a grout plug to a depth of 20 feet. The heat transfer fluid is a solution of water 25% propylene glycol by volume, at a flowrate of 7.7 gallons per minute. At this flowrate, and at ARI Standard 330 rating conditions, the manufacturer's performance data indicates that the heating capacity of the heat pump is 18,400 BTU/hr with a COP of 3.6 and a cooling capacity of 28,000 BTU/hr with an EER of 18.7.

The Sun Prairie heat pump does not include a desuperheater. Water heating is provided by a natural gas water heater. A unique feature of the residence is an air-to-air heat exchanger: heat is recovered from air exhausted from the kitchen and bathroom and transferred to outdoor air, which is blown into the living room.

Located just outside of Madison in Southern Wisconsin, Sun Prairie's climate is dominated by heating, with a winter design temperature of −6°F. A typical year has 7576 heating degree days and 748 cooling degree days (both base 65°F).

The Sun Prairie residence was one of a group of seven sites monitored by the Energy Center of Wisconsin (1997) to document the performance and economics of residential geothermal heat pumps in the state. Two of the sites used vertical bore heat exchangers; of these, construction plans were available only for the Sun Prairie residence. Operating data from June 1995 through April 1998, along with the as-built construction plans, allowed the development of a calibrated simulation model of the residence.

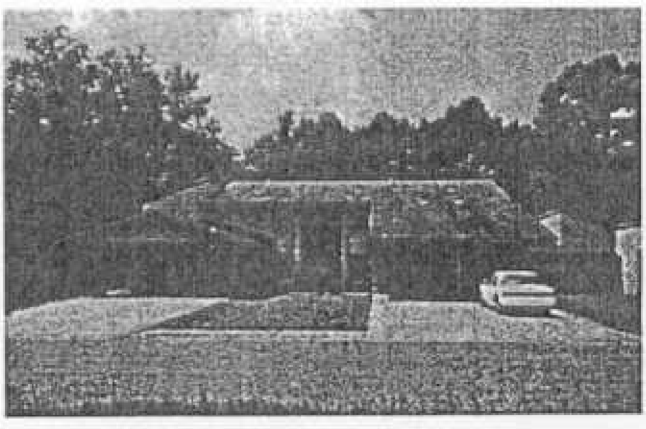

Figure 1.1 Fort Polk GHP residence (lower left apartment of a five-plex).

Figure 1.2 Sun Prairie GHP residence.

3. SIMULATION MODELS

In addition to details about the operation of the heat pump, the properties of the soil, borehole geometry, and the characteristics of the u-tubes, each of the design programs requires some type of information about the heating and cooling loads for the site. Because each program uses a different algorithm to size the ground heat exchanger, each requires the loads to be entered in a slightly different format. For example, some programs require the loads on a design day only, while others require monthly peak and total loads for a typical year at the site. The data available from a monitored site usually includes heat pump status, heat pump electrical use, indoor and outdoor temperature, and ground heat exchanger inlet and outlet water temperature. Although the load information required by the design programs can be calculated for the year in which the data was collected, this actual year will never have the same weather as an average or typical year for the site. In general there is no consistent way to determine the loads for a typical year using data collected from one actual year. To perform the comparison presented in this paper, simulation models were developed for each site. The models were calibrated to match the monitored data for the actual year, and then driven with typical meteorological year data for each site to produce consistent information for all of the sizing programs.

The TRNSYS simulation software package (Klein, 1996) was used to create detailed simulations of the geothermal heat pump systems and the residences. TRNSYS is a modular system simulation package; the user describes the components that comprise the system and the manner in which these components are interconnected. Components may be typical pieces of equipment like a pump or thermostat, or utility modules like occupancy forcing functions, weather data readers, integrators and printers. Because the program is modular, new component models for the heat pump and vertical ground heat exchangers were easily added to the existing component libraries to expand the capabilities of the program.

As-built construction plans were used to develop building load models for both sites. The heat pump models were based on manufacturer's operating data. The DST algorithm (Pahud and Hellstrom 1996) was used to model the performance of the ground heat exchangers. In simplified terms, the simulations operate as follows: at the beginning of each time 15-minute time increment, the heat loss (or gain) is calculated based on indoor air temperature, internal heat generation, outdoor air temperature, solar gain, outdoor air infiltration rate and other factors (ambient conditions are read from a typical meteorological year [TMY] file for each site). This rate of heat loss or gain determines the indoor air temperature at the end of the time period. If the indoor air temperature deviates from the thermostat setpoint, the heat pump is energized to provide heating or cooling to the space, and the temperature for that time increment is recalculated. The ground loop model determines the entering water temperature to the heat pump based on the flow rate and temperature into the heat exchanger, and ambient and soil conditions. The entering water temperature and flow rate determine the capacity and power of the heat pump.

4. CALIBRATION OF SIMULATION MODELS

The data available from both sites included outdoor air temperature, total residence electrical use, heat pump electrical use (compressor, blower, water pump and controls), inlet and outlet water temperature, reversing valve status, and heat pump runtime, all collected at 15 minute intervals. One-time measurements of water flow rate were made at both sites, and the flow rates were assumed to remain constant.

Calibration of the simulation models proceeded in two steps, beginning with the calibration of the ground loop model. Where possible, known values of the ground heat exchanger parameters were used, for example the heat exchanger geometry (borehole diameter and depth, header depth, borehole spacing, U-tube pipe sizes and shank spacing), and the thermal properties of the polyethylene pipe and the grout (backfill) material. The detailed simulation did not include the piping runouts to the ground heat exchangers nor the horizontal buried pipes between the ground heat exchangers. The remaining parameters—deep earth temperature and the soil thermal properties—were varied to achieve a "best fit" soil. Given an initial guess for the soil parameters, and the site-collected interval data on water temperature entering the ground heat exchanger, the DST model is used to determine the temperature exiting the heat exchanger. This value is compared with the site-measured exit temperature in each time interval. The best fit soil is that set of soil properties which minimizes the sum of squared errors between the predicted and site-collected heat exchanger exiting water temperature over the calibration period.

At the time the previous design comparison was made (Thornton et al. 1997a), only one month of water inlet and outlet data were available to perform the soil property calibration. Because the data were from the end of the heating season, the best fit deep earth temperature converged to 62°F, which is 7°F lower than handbook values indicate for the site. For this reason the previous paper contained two different comparisons: one that assumed a deep earth temperature of 62°F, and another that assumed a deep earth temperature of 69°F, which is the value recommended by

TABLE 1
Best fit soil properties for each site based on monitored data

	Fort Polk	Sun Prairie
Deep earth temperature	67.8°F	49°F
Density-specific heat product	40 BTU/ft^3-°F	64 BTU/ft^3-°F
Thermal conductivity	1.40 BTU/hr-ft-°F	1.64 BTU/hr-ft-°F

Bose et al. (1985) for the Fort Polk area. Later, an entire year of inlet and outlet water temperature data became available from the Fort Polk site, and a new soil calibration was performed. The comparisons for Fort Polk presented in this paper use the new soil properties only.

The final best fit soil properties for each site are presented in Table 1. Since the best fit soil lumps together vertical variations in soil properties and the impact of the horizontal runouts and the horizontal buried pipe between the ground heat exchangers, it may not represent actual soil properties at the site. However, in many cases the properties do match the properties derived independently using other techniques. At Fort Polk, the deep earth temperature which best fit the data was 67.8°F. For comparison, deep earth temperature measurements taken at three sites around Fort Polk prior to installation of the heat pumps were all at 67.8°F. Note that the thermal conductivity and volumetric heat capacity are the same as the values obtained in the previous study (Thornton et al. 1997a); only the deep earth temperature is different.

The deep earth temperature at the Sun Prairie site corresponds to the value given by Bose et al. (1985). A published report (Energy Center of Wisconsin 1997) indicates that the heat exchanger is in rock below 30 feet, so the best fit thermal conductivity of 1.64 BTU/hr-ft-°F appears to be reasonable.

With the soil calibrated, and the building models entered into TRNSYS, the only remaining unknown was outdoor air infiltration. The infiltration model used at both sites was based on an earlier ASHRAE method where the infiltration is a function of the indoor to outdoor temperature difference and the windspeed. The format of the infiltration is:

$$\text{Infiltration} = k1 + k2 * \text{ABS}(\text{Tinside} - \text{Tambient}) + k3 * \text{Windspeed}$$

where the infiltration is measured in air changes per hour, the temperatures are in Celsius, and the windspeed is in meters per second. The parameters k1, k2 and k3 were adjusted from nominal values until the models' average heating and cooling load lines matched the average heating/cooling load vs. outdoor air temperature seen in the monitored data.

To determine average heating and cooling load vs. outdoor air temperature for a given site from monitored data, the interval data is separated into 5°F bins according to outdoor air temperature, and further subdivided according to heating and cooling season. The heating load in the 22°F bin, for example, is found by averaging the loads in every time interval during the heating season when outdoor air temperature is greater than 19.5°F and less than 24.5°F. Heating load is determined from the data by summing the measured heat pump electrical use and the heat of absorption from the ground loop during a time interval; cooling load is determined by subtracting the measured heat pump electrical use from the heat of rejection from the ground loop during a time interval.

Figures 2.1 and 2.2 compare the loads as determined from the site-collected data and the loads as simulated by the TRNSYS models for the Fort Polk and Sun Prairie residences. The model matches the Fort Polk data quite well for the single year of interval data available. For the Sun Prairie site, three years of data were available, and although the calculated heating loads were approximately the same for each year, cooling loads varied considerably. To calibrate the TRNSYS model, infiltration parameters were adjusted until the load line fell approximately in the middle of the three years' data.

A final check on the calibration is to use the site data to compare plots of daily HVAC energy use (which includes heat pump, loop pump, fan and controls) vs. daily average temperature, both from the data and from the simulation. The simulated plot should have the same shape as the plot of actual data, and should lie roughly in the middle of the actual data. Plots of daily heat pump energy use vs. daily average temperature for both sites are presented in Figures 3.1 and 3.2.

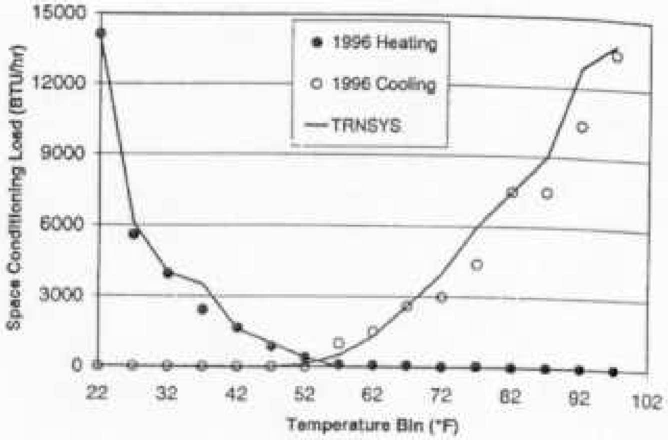

Figure 2.1 Binned 1996 space conditioning loads for Fort Polk residence (from site data), and loads from TRNSYS simulation.

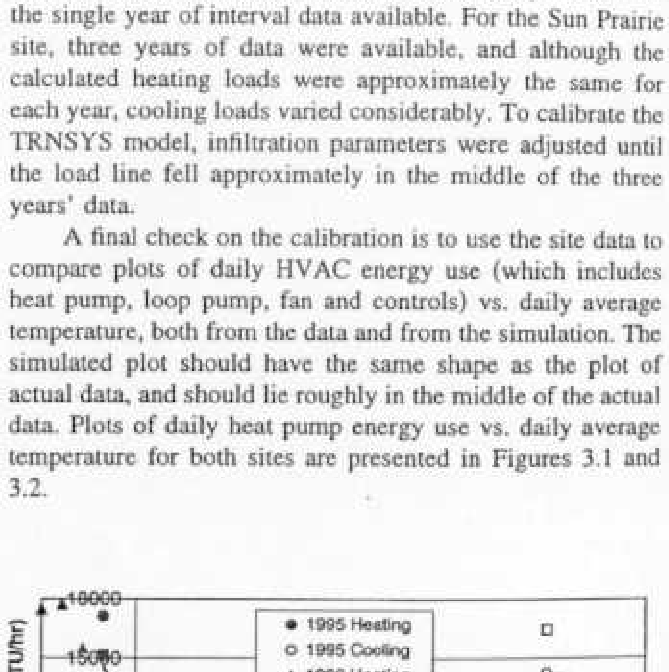

Figure 2.2 Binned 1995, 1996 and 1997 space conditioning loads for Sun Prairie residence (from site data), and loads from TRNSYS simulation.

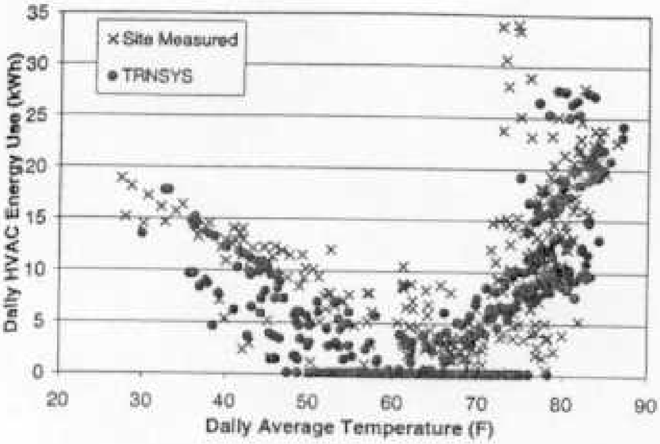

Figure 3.1 Daily energy use by Fort Polk GHP vs. daily average temperature: site collected 1996 data, and TRNSYS simulation.

5. GROUND HEAT EXCHANGER SIZING PROGRAMS

As in the previous comparison, the heat exchanger sizing programs will be referred to by a letter designation (A to F) instead of their software titles. Letters A through E correspond to the same programs tested in the previous study; the new programs is designated by the letter F.

Each of the six sizing programs requires a different set of user inputs. The general factors which influence the design size of the vertical ground heat exchangers are the building design loads, the building loads (monthly and annual), the weather, the soil thermal properties, the ground loop properties (both geometric and thermal), the working fluid, and the installed heat pump. The inputs used, and the method of deriving these inputs from the detailed simulation model, are discussed below.

Program A

Program A prompts the user to select a heat exchanger configuration from a set of standard arrangements. Both sites

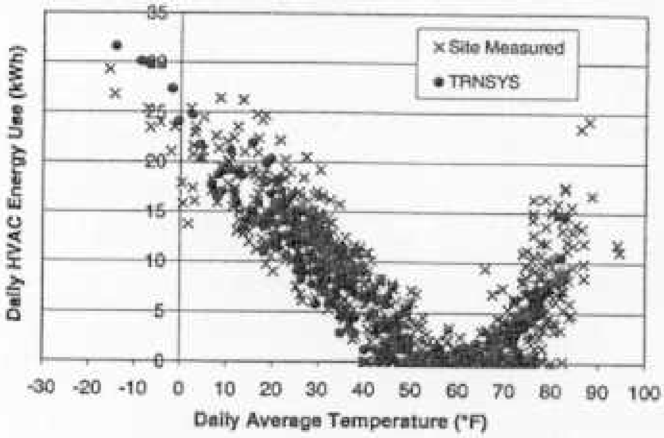

Figure 3.2 Daily energy use of Sun Prairie GHP: site collected data from 1995–1997 and TRNSYS simulation.

used vertical bore heat exchangers, for which the program required the distance between the u-tubes, u-tube diameter and material, distance below surface of the top of the u-tube, borehole diameter, and type of grout. The program did not allow natural soil to be selected as the backfill material, as was used at the Sun Prairie residence; for that case thermal grout was selected. Soil type is selected from a menu. Heavy saturated soil was chosen for the Fort Polk site; for the Sun Prairie site a new soil type was added to the program with the best fit soil properties obtained from the data. Alexandria, LA was selected as the ground temperature location for the Fort Polk site, and Madison, WI was selected for Sun Prairie.

In addition to the properties and flowrate of the heat transfer fluid, Program A requires the rated capacity of the heat pump in heating and cooling, and COP and EER at design conditions. These values are presented in Table 2. Winter peak load factors were 1 for both sites; summer peak load factors were 1 for Fort Polk and 0.53 for Sun Prairie.

Given the above information, the only input required by Program A from the simulations was monthly heat absorption and heat rejection. These values are included in Tables 3 and 4 for the two sites.

It should be noted that Program A includes two methods of calculating design lengths: the "average monthly load" and "peak load" methods. The lengths reported below correspond to the "average monthly load" method. Lengths calculated using the "peak load" method were some 45% higher, and are not included in the results.

Program B

In addition to the basic design parameters required by Program A, Program B requires the user to input borehole resistance. Fortunately, the DST software used in the TRNSYS simulation calculates this resistance. A value of 0.2281°F/BTU/ft-hr was used for Fort Polk, and 0.166°F/BTU/ft-hr was used for Sun Prairie. Program B also requires the B/H ratio for the borehole; for Fort Polk a value of 0.05 was used, and for Sun Prairie the value was 0.10. Best fit soil properties were input for each site. Operating data for the Sun Prairie heat pump was included in the program; for the Fort Polk heat pump, correlations of manufacturer's operating data at the measured flow rate were developed using the curve fit routine built into the program.

TABLE 2
Rated heating capacity and COP, cooling capacity and EER, for the Fort Polk and Sun Prairie heat pumps.

	Sun Prairie	Fort Polk
Heating capacity	5.40 kW	3.65 kW
Heating COP	3.6	3.7
Cooling capacity	8.20 kW	5.32 kW
Cooling EER	18.7	16.4

TABLE 3
Monthly total and peak heating and cooling loads, monthly heat absorption and rejection for the Fort Polk residence, simulated for a TMY

	Total	Total	Peak heating	Peak	Peak cooling	Peak	Heat	Heat
	heating	cooling	load	heating	load	cooling	absorbed	rejected
Month	MBTU	MBTU	MBTUh	load hours	MBTUh	load hours	MBTU	MBTU
January	2,962	0	16.3	2	0	0	2,201	0
February	1,878	0	16.2	4	0	0	1,393	0
March	1,174	0	16.2	2	0	0	867	0
April	0	286	0.0	0	15.8	1	0	331
May	0	1,818	0.0	0	15.3	3	0	2,133
June	0	2,856	0.0	0	14.8	13	0	3,369
July	0	6,214	0.0	0	13.5	13	0	7,724
August	0	6,229	0.0	0	13.7	3	0	7,751
September	0	4,114	0.0	0	13.7	2	0	5,089
October	296	332	10.8	1	12.8	3	201	410
November	121	0	15.8	4	0	0	89	0
December	1,030	0	16.2	5	0	0	761	0
Total	7,461	21,849					5,512	26,807

For each month in a design year, Program B requires total heating load, total cooling load, peak heating load, and peak cooling load. The values obtained from the TRNSYS simulation for each site are included in Tables 3 and 4. In addition to monthly loads, the program requires the number of peak heating hours and the number of peak cooling hours in any one month in the design year. A default value of six hours is recommended by the program developer. From the Fort Polk simulation, peak heating and cooling hours were determined to be 4 and 13, respectively. Following the program developer's recommendation, values of 6 hours for heating and 13 hours for cooling were used. From the Sun

TABLE 4
Monthly total and peak heating and cooling loads, monthly heat absorption and rejection for the Sun Prairie residence, simulated for a TMY

	Total	Total	Peak heating	Peak	Peak Cooling	Peak	Heat	Heat
	Heating	Cooling	load	heating	load	cooling	Absorbed	Rejected
Month	MBTU	MBTU	MBTUh	load hours	MBTUh	load hours	MBTU	MBTU
January	6,078	0	19.7	11	0	0	4,727	0
February	4,514	0	14.6	4	0	0	3,503	0
March	3,551	0	14.0	7	0	0	2,778	0
April	977	8	7.7	4	1.6	1	775	8
May	211	316	3.6	5	12.8	1	170	392
June	0	1,115	0.0	0	13.6	4	0	1,212
July	0	1,888	0.0	0	13.0	3	0	2,055
August	0	1,347	0.0	0	10.9	2	0	1,495
September	0	599	0.3	1	11.4	4	0	624
October	511	8	6.3	2	1.5	1	438	8
November	2,617	0	10.4	7	0	0	2,108	0
December	4,677	0	10.8	4	0	0	3,657	0
Total	23,136	5,265					18,156	5,794

TABLE 5
Average loads on peak heating and cooling days for the Fort Polk residence, simulated for a TMY

	Average	Average
	Heating Load	Cooling Load
Block	(1000 BTU/hr)	(1000 BTU/hr)
8AM–Noon	11.2	7.6
Noon–4PM	3.8	13.8
4PM–8PM	2.2	16.9
8PM–Midnight	8.3	11.8

Prairie simulation, there were 11 peak heating hours and 4 peak cooling hours. Values of 11 and 6 hours respectively were used.

Program C

Program C requires only basic information about the heat exchanger: diameter and thermal resistance of the u-tube pipe (values of these parameters for various nominal pipe sizes are included in a table), heat transfer fluid flow rates, separation distance between the bores, and number of bores. The program also requires the user to specify turbulent, laminar or transition flow inside the u-tube. The flow was determined to be turbulent at both sites. Given this information, the program calculates a borehole resistance. It should be noted that the values calculated were not the same as the values calculated by the DST model. For Fort Polk, Program C calculated a borehole resistance of 0.344, compared with the value of 0.228 calculated by DST. For Sun Prairie, Program C calculated a borehole resistance of 0.183, compared to the value of 0.166 calculated by DST. In order to be consistent, the DST-calculated borehole resistances were used with Program C, not the borehole resistances it calculated from the inputs.

Operating data for the Sun Prairie heat pump was included in the program's database; for the heat pump at Fort Polk, an external utility program was used to generate a new heat pump data file from manufacturer's performance data. The best fit soil properties for each site were used.

TABLE 6
Average loads on peak heating and cooling days for the Sun Prairie residence, simulated for a TMY

Block	Average Heating Load (1000 BRU/hr)	Average Cooling Load (1000 BTU/hr)
8AM–Noon	13.1	11.1
Noon–4PM	7.0	13.3
4PM–8PM	11.6	10.5
8PM–8AM	17.4	4.7

As opposed to the monthly loads required by other programs, Program C requires the average loads in each of four blocks on a heating design day and a cooling design day. For the purposes of this analysis, a design heating day was determined from the simulations as the day on which the total heat added to the space was a maximum; a cooling design day was the day on which the total heat extracted from the space was a maximum. The average heating and cooling loads in the four blocks for the design day at each site are presented in Tables 5 and 6.

Program C also requires annual equivalent full load heating and cooling hours. These were determined by summing the hourly heating and cooling loads from the annual simulation of each site. Equivalent full load heating hours is defined as the total annual heating load divided by the heating capacity of the heat pump with the given flowrate and an entering water temperature of 40°F for Fort Polk and 30°F for Sun Prairie. Likewise, equivalent full load cooling hours are defined as the total annual cooling load divided by the rated cooling capacity with the given flowrate and an entering water temperature of 95°F for Fort Polk and 77°F for Sun Prairie. At Fort Polk, the simulation predicts 534 annual full load heating hours and 1852 full load cooling hours. The Sun Prairie simulation gives 1327 full load heating hours and 207 full load cooling hours.

Program D

This method begins with selection of the "Weather city," "Bin data city" and "Earth temperature city." For the Sun Prairie case, all three were chosen to be Madison, WI. For the Fort Polk simulation, the weather city was chosen as Lufkin, TX; the bin data city as Alexandria, LA; and the earth temperature city as Lake Charles, LA. The program then requires information about the ground loop, including the u-tube diameter and material, the heat transfer fluid, the flow rate, and the soil type. For the Fort Polk case, heavy saturated soil was chosen. Average rock was chosen for the Sun Prairie case. Information on the Sun Prairie heat pump was contained in the program's database, but the Fort Polk heat pump was not. In this case, the program required the heating capacity and EER at the minimum entering water temperature, and cooling capacity and COP at the maximum entering water temperature. These were determined from the operating data for the heat pump.

Program D also required design heating and cooling loads. These would normally come from a manual J-type calculation, but since the simulation data was available, the loads were determined as the maximum heating and cooling loads from the TMY simulation for each site. For Fort Polk the loads were 19,348 BTU/hr in cooling and 15,760 in heating; the values for Sun Prairie were 13,628 BTU/hr in cooling and 19,670 in heating. The cooling load at both sites was assumed to be 65% sensible and 35% latent.

Program E

As with the other programs, Program E requires the dimensions and material of the u-tube and the soil type. The user must select soils from a menu. For Fort Polk, heavy saturated soil was selected, and for Sun Prairie saturated sand/gravel was selected, as this best matched the thermal conductivity.

The heat pump for the Fort Polk residence was included in the database of Program E. For the Sun Prairie machine, a heat pump was entered with the design heating and cooling capacity and COP of the actual machine.

Program F

Program F requires the same basic information as Program B. In addition to the monthly peak loads, the user must also specify the number of hours during each month during which the peak heating and cooling loads occurred. No guidance was provided on how to obtain this input. For the purposes of this paper, hours in the simulated month were assumed to be at peak if the load (heating or cooling) was within 95% of the absolute peak load for that month. Peak heating and peak cooling load hours for both sites are presented in Tables 3 and 4.

This program also required heating and cooling season performance factor. These were calculated from the simulations of each site. For Fort Polk, the heating season performance factor was 4.08 and the cooling season performance factor was 3.89. For Sun Prairie, heating season performance factor was 3.95 and cooling season performance factor was 5.63.

6. COMPARISON OF RESULTS FROM THE SIX DESIGN PROGRAMS

Table 7 compares the heat exchanger designs from the six programs for the Fort Polk residence at entering water temperatures of 85, 90, 95, 100, and 105°F. These are one-year lengths, i.e., the heat exchanger lengths required such that the maximum EWT does not exceed the given value in the first year of operation. These lengths are most appropriate

TABLE 7
One year heat exchanger design lengths for the Fort Polk residence, bore feet per nominal ton of installed capacity.

	Design Program						
Max EWT	A	B	C	D	E	F	TRNSYS
85°F	309	309	344	348	336	324	377
90°F	245	256	283	271	269	240	300
95°F	203	219	241	223	227	192	252
100°F	173	192	211	189	197	163	216
105°F	152	171	188	164	171	140	189

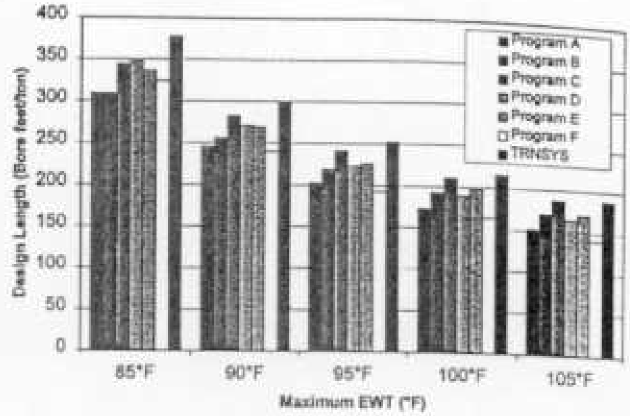

Figure 4.1 Comparison of six design methods and TRNSYS benchmark for Fort Polk residence.

TABLE 8
Ten year heat exchanger design lengths for the Fort Polk residence, bore feet per nominal ton of installed capacity.

	Design Program				
Min EWT	A	B	C	F	TRNSYS
85°F	340	325	427	352	399
90°F	269	269	351	260	316
95°F	223	229	299	207	265
100°F	191	200	261	173	228
105°F	167	179	233	149	199

TABLE 9
One year heat exchanger design lengths for the Sun Prairie residence (bore feet per nominal ton of installed capacity).

	Design Program						
Min EWT	A	B	C	D	E	F	TRNSYS
25°F	94	74	88	112	103	101	100
30°F	118	97	110	150	135	132	126
35°F	158	125	146	214	193	179	182

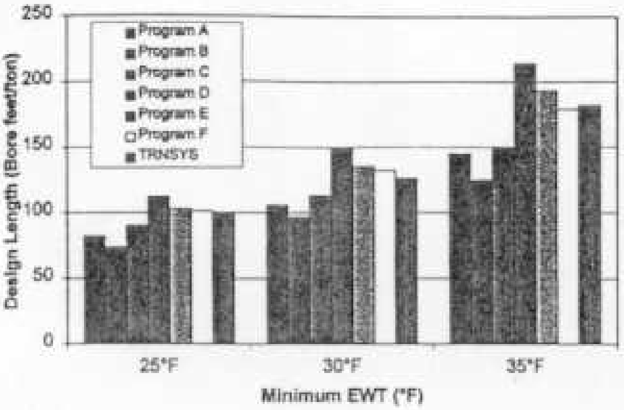

Figure 4.2 *Comparison of six design methods and TRNSYS benchmark for Sun Prairie residence.*

TABLE 10
Ten year heat exchanger design lengths for the Sun Prairie residence (bore feet per nominal ton of installed capacity).

	Design Program				
Min EWT	A	B	C	F	TRNSYS
25°F	100	78	105	110	110
30°F	126	99	132	143	146
35°F	169	132	175	196	208

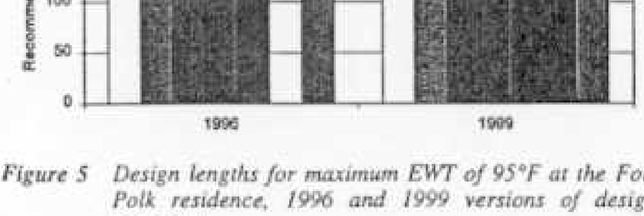

Figure 5 *Design lengths for maximum EWT of 95°F at the Fort Polk residence, 1996 and 1999 versions of design programs.*

for applications where heat rejection and extraction roughly balance over the year, but are often used for residential sizing even in extreme locations like those addressed here, because small borefields have modest multi-year effects.

Figure 4.1 presents the one-year Fort Polk results in graphical form. Compared to the study performed in 1996, there is now much closer agreement among the various design methods. Previously at 95°F EWT the design lengths varied by ±27% among the five programs tested. Among the six programs tested here the variation is only 7%.

Although the programs appear to undersize the heat exchanger somewhat when compared to the TRNSYS benchmark, there is reason to believe that the TRNSYS benchmark lengths are accurate. The length of the heat exchanger installed on the Fort Polk residence was 258 feet, or 344 bore feet per ton. Interpolating between the TRNSYS design lengths for maximum EWTs of 85 and 90°F, a heat exchanger with length of 344 feet per ton should see a maximum EWT of 87.1°F during the first year of a typical meteorological year. The observed maximum for 1996 was in fact 85.1°F, but as shown in Hughes and Shonder (1998), the summer of 1996 at Fort Polk was relatively mild compared to a TMY. When the TRNSYS model was run with actual weather conditions for 1996 and the installed heat exchanger length, the predicted maximum EWT was 85.1°F, exactly the value observed in the data.

Table 8 compares the ten-year values for Programs A, B, C, and F, and for the TRNSYS benchmark. At an entering water temperature of 95°F, the design lengths from the four programs vary by about 17%. The larger variation in the ten-year lengths is not unexpected, since any inherent inaccuracy in the one-year calculations will be magnified over the ten-year period.

The one-year design lengths for the Sun Prairie residence are given in Table 9, and presented graphically in Figure 4.2. At a minimum EWT of 30°F, the variation among the six programs is ±16% about the mean value. This is about twice the variation seen in the design lengths for the Fort Polk site. One reason for this may be the lower loads at the Sun Prairie site: the bore depth at Sun Prairie is only 160 feet compared to 258 feet at Fort Polk. The results would be expected to be more consistent for longer bores than for shorter ones. It may also be the case that the design algorithms are more accurate for cooling-dominated sites than for heating-dominated sites. Further research will be required to determine the reason for the difference. The ten-year design lengths for the Sun Prairie site are presented in Table 10. The variation about the mean is ±15%, nearly the same as variation for the one-year values.

7. CONCLUSIONS

At least six computer programs are available commercially to size vertical ground heat exchangers for geothermal heat pumps. In general, each of the programs requires different information and uses a different design algorithm. A previous comparison of five of these programs with a consistent set of inputs from a calibrated simulation found that the programs did not agree—the recommended heat exchanger lengths varied by 27% among the various programs.

A new comparison, performed with updated versions of these five programs and one new program shows much better agreement. The situation is best illustrated by Figure 5, which compares the design lengths from each program required to limit EWT to 95°F at the Fort Polk residence. Note the difference between the 1996 and 1999 versions of the programs. At a maximum EWT of 95°F, the heat exchanger sizes recommended by the six programs are now within 7% of each other.

The results for the Sun Prairie site are not quite as good, though still much more consistent than the results of the original Fort Polk comparison. At a minimum EWT of 30°F the design lengths for the Sun Prairie site vary by about 16%. This result indicates that some of the software providers may need to examine the algorithms used to determine heat exchanger lengths for heating-dominated climates. It should not obscure the fact that there are design methods available that perform consistently well in both heating- and cooling-dominated climates.

REFERENCES

Bose, J.E., Parker, J.D. McQuiston, F.C. 1985 "Design/Data Manual for Closed Loop Ground-Coupled Heat Pump Systems." American Society of Heating, Refrigeration and Air Conditioning Engineers.

Energy Center of Wisconsin. 1997. "Enhanced Residential Heat Pumps: Wisconsin Case Study Results." Energy Center of Wisconsin, September.

Hughes, P.J. and J.A. Shonder. 1998. "The Evaluation of a 4000-Home Geothermal Heat pump Retrofit at Fort Polk, Louisiana: Final Report," ORNL/CON-460.

Klein, S.A. et al., TRNSYS Manual, "A Transient Simulation Program." 1996. Solar Energy Laboratory, University of Wisconsin, Version 14.2 for Windows.

Pahud D. and G. Hellstrom. 1996. "The New Duct Ground Heat Model for TRNSYS" Eurotherm Seminar N* 49, Eindhoven, The Netherlands, pp. 127-136.

Thornton, J.W., T.P. McDowell, and P.J. Hughes. 1997a, "Comparison of 5 Practical Vertical Ground Heat Exchanger Sizing Methods to a Fort Polk, LA Data/Model Benchmark," ASHRAE Transactions.

Thornton, J.W., T.P. McDowell, J.A. Shonder, P.J. Hughes, D. Pahud, and G. Hellstrom, 1997b, "Residential Vertical Geothermal Heat Pump System Models: Calibration To Data," ASHRAE Transactions.