ANNUAL PERFORMANCE OF A HORIZONTAL-COIL GROUND-COUPLED HEAT PUMP

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ABSTRACT

Performance of the ground-coupled heat pump system located in TECH House I at the University of Tennessee has been measured for the 1983-84 cooling and heating seasons. Hourly measurements of heat flows, power consumptions, and various ground, space, and system temperatures have been recorded and analyzed to give overall seasonal performance. For the heating season, the performance factor was found to be 2.6, which is higher than a typical air-air system. However, performance factor for the cooling season was determined to be only 1.1, considerably lower than a typical air-air system. Reasons for this low performance in the cooling mode include poor backfilling procedure when the ground coil was buried, soil drying, and possibly too short a ground coil. Also, the heat pump system itself had a low coefficient of performance for cooling compared to other high-efficiency systems. Future work on this project will involve reinstallation of a longer ground coil with better backfill, the installation of a ground irrigation system, a more efficient heat pump, and eventually the optimization of the ground coil and heat pump system.

INTRODUCTION

As energy costs have steadily increased in recent years, much attention has been given to the optimization of heat pump systems. The most significant external parameter affecting heat pump performance is the difference between the temperatures at which heat is added to and rejected from the refrigerant. Numerous methods to reduce this temperature difference, including solar assist, energy storage, groundwater and ground-coupled systems, have been studied. The ground- coupled heat pump (GCHP) system uses a heat exchanger buried in the ground where the seasonal variation in temperature is small relative to the variation in air temperature. The ground is normally at a more favorable source temperature than the outside air; however, in order for ground coupled heat pumps to compete successfully with conventional systems, the thermal conductivity of the soil must be high enough to transfer the required amount of heat as effectively as the convection coil in air-to-air heat pumps. The soil thermal conductivity is a variable, however, and changes throughout the year because of two effects. First, the natural cycle of soil moisture causes the soil to be dryer during the summer than in winter. Second, and perhaps more important, is the phenomenon of moisture migration in the soil, which is induced by a temperature gradient (Hadley et al. 1953). In the heating season, cooling of the ground tends to increase moisture near the coil, and this increases the thermal conductivity near the pipe. Operation in the summer season heats the soil near the pipe and drives moisture away, thus reducing the soil thermal conductivity.

Intensive experimental investigation of the ground-coupled heat pump began in the mid'40s. The ASHVE (Now ASHRAE) Transactions report much of this early design work. The results of ground-coupled heat pumps from 28 major research projects were monitored by an

association of companies and the Edison Electric Institute (1953). Their final report cites investigations from 1945 through 1953 and includes correlated information on coil data, heat pump equipment, test durations, heat flows, and soil temperatures and also includes a brief summary of results and conclusions from these studies. Although much progress was shown, the AEIC-EEI heat pump committee concluded that "even with this considerable amount of information, there is still no apparently workable design equation which can be used by the individual contractor." As electricity became cheaper and more abundant in the 1950s and 1960s, much of the GCHP work in this country was abandoned.

Recently, as the price of electricity has increased, interest has again been focused on the ground-coupled heat pump system. Metz (1979) reports on ground-coupled heat pump research at Brookhaven National Laboratory including the testing of four buried tanks, six earth coils, and six sealed vertical wells. A heating seasonal performance factor of 2.3 is reported for a horizontal ground coil in Upton, New York. Bose (1982) reports studies with six experimental earth coils involving different pipe materials, water/antifreeze solutions, and several brands of water-source heat pumps. Seasonal performance factors of 2.8 for heating and 2.7 for cooling have been reported for his site in Oklahoma. In a 1982 survey of ground-source heat pump investigations, Ball (1983) summarized data from various investigations and reports a range of seasonal performance factors for heating from 2.0 to 3.35 for 17 different installations and two values for cooling, 1.8 and 2.7. Cooling season performance data appear to be scarce compared to heating data.

This paper presents the annual performance evaluation for the 1983-84 cooling and heating seasons of a ground-coupled heat pump with a single pipe horizontal coil. The system was installed as part of the Tennessee Energy Conservation in Housing (TECH) program, which operates five different test houses at the University of Tennessee. The ground-coupled heat pump system was installed in TECH House I, which is a 1800 ft^2 (165 m^2) occupied single family residence of frame construction with R-19 walls and R-22 ceiling insulation. The house has passive solar features consisting of south-facing glass with manually operable insulated shutters and overhang shading. The design heating load of the house is 30,000 Btu/h (8.8 kw) while the design cooling load is 22,000 Btu/h (6.4 kw). Heating degree-days for the Knoxville area average 3478F (1932°C) based on 65F (18°C), and cooling degree days average 1569F (872°C) with the same base (TVA 1979). The soil in the Knoxville area is primarily clay.

Considering factors such as the heating and cooling loads on the Knoxville house, the lower soil thermal conductivity expected during the summer months, and the significantly higher ground heat transfer in the cooling mode leads to the conclusion that the ground heat exchanger should be sized to meet summer design conditions.

System Description

The ground-coupled heat pump system at the TECH Facility uses a water-source, heating-only heat pump. A schematic of the ground-coupled heat pump system is presented in Figure 1. Space cooling is provided by re-directing the fluid in the ground loop (hereafter called brine) with three-way valves. Prior to installation, tests were performed to determine the heat pump capacity. The heating capacity of the heat pump in use is 34,100 Btu/hr (10 kw) at T_{EVAP} = 35.6 F (2°C) and T_{COND} = 86.0 F (30°C). The cooling capacity of the heat pump was determined to be 25,600 Btu/h (7.5kw) at T_{EVAP} = 44.6 F (7°C) and T_{COND} = 98.6 F (37°C). The compressor, indoor fan, and ground-coil circulation pumps are engaged simultaneously and are governed by a single-stage thermostat.

The design (Fisher 1981) of the ground-coupled heat pump system called for a ground-coil pipe length of 700 feet (213 m) utilizing 1 1/4 inch (3 cm) polybutylene pipe buried 4 feet (1.2 m) deep. This design was based on an assumed cooling load of 16,800 Btu/h (4.9 kw). As was previously stated, the design cooling load has been calculated to be 22,000 Btu/h (6.4 kw) using standard ASHRAE techniques (ASHRAE 1981). Although the design called for a ground-coil length of 700 feet (213 m), the actual installed length was 675 feet (205 m) due to rock that was encountered during the installation. The pipe was laid in a horizontal, serpentined array such that any one run was at least 6 ft (1.8 m) from another parallel run of pipe. The soil was excavated with a commercially available motorized trencher. Backfilling was with the original material and was difficult due to the tendency of clay soil to agglomerate. An analysis of the soil showed a composition of 85% clay and silt and 15% sand.

The brine is a solution of 20% by weight methanol in water. Small amounts of corrosion inhibitors and microbiocide were also added, and the solution was then buffered to a final pH

of approximately 7.0. The flow rate in each loop was determined to be about 9.5 gpm (2.5 m^3/h) for each mode of operation giving a flow well into the turbulent regime.

It is estimated that the installed cost of the ground-coupled heat pump system in 1982 dollars is $5,290. This estimate is for the ground coil, heat pump, and associated piping and controls; it does not include costs for ductwork. Table 1 shows a breakdown of the cost of the major items associated with the system's installation.

Procedure and Instrumentation

Most data at the TECH facility are automatically fed into a hybrid data acquisistion system (DAS). Every hour the integrated digital signals from electronic counters and the instantaneous analog signals are recorded on magnetic tape. These data include hourly heat flows, energy consumptions, and specified temperatures as well as hourly meteorogical conditions consisting of dry-bulb and dew-point temperature, wind speed and direction, barometric pressure, total global solar insolation, and rainfall. In addition to data for this project, the DAS also records data for projects involving the other four houses on the TECH site (McGraw et al. 1983). Usable hourly data were obtained for over 98% of the total possible hours of this study.

All values of electric power use and heat flows to or from the house and ground are recorded as sums for each hour. For electric power, revolutions of the eddy disk of standard electric meters are counted optically. A flow meter and two platinum resistance temperature devices (RTDs) form the basis of each measured heat flow. The ground-coil heat flow and the water-to-air-coil heat flow are measured with these devices. The temperature difference measured by the two RTDs is electronically converted to a frequency. That frequency is then electronically multiplied by the frequency output of the flowmeter. The product of the flow rate and the temperature difference, which is directly proportional to the heat flow, is sent to a summing circuit in the data acquisition system (DAS).

Soil and brine temperatures are measured with platinum RTDs using standard resistance thermometry. These RTDs were selected for durability, electrical stability, and linearity.

Soil moisture measurements were made around the pipe near the mid-length using ceramic moisture sensors that were calibrated using soil samples obtained from the site (Appendix). Nine sensors were used at this location with one next to the pipe and the remaining sensors spaced 6 in (.15 m) apart in both the horizontal and vertical directions. Because of slow response, these sensors were read manually each week. The measurement was made by determining the resistance between two metal plates that are enclosed within ceramic material, which in theory is in moisture equilibrium with its surrounding soil. The resistance was measured with an AC bridge circuit.

Conditioned space dry-and wet-bulb temperature measurements were made with solid state temperature transducers. The latent cooling load was measured by recording the total mass of condensate removed from the air by the water-to-air-coil. The condensate is gravity fed to a tipping bucket rain gage, where each tip of the bucket is counted and recorded by the DAS.

The ground-coupled heat pump system operation is regulated by a single thermostat during both the heating and cooling seasons. All instruments were calibrated prior to installation. At the beginning of each heating and cooling season and on a monthly basis during the seasons, the sensors are recalibrated.

DISCUSSION OF RESULTS

Heat pump systems are normally rated by a coefficient of performance (COP), defined as the energy added to/removed from the conditioned space at the heating/cooling coil divided by total electrical energy input. Another method of rating the performance of a system is the performance factor (PF) (Bedinger and Sullivan 1982) defined as the total useful energy supplied to (removed from) the conditioned space divided by the total purchased power required to deliver that energy for the appropriate time period. Since the ground-coupled heat pump system is packaged in such a manner that it could be installed either inside or outside the conditioned space, two separate performance factors are presented.

PF_i is the performance factor for the case in which the heat pump package and all other power-consuming components (pumps and the blower) are located within the conditioned space.

The ground coupled heat pump system is presently installed in this manner so that all losses due to equipment inefficiencies result in heat addition to the conditioned space, which are therefore included in PF_i. For example, the heating PF_i is calculated as the sum of the ground-coil heat flow and the total purchased power divided by the total system purchased power during the entire heating season. PF_o is calculated assuming the entire package (compressor, refrigerant piping, refrigerant-to-brine heat exchangers and pumps) is located outside the conditioned space. Consequently, heat losses from these components are not included in heat delivered to the space. Heating PF_o is then calculated as the sum of the heat transferred through the condensing coil and blower power divided by the total purchased power.

Likewise, for cooling operation, PF_i is ground heat transfer less total purchased power divided by total purchased power, and PF_o is evaporating coil heat transfer less blower power divided by total purchased power. Locating the heat pump package within the conditioned space will be beneficial to the user during the heating season but will be a detriment during the cooling season. The location of the heat pump package has a profound effect on the performance of the ground-coupled heat pump system. Therefore, depending upon the type of climate, the designer should give serious consideration as to whether the heat pump package is located inside or outside the conditioned space.

Performance of Heat Pump Package

The heat pump package itself has a significant effect on overall performance; therefore, it is desirable to know the performance of the system exclusive of the ground heat exchanger. Data from the actual experiment were used to obtain the coefficient of performance of the package unit as a function of brine inlet temperature. In order to reduce the effects of transient operation, data were used only if the heat pump had operated for a significant fraction of a given hour. The conditioned space was controlled by a thermostat located directly over the return air grille. The thermostat was set so that the air temperature entering the inside coil was 70 F (21°C) in winter and 80 F (27°C) in summer with a maximum variation in temperature of ± 2 F (± 1.1°C).

According to the "Directory of Certified Applied Air-Conditioning Products," (ARI 1983), water-source heat pumps should be rated at a water source temperature of 70 F (21°C) for heating and 85 F (29°C) for cooling. Our data show a COP of 3.6 for heating and 2.6 for cooling at these temperatures. Cited values range between 2.4 and 3.9 for heating and 2.3 to 3.4 for cooling, indicating that the performance of the system used in this study is in the upper range of commercially available units in the heating mode and in the lower range for cooling.

System Performance - Cooling

The performance of the horizontal coil ground coupled heat pump system operating in the cooling season was evaluated from June through September 1983.

Table 2 presents monthly and seasonal totals of the electric power consuming elements of the system, the condenser and evaporator heat flows, and the monthly performance factor. System performance is seen to generally decrease throughout the season. The measured summer seasonal performance factor (PF_i) was 1.11 and the estimated value of PF_o was 1.31. These are low by any standard of comparison. Of the total power consumed during this summer, 80% went to the compressor, 12% was used by the fan, and 8% by the pumps.

After the first few weeks of the summer, the inlet brine temperatures increased to temperatures well above 85 F (29°C) and the corresponding capacity and COP of the unit decreased significantly. Consequently, the unit often ran constantly during daylight hours shutting off only late at night. Because of the low level of performance, the sensible heat load on the house was met only when the ambient temperature was below 98 F (37°C). Above this temperature, the unit ran constantly but could not maintain the conditioned space within set limits of the thermostat. The latent load on the house was also frequently unmet, as the inside coil temperature was often above the dew point of the inside air. This coil surface temperature was frequently as high as 60 F (15°C) while 45 F (7°C) is generally considered sufficient for dehumidification purposes. A latent load of about 10% of the sensible load was measured as condensate as previously described. A building such as this normally has a latent load of about 25% of the sensible load (ASHRAE 1981).

System Performance - Heating

The performance of the horizontal ground-coupled heat pump system, operating in the heating mode, was evaluated for the time period November 1983 through March 1984.

Table 2 presents the monthly and seasonal totals of the three electric power consuming elements of the heat pump system, the condenser and evaporator heat flows, and the monthly performance factor.

The ground-coupled heat pump system provided heat to the conditioned space throughout the entire heating season without the need for auxiliary electric resistance heat as is normally required in conventional air-to-air heat pumps. Of the total electric power consumed during the heating season, the compressor consumed 75% of the total, the blower consumed 15%, and the pumps 10%.

A heating Seasonal Performance Factor (PF_i) of 2.59 was determined for the sytem. Assuming that the package had been located outside the conditioned space, the PF_o is estimated to be 2.15. System performance shows a slight decrease during the season, probably due to the normal winter variation in far field ground temperature and moisture. A discussion of soil conditions follows this section.

Soil Temperatures

The thermal response of the soil is a primary indicator of the ability of the ground to both store thermal energy and to transfer it away from (toward) the pipe. The average daily ground temperatures for different horizontal distances from the buried pipe are shown for the entire season on Figure 2. As expected, the temperature fluctuations of the soil are less prominent as distance from the pipe increases. In addition, the temperatures approach the far-field values as the distance from the pipe increases

The temperature difference between the pipe wall and a point 36 in (.9 m) from the pipe is used to compare the relative effectiveness of the ground in heat transfer between the cooling and heating seasons. The larger difference seen in the summer months shows the difficulty of dissipating the summer heat flux. This can be explained by a combination of higher heat flux (an average of 3.7 kw for summer compared to 2.3 kw for winter) and the lower thermal conductivity expected for the summer conditions. Figure 3 illustrates typical horizontal temperature profiles in the soil for both the heating and cooling mode of operation. In each case it is noted that the major temperature difference between the pipe and the far-field occurs within the first 6 in (.15 m) from the pipe coil. For each case a reference profile taken the same day with the system off is also shown.

Freezing

Much note is made in the literature with regard to freezing the soil near the ground coil during winter operation and its effect on performance. Freezing temperatures were frequently observed in the soil near the pipe during January and February (Figure 2). Since these temperatures were measured at the midpoint of the ground coil, it is likely that more extensive freezing occurred near the first segment of pipe length where brine temperatures would be lowest. However, there were no temperature probes located in this region. Freezing of the soil and subsequent release of the latent heat has the effect of increasing the effective thermal conductivity of the soil during the winter season. Freezing effects are not likely to be dominant in the Knoxville area due to relatively mild winters and the additional lengths of ground coil required by summer design conditions.

Soil Moisture

Moisture content is one of the major factors in determining the soil thermal conductivity. Measurements made during the summer indicate a general decrease from around 35% in early June, which is considered saturated, to a value of near 20% by the end of September. Although the moisture content very close to the pipe could not be measured due to the large size of the moisture probes, the variation of soil moisture with distance from the pipe was very small, indicating almost uniform drying over a large region away from the pipe.

Soil moisture measurements taken during the winter indicate that the soil remained near saturation throughout the season with values of moisture content above 30%. This was expected

because of the natural moisture cycle and the cooling effect of the coil on the adjacent soil. The saturated soil conditions were further verified by periodic digging into the soil to reposition and examine various instruments and cable.

Soil Thermal Conductivity

The measured soil moisture remained virtually constant during the month of June, while the average effective soil thermal conductivity as calculated from measured data decreased significantly from a value of above 0.6 Btu/h•ft•F (1 W/m•°C) to a value near .35 Btu/h•ft•F (.6 W/m°•C). This could indicate significant drying close to the pipe, where the sensors are unable to measure, or uneven drying along the pipe. Another possibility considered is that the dynamic response of the sensors to drying was inadequate. Dynamic calibration of the sensors (Appendix) indicates, however, that this should not be the case.

Values of effective soil thermal conductivity were calculated based on measured values of ground heat transfer and the temperatures of the brine and the ground. The heat transfer was modeled as steady-state one-dimensional radial heat flow through a composite cylinder, assuming no mass transfer, no freezing, and a homogeneous soil. The control volume used in the analysis extended from the inside radius of the pipe to a point in the soil having a radius of 6 in (.15 m) where the temperature fluctuations with time were relatively small. Because the pipe flow was well into the turbulent regime, heat flow resistance due to the inside film coefficient was ignored. Transient effects due to heat pump cycling were minimized by using only data taken when the heat pump had been operating a minimum of 90% of a given hour. Approximately one-third of the available summer data met this criterion. Typically, the heat pump would run continuously for several hours during the summer season and shut off only late at night. This reflects the poor system performance of the cooling mode but allowed steady state equations to give a good estimate of soil thermal conductivity. Because of much shorter cycling periods during the winter operation, only 5% of the available data met the 90% runtime criterion, and the estimated values of thermal conductivity for the winter season are considered less reliable.

The time-weighted average hourly thermal conductivities were calculated and an average seasonal effective soil thermal conductivity of 0.32 Btu/h•ft•F (0.56 W/m•°C) was obtained for the summer season. Table 3 compares values of thermal conductivity calculated from this study with predictions from Sundberg (1979) and Lunardini (1981) for similar soils. For the week of June 6 at the beginning of the cooling season, the soil was near saturated at 30% moisture and agreement is reasonably good. However, by mid-July, the soil moisture decreased to 25% and the calculated values of thermal conductivity are considerably lower than predicted. This difference could be attributed to void spaces near the pipe, to significant drying in a thin layer around the pipe (moisture sensors are large enough that such drying would not be detected), to slow response of the moisture sensors, or, perhaps, to all of these.

The average soil thermal conductivity calculated for the winter season was 0.63 Btu/h•ft•F (1.1 W/m•°C) using the steady-state assumption. This approach for the winter data is open to serious question given the shorter run times involved. Consequently, at the end of the heating season, the system was locked on until steady state had been obtained. The value of thermal conductivity calculated from this test was .64 Btu/h•ft•F (1.15 W/m•°C) which compares very favorably with that obtained from the hourly data and from Sundburg (1979) and Lunardini (1981) (Table 3).

Figure 4 is a plot of the system performance (PF_i) factor and the calculated weekly average soil thermal conductivities. A similarity in the trends of the heat pump system performance deterioration and the decrease in experimental thermal conductivity is evident during the summer season. The majority of the heat pump performance deterioration occurs at the beginning of the cooling season as does the major portion of the change in thermal conductivity. The comparison between the experimental thermal conductivity and the heat pump performance indicates that the soil thermal conductivity is a major contributor toward the heat pump performance deterioration. During the winter season, however, the system performance remains almost constant while the effective soil thermal conductivity increases sharply during the months of January and February. This represents further evidence of freezing and thawing around the pipe, which is known to increase the effective thermal conductivity. However, this improved effective thermal conductivity does not appear to signigicantly improve system performance.

Near the end of the cooling season, soil in the trench was excavated in two locations for inspection. In one of the locations, voids were present in the backfilled soil, particularly

at the interface of the disturbed and undisturbed soil. Also, voids were formed adjacent to the pipe, particularly where the pipe was near the edge of the trench. The other excavation revealed fewer voids and none were evident around the pipe. From this evidence, it is not possible to infer the extent of voids in the soil, although the discrepancy in soil thermal conductivity in late summer indicates that voids may be a significant factor. During the winter season, these voids would be filled with water and would have little effect on soil thermal conductivity. In the summer, water would disappear, leaving an insulating gap of air near the pipe.

Source Temperatures

Figure 5 shows the daily average temperatures for ambient air, the "far field" soil temperature at the pipe depth, and the brine temperature entering the heat pump from the ground. The ambient air temperature varies from 5 to 81 F (-15 to 27°C), and the ground varies only from 48 to 79 F (9 to 26°C). Since the ambient air temperatures are represented as daily average values, the figure does not show the temperature extremes that would occur for a particular day, which would show that the fluctuation in air temperature as being much greater. The ground temperature, however, is much more slowly influenced by the daily weather patterns and serves as a more consistent temperature source.

The difference between the brine temperature and the far-field soil temperature increases as the cooling season progresses, thus indicating the difficulty that the soil had in diffusing the summer heat load. The difference between the far-field soil temperature and the ambient air temperature is small, and our experience shows that the ambient air would have been the preferable heat sink for this season. The temperature difference between the brine and the far field soil during the winter, however, is almost constant and about half the magnitude as seen in the summer. The far field ground temperature is relatively much higher than the ambient air temperature during the winter, particularly at temperatures that would cause a high load. This further demonstrates the potential of the ground as a heat source for this season.

CONCLUSION

Based on data from one complete cooling season and heating season, the horizontal coil ground-coupled heat pump system investigated herein gives good heating performance and poor cooling performance. Table 4 shows a seasonal performance summary.

In addition to a high level of performance for the winter season, the heating operation required no electric backup heat, which has the potential of significantly reducing electric utility peak loads. The low value of cooling performance factor is due to both poor performance of the ground heat exchanger and a heat pump unit selected primarily for its high performance in only the heating mode. Improved cooling mode performance can be obtained by utilizing a more efficient heat pump and improving the performance of the ground heat exchanger through better backfilling procedure and increased coil surface area and increasing the moisture content of the soil adjacent to the coil.

The study demonstrates that very careful attention should be focused on the design of a ground-coupled heat pump system in order to achieve a high level of performance. Near term future work on this project will include replacing the existing ground coil with a larger coil using sand for backfill and the installation of a ground irrigation line. Additional work will be directed toward the optimization of the system. An optimum ground-coupled heat pump system may eventually prove to be equal to or better than a conventional air-to-air system.

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APPENDIX
Calibration of Moisture Sensors

The ceramic sensors were primarily intended for agricultural uses and the manufacturer provided no calibration data. Consequently, a calibration was done using actual soil samples from the site, which were completely dried and broken into a powdered texture.

Sample preparation consisted of adding a known amount of water to a known amount of soil on a mass basis and mixing the sample in order to make it as homogeneous as possible. The soil was then compressed around the sensor to approximate the actual soil density. After allowing the sensor to come to equilibrium with the surrounding soil, probe resistance was measured with an AC bridge circuit. Soil moisture content was obtained by taking a soil sample from around the sensor and weighing it before and after drying in an oven.

The effect of soil temperature on the calibration result was determined to be negligible for samples in the range of 40 F (4°C) to 100 F (38°C). However, when the soil composition was changed (by mixing in more sand), the effect on the calibration curve was significant, indicating that the probes must be calibrated in the soil where they are to be used.

Since the ceramic sensors are "equilibrium" type devices that depend on reaching a moisture content in equilibrium with the surrounding soil, some tests were undertaken to evaluate the response time of these devices. Three different tests were performed. When a dry sensor was sprinkled with a few drops of water, it showed a response time of a few minutes. Then a saturated sensor was subjected to dry air and a response time of a few hours was measured. Then, for a more realistic test, a saturated sensor was packed into soil having a moisture content of about 20%. The resulting response time was about three days.

TABLE 1
Estimated Ground Coupled Heat Pump Cost Breakdown

	1982 Dollars
Earth Coil	$ 585.00
Earth Coil Installation	350.00
Heat Pump	2,500.00
Heat-to-Air Coil	655.00
Air Handling Unit	200.00
Heat Pump & Water Coil Installation	1,000.00
TOTAL	$5,290.00

TABLE 2
Monthly Performance Data

Month	Power Consumption Btu x 10^{-6} (KWH)	Heat Flows - Btu x 10^{-6}		COP	PF_i	PF_0
		WTAC	GRND			
June	1.83 (538)	3.31 (968)	4.35 (1274)	1.8	1.4	1.7
July	5.13 (1502)	7.60 (2227)	10.98 (3218)	1.5	1.1	1.4
August	6.92 (2027)	9.22 (2701)	14.10 (4130)	1.3	1.0	1.2
September	2.27 (665)	3.04 (891)	4.69 (1373)	1.3	1.0	1.2
Cooling Season Total	16.15 (4732)	23.17 (6787)	34.13 (9995)	1.4	1.1	1.3
November	1.98 (581)	4.28 (1254)	3.54 (1038)	2.2	2.8	2.3
December	4.47 (1310)	9.38 (2747)	7.93 (2323)	2.1	2.8	2.3
January	4.60 (1346)	8.76 (2564)	7.02 (2055)	1.9	2.5	2.0
February	3.19 (935)	5.94 (1738)	4.89 (1432)	1.9	2.5	2.0
March	3.31 (970)	6.16 (1803)	4.57 (1338)	1.9	2.4	2.0
Heating Season Total	17.55 (5142)	34.52 (10107)	27.96 (8186)	2.0	2.6	2.1

WTAC: Water-to-Air Coil Heat Flow
GRND: Ground Coil Heat Flow

TABLE 3
Comparison of Thermal Conductivities, (W/m°C)

Date	Moisture Content	Thermal Conductivity		
		Measured	Lunardini	Sundberg
June 6	30%	1.05	1.2	1.1
July 18	25%	.58	.95	.80

TABLE 4
Overall System Performance

Season	Average COP	SPF_i	SPF_0
Heating	2.0	2.6	2.2
Cooling	1.4	1.1	1.3

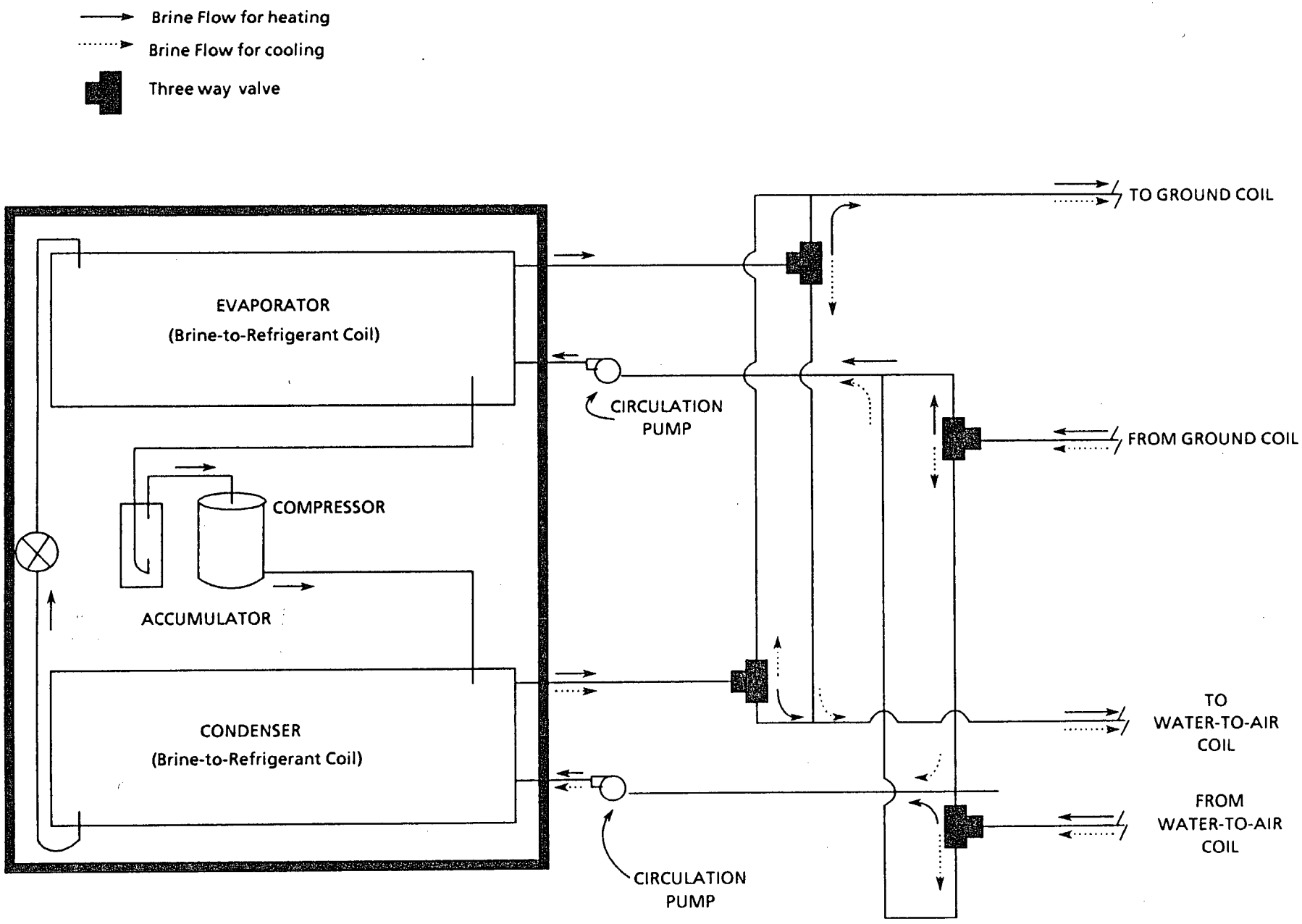

Figure 1. Schematic of ground-coupled heat pump system

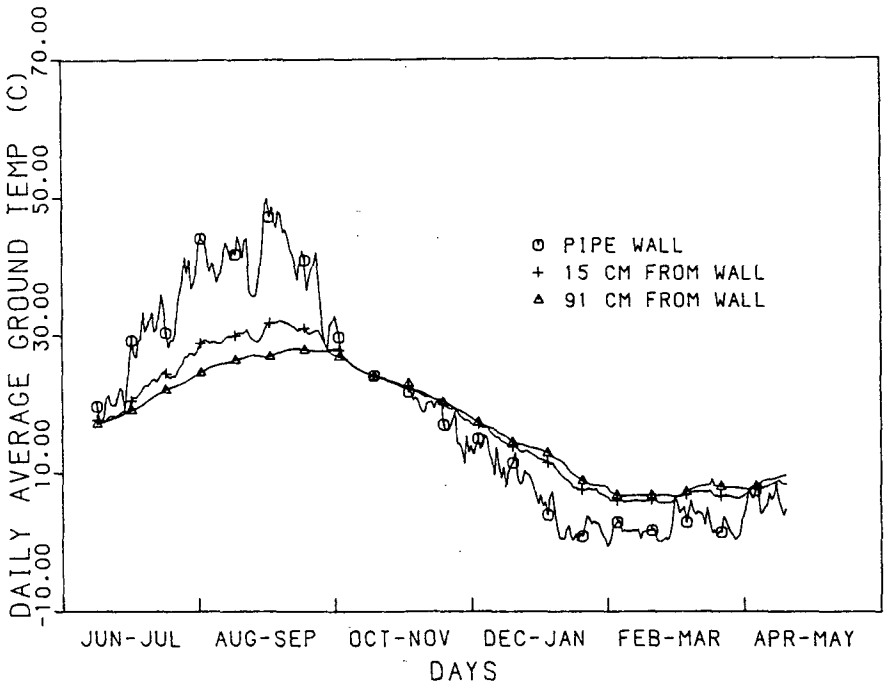

Figure 2. Daily ground temperatures near the coil

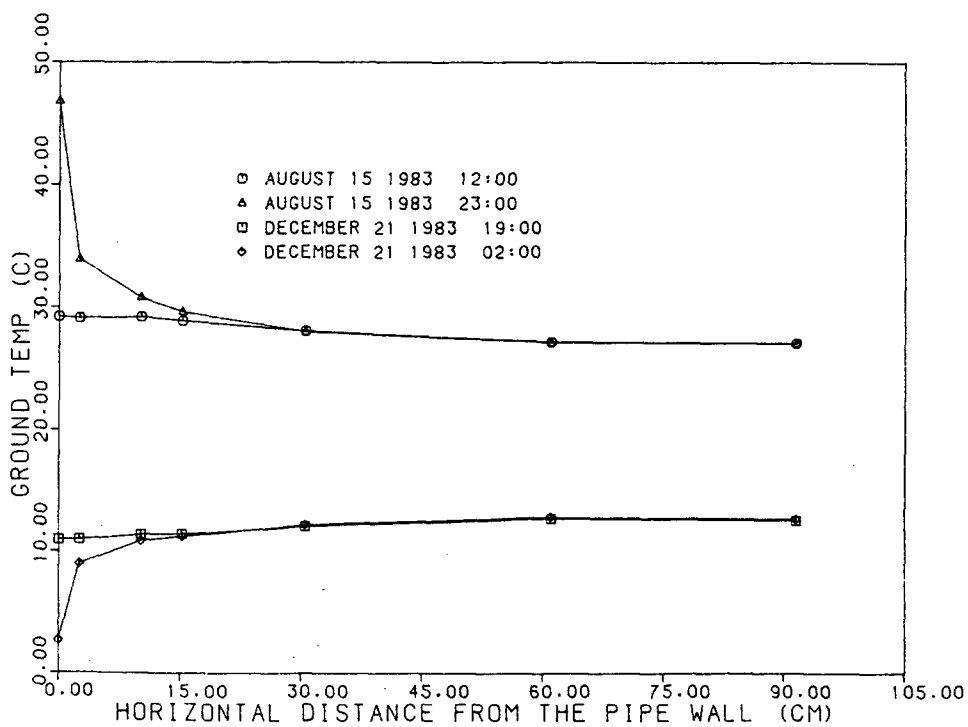

Figure 3. Typical temperature profiles near the ground coil

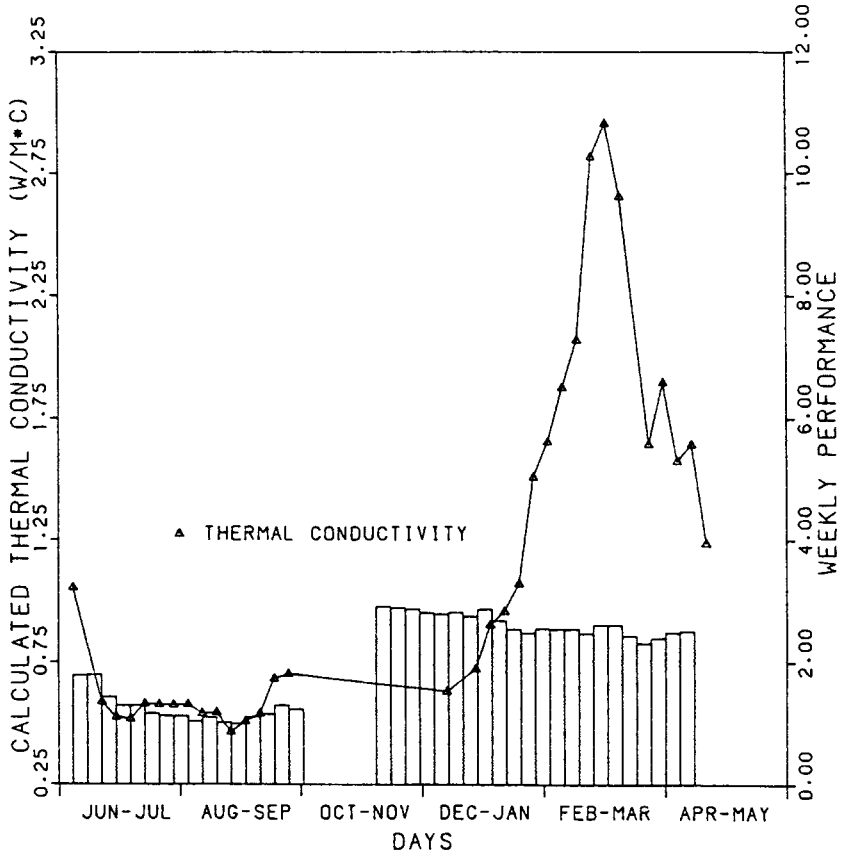

Figure 4. Soil thermal conductivity and system performance versus time

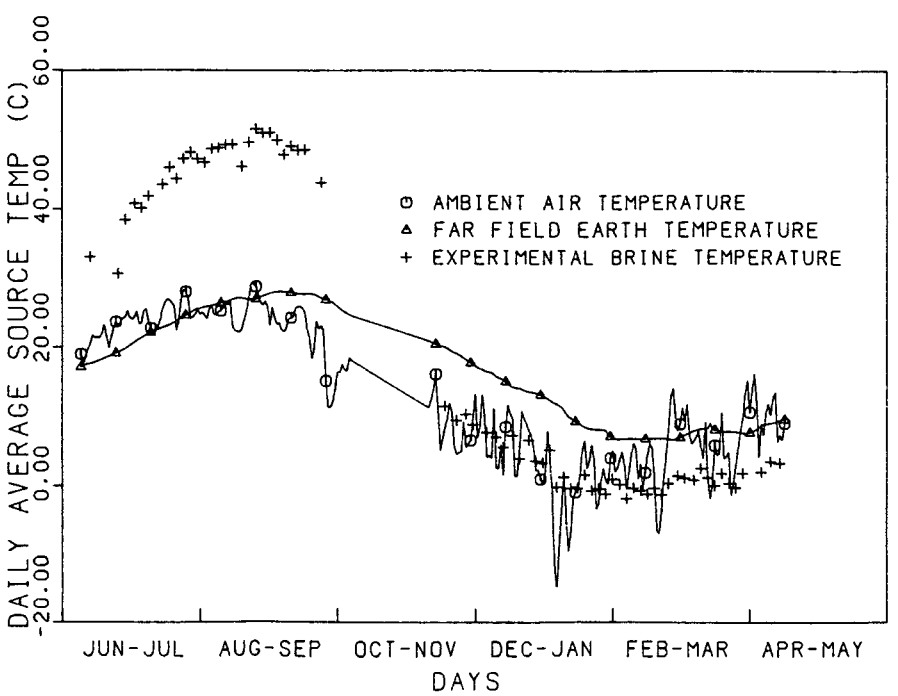

Figure 5. Comparison of the temperature of the ambient air, the far field ground, and the brine entering the heat pump