SEASONAL PERFORMANCE EVALUATION OF TWO HORIZONTAL-COIL GROUND-COUPLED HEAT PUMP SYSTEMS

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ABSTRACT

Performance of two different ground-coupled heat pump installations in occupied single family residences in a Tennessee experimental facility is reported for the 1984-85 heating season and the 1985 cooling season. Hourly measurements of various power consumptions, heat flows, and temperatures were made over the entire seasons in order to determine overall system performance.

The system in House I is a heating-only unit (field modified for cooling operation), which has been operating continuously since 1982. The second system is a water-air unit in House V of the facility. It was designed and installed by the private sector in November 1984 and has been tested over only one season.

The seasonal performance factors of the House I system were found to be 2.23 and 1.51 for heating and cooling, respectively. The corresponding seasonal performance values of the new GCHP system in House V were found to be 2.84 and 2.59.

System V performance is superior to system I primarily due to an increased length of ground coil and a heat pump unit having better cooling performance characteristics.

A comparison of the GCHP system in House V with previously tested air-air heat pump systems shows that a well-designed GCHP system (with the ground coil sized for summer design conditions) offers a significant performance improvement over even a high efficiency air-air unit.

INTRODUCTION

Since 1982, a ground-coupled heat pump (GCHP) system has been operated in a house at a university testing facility in Tennessee. This site consists of five experimental houses. Previous testing of this GCHP system (Johnson et al. 1985) has indicated superior performance in the heating mode and poor performance in the cooling mode compared to a standard air/air heat pump system. Because of a ground heat exchanger of inadequate capacity for cooling mode heat transfer and a heat pump unit with below average performance in the cooling mode, it was decided to install a new system based on more up-to-date technology and improved design criteria. This new system was designed and installed by a commercial GCHP contractor and is located in House V at the Facility. The original system is in House I.

The objective of this study was to evaluate the performance of the House V GCHP system throughout a complete heating and cooling season to determine its overall performance in the Knoxville, TN, area and to compare it both to the original House I GCHP system and to typical air/air heat pumps.

System Description - House I.

House I is an 1800 ft^2 (165 m^2) occupied single-family residence of frame construction with R-19 walls and R-22 ceiling insulation. The design heating and cooling loads of the house are 30,000 Btu/h (8.8 kW) and 22,000 Btu/h (6.4 kW) at 13 F(– 10°C) and 95 F (40°C), respectively. The House I system includes a water-source, heating-only heat pump rated at 36,000 Btu/h at 70 F inlet water temperature. Space cooling is provided by re-directing the fluid in the ground loop (hereafter called brine) with three-way valves. A brine flow rate of 9.5 gpm (2.2 m^3/h) was maintained in the ground loop. Prior to June 1984, the ground coil consisted of 675 ft (205 m) of $1\frac{1}{4}$ in (.03 m) polybutelene pipe laid in a horizontal, serpentined array, 4 ft (1.2 m) deep, so 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.

During April 1984, the original ground coil was excavated and a new one of identical length, depth, and layout was installed. This new coil is polyethylene pipe with about 3 in (.08 m) of sand backfill all around the pipe. The coil layout is given in Figure 1. Additional information regarding this system may be found in the contract reports of this study (Johnson et al. 1984, 1985).

System Description - House V

House V is a 1200 ft^2 (110 m^2) single-family residence with R-19 walls and R-38 roof insulation. Design loads are 24,000 Btu/h (7 kW) at 13 F(– 10°C) and 16,000 Btu/h (4.7 kW) at 95 F(40°C) for heating and cooling, respectively. The heat pump unit for this system is a water-to-air heat pump with a heating capacity of 30,000 Btu/h (8.8 kW) at 70 F (24°C) entering water temperature and a cooling capacity of 24,000 Btu/h (7 kW) at a water inlet temperature of 85 F (33°C). The ground coil is 1135 ft (345 m) of weldable polybutylene $1\frac{1}{2}$ in (.04 m) in diameter and buried between 4 and 6 ft (1.2 and 1.8 m) deep. Flow rate in the coil was measured to be 6.7 gpm (1.5 m^3/h). The layout of this coil is also shown on Figure 1.

Procedure and Instrumentation

Most data at the facility are automatically fed into a hybrid data acquisition system (DAS) (McGraw and Miller 1983). 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 meteorological 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 site. Usable hourly data were obtained for over 98% of the total possible hours of this study.

All values of electric power consumption and heat flow 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 flowmeter and two platinum resistance temperature devices (RTDs) form the basis for measurement of the ground-coil and water-to-air-coil heat flows. The temperature difference measured by the two RTDs is electronically converted to a frequency that is then electronically multiplied by the frequency output of the flowmeter. This product which is directly proportional to the heat flow, is sent to a summing circuit in the DAS. 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 gauge, where each tip of the bucket is counted and recorded by the 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. 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.

The ground coupled heat pump system operation is regulated by a single thermostat during both the heating and cooling seasons. The house thermostat was set to maintain 78 F (25°C) inside temperature throughout the summer and 68 F (20°C) during the winter. No night setback was utilized.

All instruments were calibrated prior to installation at the beginning of each heating and cooling season and on a monthly basis during the seasons.

DISCUSSION OF RESULTS

Heat pump systems are normally rated by a coefficient of performance (COP), defined as the rate of energy added to(removed from)the conditioned space at the heating/cooling coil divided by compressor power. A better method of rating the overall performance of a system is the performance factor (PF), 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. The Seasonal Performance Factor (SPF) is the evaluation of PF over an entire heating or cooling season.

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. Both ground-coupled heat pump systems are presently installed in this manner. Therefore all losses due to equipment inefficiencies result in heat addition to the conditioned space and are 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 purchased power.

PF_o is estimated by calculation 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. Cooling 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.

House I Heat Pump Performance Summary

The GCHP system located in House I has been operated for three consecutive heating and cooling seasons. Tables 1 and 2 present a summary of the seasonal performance factor (SPF) measured during these seasons.

Measured values of SPF for the 1982-83 and 1983-84 heating seasons were 2.60 and 2.59, respectively, although during the 1984-85 heating season it was found to be only 2.23. This decrease in performance is primarily attributed to the fact that the sand backfill did not fully rehydrate to a saturated moisture level as the soil had done in the weeks just prior to both the '82-'83 and '83-'84 heating seasons when indigenous clay was surrounding the pipe.

The SPF values for the 1983,1984, and 1985 cooling seasons were measured to be 1.11, 1.35, and 1.51, respectively. The increase in performance during the 1984 and 1985 cooling season (operation with sand backfill) may be partially due to the ground coil having a better soil to pipe contact. However, a significant part of the improvement in performance can be attributed to a decrease in system runtime as a result of reduced cooling degree-days. During the summer of 1983, 41% more cooling degree-days were incurred than in the 1984 cooling season and 75% more than during the 1985 cooling season.

Thus, it appears that while the sand backfill possibly helped to improve the cooling performance, it lowered the heating performance due to a reduction in soil thermal conductivity because of a reduced level of moisture in the vicinity of the ground coil.

House V Heat Pump Performance Summary

Seasonal performance factors for both heating and cooling operation of the House V system are shown in Table 3 along with degree days and average percent runtime.

This new system exhibited higher performance than the older system in House I. Although heating performance is only moderately improved, cooling performance shows a significant improvement due to a more efficient heat pump unit and a more effective ground coil.

GCHP SYSTEM EVALUATION

There are three primary factors that determine the effectiveness of the GCHP system relative to an air/air system. These are (1) difference between the ground temperature and the ambient air temperature, (2) proper design of the ground heat exchanger, and (3) the performance of the heat pump unit itself.

Ground Temperatures

In order to evaluate the potential of a GCHP at any location, it is instructive to examine the ground temperature relative to ambient air temperature. The potential advantage of the ground-coupled system is the fact that ground temperatures fluctuate less and are normally more favorable than air temperatures. Table 4 shows a comparison of various temperatures measured at the site. By comparing ground and air temperatures, the potential advantage of the ground-coupled systems over an air-air system can be seen. For example, there is a significant difference favorable to the GCHP between air and ground temperatures when the air is at its highest summer temperatures and its lowest winter temperatures, conditions requiring maximum energy use. These conditions show a much greater advantage than is shown by comparison of seasonal averages, particularly for the cooling season. It is noted, however, that at the summer average temperature, no cooling is required. A comparison of fluid temperature entering the heat pump (leaving the ground) to the far-field ground temperature gives a general indication of the effectiveness of the ground heat exchanger (these temperatures would be equal for a heat exchanger of infinite length). A comparison of fluid temperatures between System I and System V clearly shows the superiority of the heat exchanger in System V over that in System I.

Perfect Heat Exchanger Tests

In order to make a direct comparison between the heat pump units of both GCHP systems, a test was run using city water at a constant temperature of 68 F (20°C) in place of the ground loop to supply the unit. After steady state was attained, performance factors as listed in Table 5 were measured. These measured performance factors approximate the upper limit of performance for the system with a perfect heat exchanger and a far-field temperature of 68 F (20°C). This ground temperature is normally realized in the Knoxville area during the time period between heating and cooling seasons. These results show that the two units have nearly equal performance in the heating mode, while the House V system performs significantly better than the House I system in the cooling mode.

Ground Heat Exchanger

A comparison between the two ground heat exchangers can be made by an evaluation of the actual seasonal performance of each unit compared to the performance with an ideal heat exchanger as discussed in the previous section. A comparison of data from Tables 1, 2, 3, and 5 shows that in the heating mode, both GCHP systems produced an SPF_i of about 90% of their upper limit. This indicates that (with clay backfill) both ground heat exchangers are equally effective in the heating mode, although the coil for House I is only 340 ft (104 m) per ton of installed cooling capacity compared to House V, which has a coil length equal to 570 ft (175 m) per ton. These results support the conclusion of previous analytical studies, (Conlin et al. 1985) whose computer model predicted only a small effect of coil length on heating performance once a minimum length was exceeded.

The added coil length proved significant in the cooling mode; however, since the summer performance factor for the House V system was 93% of the ideal value shown in Table 5 compared to an average value of 65% for the House I system.

GROUND COIL DESIGN

The ground coil for House I was designed (Fisher 1981) using the GROCS Finite-Difference model (Andrews 1979). This appears to be an appropriate sizing method. However, the soil thermal conductivity used was that for undisturbed soil with no variation between summer and winter seasons. Consequently, the coil proved inadequate for cooling seasons when values of soil thermal conductivity of less than half the design value were experienced near the gound coil.

The ground coil for House V was designed by the contractor based on techniques developed by his own company. The original specification called for 850 ft (260 m) of coil length. However, after examining the soil at the site (no quantitative measurements were made) the contractor increased the coil length to 1135 ft (345 m).

A recent ASHRAE publication (Bose et al. 1985) presents comprehensive information regarding the design of ground coil systems. Use of the techniques reported there results in a coil length of between 425 and 475 feet per ton of installed cooling capacity, which should be adequate for conditions at the test site.

SOIL CONDITIONS

Soil moisture and its relationship to performance of the system in House I has been reported previously (Conlin et al. 1985). With indigeneous clay as the backfill material, moisture migration was found to be a signficant factor. The soil stayed near a saturated condition throughout the heating season and began to dry out at the beginning of the cooling season. System performance was shown to "track" soil moisture somewhat, since it remained high and almost constant during the winter months and showed a decrease early in the cooling season, which closely followed the decrease in soil moisture around the pipe. The performance decrease, however, was more than would be indicated by the decrease in degree of soil saturation as measured at a location of 1 in (.025 m) from the pipe, which was as close as a measurement could be made. Subsequent tests indicated that a large contact resistance existed between the pipe and soil, either from poor soil-pipe contact or from significant soil drying in the thin layer around the pipe. A limited amount of local excavation showed some voids next to the pipe that would become dry air pockets as the moisture moved away from the warm pipe, resulting in significantly reduced thermal conductivity.

Prior to the 1984 cooling season, a replacement coil of the same length was installed with about 3 in (.08 m) of sand around the pipe and the remaining backfill being soil from the trench. It was felt that the sand would minimize problems due both to the moisture migration and air pockets around the coil because of its larger granular structure and a tendency not to agglomerate. Such was the case during the summer of 1984, as the sand maintained a relatively constant moisture level of about 60% saturation over most of the season and the seasonal performance factor was 1.35 compared to 1.11 for the previous season. Following a moisture dip at the very end of the cooling season, the moisture level of the sand quickly returned to near 60% saturation. No further increase in moisture was obtained, however, and the moisture level remained near 60% saturation during the entire heating season, resulting in a lower seasonal performance factor (2.23) compared to 2.59 and 2.60 for the previous seasons.

During the 1985 cooling season, drying was much more pronounced than in 1984, with the sand surrounding the pipe becoming dry (less than 10% of saturation) during June and remaining at that level until late August when moisture was artificially induced through a soaker pipe buried in the trench with the coil. Figure 2 shows calculated soil thermal conductivity adjacent to the pipe and measured performance factor as a function of time before and after the moisture addition. Thermal conductivity calculations were made using line-source theory assuming quasi-steady state (Johnson et al. 1984). It is noted that within a period of two days following the moisture injection, the thermal conductivity near the pipe had returned to the value prior to the injection. Performance factor is seen to closely track soil thermal conductivity, as has been reported previously in this series (Conlin et al. 1985).

It should be noted that the region over which thermal conductivity was obtained was out to a distance of 1/2 in (.0125 m) from the tube wall. Moisture probes were located 1 in (.0254 m) from the tube due to the fact that their size was much greater than the temperature probes. Soil moisture at the locations of the moisture probes remained almost constant for several weeks following the injection.

The average PF for the remainder of the cooling season following water injection was only about 4% higher than for the previous period. Much of this increase may be due to milder weather since the effect of water injections was apparently so short lived.

Soil moisture at the midpoint of the House V coil, which is 6 ft (1.8 m) deep with indigeneous clay backfill, remained near 80% saturation throughout both the 1985 winter and summer seasons. A drop to 60% was observed in late September followed by an increase back to 80% early in November. System performance was virtually constant over the heating and the cooling season with little or no change from one week to the next.

COMPARISON TO AIR-AIR SYSTEMS

Performance of the GCHP compared to both a standard and a high performance air-air system is shown in Table 6. Both air-air systems were tested at the site and, consequently, seasonal performance factor was consistently determined in all cases. The tests were not carried out over the same season and were done in different houses, however, so that the comparison should be carefully interpreted. Also shown is a typical value of winter peak electric demand for the GCHP in House I compared to the standard air-air system. This comparison shows that the air-air system typically requires a 9 kW increased demand, much of which is due to backup strip heat. The GCHP system in House I was used as a basis of this comparison because Houses I and III (where the air-air heat pumps were tested) have virtually the same design loads. Johnson et al. (1986) give an economic comparison between the GCHP and an air-air system based on the installations.

CONCLUSIONS

Based on tests of the GCHP system in House V compared to previously completed tests of two air-air heat pump systems, it is evident that a well-designed ground-coupled heat pump system (with the ground coil sized for summer design conditions) offers a significant performance improvement over even a high efficiency air-air unit.

From hourly data obtained over the 1984-85 heating season and the 1985 cooling season, the performance of the GCHP systems in Houses I and V is reported. Both GCHP systems performed well enough to meet all the reqired loads without a need for auxiliary backup heat during the winter months.

Seasonal performance factors of the GCHP system in House I were found to be 2.23 and 1.51 for heating and cooling, respectively, while corresponding values for the GCHP system in House V were 2.84 and 2.59. There were three primary differences between the two GCHP systems that would account for the difference in performance:

1. A comparison of the heat pump units exclusive of the ground coil showed the unit in House V to have a 6% higher COP in the heating mode and a 35% higher COP in the cooling mode than the unit in House I. These tests were conducted under steady-state conditions with once-through city water replacing the ground coil circulation.

2. The ground coil in House V is larger with 570 feet (175 m) per ton of installed cooling capacity compared to 340 feet (104 m) per ton for the system in House I. During the heating season, however, both units produced seasonal performance factors of about 90% of the ideal values (Table 5 and using previous seasons for House I with clay backfill in the trench). For the cooling season, however, the House V system produced a seasonal performance factor of 93% of the ideal value, while the House I system over three seasons produced an average seasonal performance of about 65% of the ideal value.

3. The ground coil of the House I system is 4 ft (1.2 m) deep and backfilled with sand, while the House V system is buried between 4 ft and 6 ft (1.2 and 1.8 m) deep and is backfilled with clay. Although the cooling performance in House I has increased in 1984 and 1985 with sand backfill over the level in 1983 with clay backfill, it should also be noted that there is a significant decrease in degree-days corresponding to the performance increase. It is, therefore, not possible to quantify the role of the sand in improving summer performance based on only this one season of data. During the winter of 1984-85, however, it appears evident that the sand is responsible for the significant drop in performance due to its inability to rehydrate to a saturated condition during the winter months as does the clay.

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TABLE 1

Heating Seasonal Performance Factor - House I

Period	SPF_i	SPF_o	F Days	Percent of Average Heating Degree Days
1982-83 heating season	2.60	2.18	3290	97
1983-84 heating season	2.59	2.16	3680	115
1984-85 heating season*	2.23	1.87	2338	119

*Includes only the months of January, February, and March

TABLE 2

Cooling Seasonal Performance Factor - House I

Period	SPF_i	SPF_o	F Days	Percent of Average Cooling Degree Days
1982-83 cooling season	1.11	1.31	1339	107
1983-84 cooling season	1.35	1.71	947	82
1984-85 cooling season	1.51	1.84	765	61

TABLE 3

Seasonal Performance Factors - House V

Period	SPF_i	SPF_o	F Days
Winter 1984-85*	2.84	2.56	2338
Summer 1985	2.59	2.87	765

* Includes January-March only

TABLE 4
Temperature Comparison

	Cooling Season			Heating Season		
	High[1]	Low[2]	Average[3]	High[1]	Low[2]	Average[3]
Ambient air Temperature	93 F (34°C)	46 F (8°C)	73 F (23°C)	75 F (24°C)	−11 F (−24°C)	39 F (4°C)
Far-Field Ground Temperature	79 F (26°C)	66 F (19°C)	71 F (22°C)	63 F (17°C)	54 F (12°C)	57 F (14°C)
Fluid Temp. Entering Heat Pump - I	123 F (51°C)	96 F (36°C)	108 F (42°C)	46 F (8°C)	32 F (0°C)	36 F (2°C)
Fluid Temp. Entering Heat Pump - V	88 F (31°C)	68 F (20°C)	79 F (26°C)	61 F (16°C)	39 F (4°C)	55 F (13°C)

1. Average of the 20 highest hourly values
2. Average of the 20 lowest hourly values
3. Seasonal average

TABLE 5
Performance with an Ideal* Ground Coil

Mode of Operation	Performance Factors	
	TECH House I GCHP System	TECH House V GCHP System
Heating	2.93	3.11
Cooling	2.07	2.79

* Replaced ground coil with once-through city water at 68 F (20°C)

TABLE 6

System	Heating SPF	Cooling SPF	Peak Demand (KW)
GCHP V[1]	2.84	2.59	-----
GCHP I	-----	-----	3.0
STD A-A[2]	1.56	1.64	12.0
Hi-Perf A-A[3]	1.99	2.27	-----

1. Rating: heating COP = 3.7 at 70 F (21°C), SEER = 9.8
2. Rating: heating COP = 2.7 at 47 F (8°C), SEER = 8.1
3. Rating: heating COP = 3.0 at 47 F (8°C), SEER = 10.1

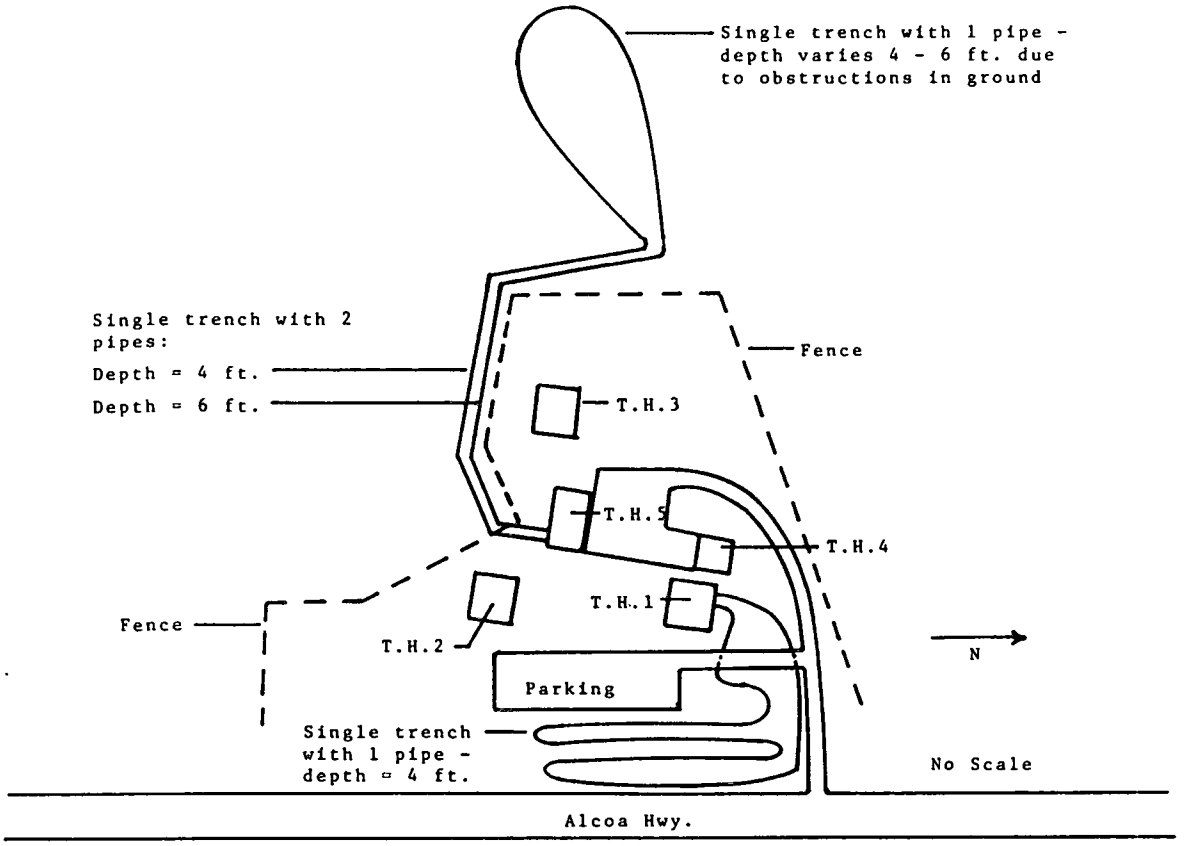

Figure 1. Layout of ground coils

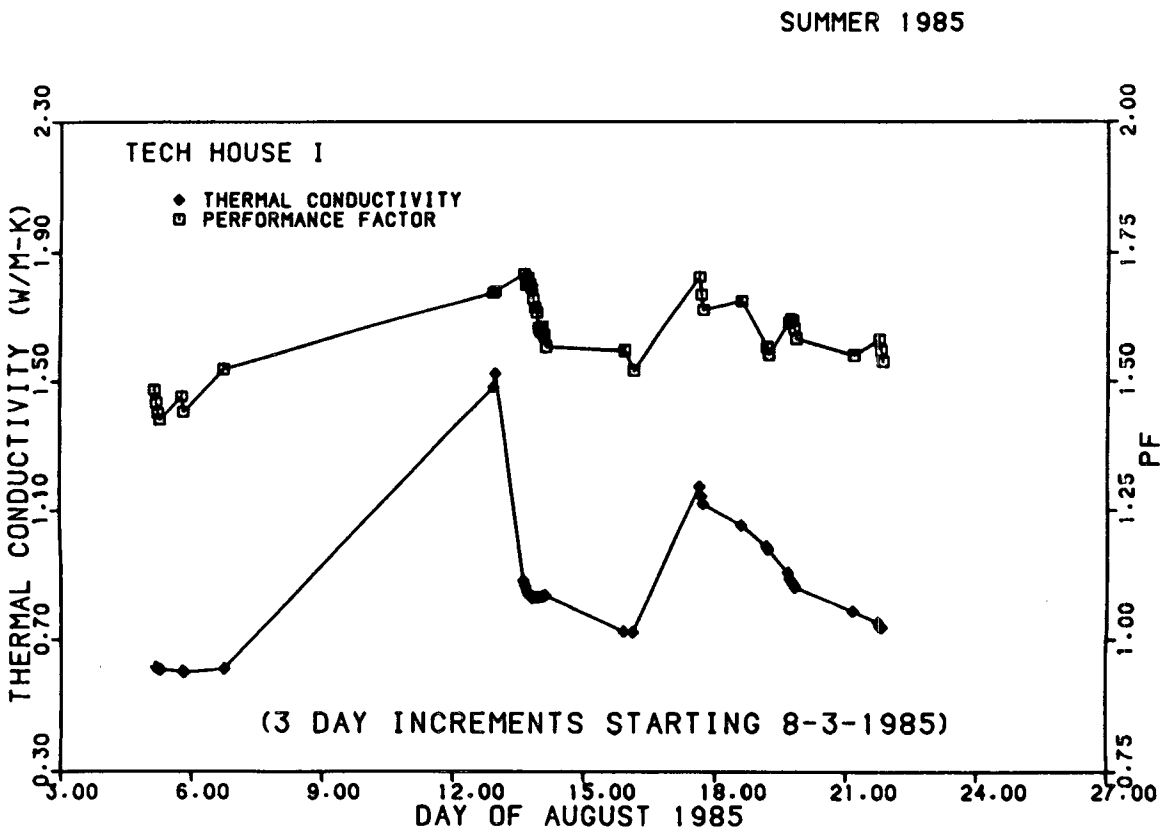

Figure 2. Soil thermal conductivity and performance factor resulting from artificial soil irrigation