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DESIGN, OPERATION AND PERFORMANCE OF A GROUND COUPLED HEAT PUMP SYSTEM IN A COLD CLIMATE*

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ABSTRACT

As part of the ground coupling research program at Brookhaven National Laboratory (BNL) a small, well insulated house on the BNL site has been equipped with a ground coupled heat pump space conditioning system. This paper describes the design and installation of the system and presents performance data for the first winter of operation, October 1980 to March 1981. The heating system heat requirement for the 3 bedroom 104 m^2 (1120 ft^2) house was measured to be about 9.5 X 10^6 J/C-day (5000 Btu/F-day) by using resistance heating of the house between February and May 1980. This leads to a design heat rate of about 3.4 kW (11.5 X 10^3 Btu/hr) at the local design temperature of -12 C (10 F). Based upon the underground heat flow computer program GROCS developed at BNL, an antifreeze filled serpentine earth coil was designed to just meet the building's design heating needs with an average brine temperature never less than 7 C (20 F). The 155 m (507 ft) long, 1.2 m (4 ft) deep serpentine earth coil made from nominal size 1-1/2 in. (actual O.D. 4.633 cm) medium density polyethylene pipe was installed by a local plumbing contractor using two different chain driven trenchers. A commercially available water-to-air heat pump was used with minor modifications. System performance has been monitored using killowatt-hour meters, a "Btu-meter" and a datalogger-microcomputer data acquisition system. The house temperature has been kept between 21 and 23 C (70 and 74 F) all winter despite outdoor temperature as low as -24 C (-11 F). During the period November 20, 1980 to March 2, 1981 while the outdoor temperature averaged -2 C (28 F), the system extracted approximately 10.2 X 10^9 J (9.7 X 10^6 Btu) from the ground with an almost constant heat pump COP (coefficient of performance) averaging about 2.3 and a system COP of 2.2. No resistance heating was used. Ways in which the system could be improved and this efficiency significantly increased are discussed.

INTRODUCTION

The Ground Coupling Research Program at BNL has investigated the use of the earth as a heat source/sink or storage element for solar and nonsolar heat pump space conditioning systems. Eleven ground coupling device experiments have been operated including:

1. four buried tanks with volumes of 8.3 m^3 (2200 gal) or 13.6 m^3 (3600 gal)
2. six earth coils all made from nominal size 1-1/2 in. medium density polyethylene pipe in various configurations and in lengths of from 18 m (60 ft) to 274 m (900 ft), and
3. a group of six sealed vertical wells each 18 m (60 ft) deep.

In addition, soil thermal property experiments have been conducted. Experimental results have been used to validate a computer program called GROCS (GRound Coupled Systems) developed at BNL to model the behavior of ground coupling devices. Some of this work has been described in other reports(1,2,3,4)

All eleven ground coupling devices usually have been operated with weekly heat inputs based on computer simulations of ground coupled solar or nonsolar heat pump systems. This strategy facilitated modeling the sensitivity of device performance to soil properties, device design and operating scenario. However, little was learned about the cycling performance or practical problems associated with an actual ground coupled heat pump installation. In order to obtain this information, beginning in February 1980, an earth coil based ground coupled heat pump system was designed, for a small house on the BNL site. The system was installed in September 1980, and has been operated and monitored since then. The goals of this project are to:

1. Experimentally test the validity of GROCS model-based earth coil design methods.
2. Determine the cost and feasibility of a residential ground coupled heat pump space conditioning system requiring no resistance heating in the local climate (3400 heating C-day [6200 F-day]).
3. Identify and solve any design, construction or operational problems which might arise.
4. Measure earth coil and system performance under realistic conditions.
5. Identify ways to improve system performance and better optimize the system.

EARTH COIL DESIGN

Building Heating Load Determination

The building retrofitted is a 12 m (40 ft) by 9 m (28 ft) single story 3 bedroom house located in the housing area of the BNL site. The house was built using "energy saving construction methods" including walls containing 2 in. X 6 in. studs on 24 in. centers with 6 in. fiberglass batts, a floor with 6 in. of fiberglass insulation over an unheated crawl space, and built up roof trusses permitting an uninterrupted 12 in. layer of fiberglass in the attic.

The house originally was heated by an air-to-air heat pump with resistance back up. The compressor and outdoor heat exchanger are located behind the house while the indoor heat exchanger and resistance elements are located in an air handler in a large centrally located closet. Heat was distributed by the air handler through a large central plenum above a lowered ceiling in the central hall of the house to a vent in each room. Hot water is provided by a small 2-element electric hot water heater located next to the air handler.

The heating load of the house was determined by first disabling the air-to-air heat pump so that only resistance heating could be used. Then, the resistances of the air and domestic hot water heating elements as well as the power consumption of the air handler fan were measured. Running time meters were

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installed on all three resistors. Between February 27 and May 15, 1980 all the time meters, the house watt-hour meter, and the indoor temperature as measured by a glass thermometer above the main thermostat in the central hall were monitored daily. Outdoor temperature and degree-day data were obtained from the BNL Meteorology Department.

Two independent methods were used to analyze the building energy consumption data in order to determine the required heating system capacity. First, the mean value of the daily total energy consumption of the air handler (fan plus resistors) per degree-day, B_1, was computed:

$$B_1 = \frac{1}{N} \sum_{i=1}^{N} \frac{E_{AH}(i)}{[T_o - T_A(i)]} \qquad (1)$$

where $E_{AH}(i)$ is the total electrical energy consumed by the air handler fan and resistors on the ith day, T_o = 18 C (65 F) is the conventional base for measuring heating degree-days, $T_A(i)$ is the mean ambient temperature on the ith day from the BNL Meteorology Department, and N is the number of days of data used. $E_{AH}(i)$ is given by:

$$E_{AH}(i) = P_{AH}\, t_{on}(i) \qquad (2)$$

where P_{AH} is the measured total power requirement of the air handler and $t_{on}(i)$ is the on-time during the ith day from the running time meter.

The second method performs a least squares fit of the house daily total energy consumption $E_T(i)$ as measured by the main watt-hour meter to a first order polynomial in degree-days, i.e., the quantity:

$$S \equiv \sum_{i=1}^{N} [E_T(i) - E_{FIT}(i)]^2 \qquad (3)$$

is minimized, where

$$E_{FIT}(i) \equiv A + B_2\,(T_o - T_A(i)) \qquad (4)$$

by adjusting the constants A and B_2. Thus, A is the best fit value of the daily base electrical consumption, assumed constant and independent of outdoor temperature, and B_2 is the best fit additional daily electrical consumption per degree-day.

B_1 and B_2 are two independent estimates of the heating system energy requirement per degree-day, each arrived at by using a different set of experimental measurements (air handler time meter for B_1, and house watt-hour meter for B_2). Each method yields a value for the heating system energy requirement of approximately 7.8 X 10^6 J/C-day (4.1 X 10^3 Btu/F-day) with a standard error less than 5% in each case, based on the data cited above.

Earth Coil Length

The serpentine earth coil design selected was a planar field of nominal size 1-1/2 i.. medium density polyethylene pipe buried 1.2 m (4.0 ft) deep on 1 m (3 ft) centers using an antifreeze heat transfer fluid. This design was selected because excavation costs escalate rapidly with depth while earlier experiments indicated little thermal advantage for deeper horizontal fields locally. Additionally, the depth selected is easily reachable with a chain driven trencher and shallow enough to prevent trenches in the low-cohesion sandy soil present from collapsing. Earlier experiments indicated that the use of antifreeze was both feasible and necessary at a 1.2 m (4.0 ft) depth for a reasonably sized earth coil in this location.

The design procedure for the length of the earth coil was as follows:

1. Determine heating load of building. In order to leave a small margin for error, the heating system design energy requirement was taken as 9.5 X 10^6 J/C-day (5.0 X 10^3 Btu/F-day). At the local (ASHRAE 97.5%) design temperature of -12 C (10 F) (5), this yields a heating design energy requirement of about 3.4 kW (11.5 X 10^3 Btu/hr).

2. Determine GROCS weekly heat inputs. The version of the computer program GROCS used is called GROC5 and requires weekly heat inputs to compute ground coupling device temperatures based on finite element finite difference heat flow equations. Moisture movement and freezing are not considered explicitly. The program is available publicly and is described in detail in (4). The weekly heat inputs were determined as follows:

a. Heating Season

1. Assuming a heating COP_H = 3.0. This is a conservative assumption and maximizes the heat "extracted" from the ground in GROC5.

2. Determine local heating degree days per week, $C_H(i)$. These were prorated from the BNL mean monthly heating degree days (6) ignoring those in June, July, August and September to give about 3300 C-days (5900 F-days).

3. Then the GROC5 heating season weekly heat input $Q_H(i)$ is:

$$Q_H(i) = -BC_H(i)\left[1 - \frac{1}{COP_H}\right] \qquad (5)$$

where B is the assumed heating or cooling requirement per degree day except during week 9 (when the coldest ground temperatures occur) when the system is assumed to operate at design conditions all week:

$$Q_H(\text{week } 9) = -B[T_o - (-12\text{ C})]\frac{\text{day}}{\text{day}} \cdot \frac{7\text{ day}}{\text{week}} \cdot \left[1 - \frac{1}{COP_H}\right] \qquad (6)$$

b. Cooling Season

1. Determine the number of cooling degree days by week, $C_C(i)$. Keeping those in June, July, August and September, a value of 282 C-days (508 F-days) per year was used and prorated by week as per the monthly distribution of cooling degree days in (6).

2. The GROC5 cooling season weekly heat input $Q_C(i)$ is:

$$Q_C(i) = B \cdot C_C(i) \cdot 1.5 \cdot 1.4 \qquad (7)$$

where the factor 1.5 is a conservative solar cooling load correction and the factor 1.4 roughly accounts for rejected compressor heat, except for week 34 (when the warmest ground temperatures occur when design conditions are imposed:

$$Q_C(\text{week } 34) = B \cdot (32\text{ C} - 21\text{ C})\frac{\text{day}}{\text{day}} \cdot \frac{7\text{ day}}{\text{week}} \cdot 1.5 \cdot 1.4 \qquad (8)$$

3. Run GROC5 to determine earth coil temperature extremes. GROC5 runs were made for 75% and 150% of the building load, i.e. for B = 0.75 X 9.5 X 10^6 J/C-day and for B = 1.5 X 9.5 X 10^6 J/C-day for soil thermal conductivities of 1.7 W/mC (1.0 Btu/ft-hr-F) and 2.8 W/mC (1.6 Btu/ft-hr-F). Based on the resultant GROC5 earth temperatures, a hand calculation described in (2) was used to compute mean fluid temperatures under design operating conditions assuming a fixed earth

coil length of 147 m (481 ft). (It is easier to vary the load than the earth coil size in GROC5). The resultant temperature extremes are shown in Table 1.

Table 1
GROC5 Plus Hand Calculation 147 m Earth Coil Temperature Extremes

Fraction of Heating Load (9.5×10^6 J/C-day)	Thermal Conductivity (W/mC) 1.7	2.8	1.7	2.8
	Winter Minimum Temp. (°C)		Summer Maximum Temp. (°C)	
0.75	-2.8	-1.7	27.8	26.7
1.50	-8.9	-5.6	33.3	30.6

4. Choose earth coil length based on acceptable temperature extremes. An allowable winter temperature minimum of -6.7 C (20 F) was deemed adequate for heat pump operation at reasonable COP based on previous experience. A summer maximum temperature of 40.6 C (105 F) was selected to minimize pipe damage at elevated temperatures. (Note that this type of pipe currently is not rated for use above room temperature.) From Table 1, it is clear that the summer maximum temperature presents no problem even for 150% of the building load required. Using the lower thermal conductivity, the 147 m earth coil is more than adequate for 75% of the actual winter load, but inadequate for 150% of the load (minimum temperature -8.9 C is less than the allowed -6.7 C). Thus the earth coil length selected is approximately correct for the actual load, and the earth coil actually installed was 155 m (507 ft) long.

SYSTEM INSTALLATION

Earth Coil

Using pipe provided by BNL, the 155 m (507 ft) earth coil was installed in September 1980 by a local plumbing contractor for $500, or about $3/m ($1/ft) including trenching to 1.2 m (4 ft), pipe installation and backfilling. The installed earth coil layout, shown in Figure 1, contains straight runs of pipe each

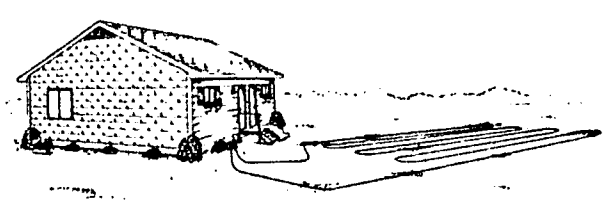

Figure 1. Installed Earth Coil Layout

about 16 m (51 ft) long on 2 m (6 ft) centers. The original plan called for crossing trenches to obtain 1 m (3 ft) centers while retaining 2 m (6 ft) diameter 180° pipe bends as in (1). This was not possible in practice because the trench walls collapsed when they were crossed and because the spoils deposited on the ground from one trench prevented the trancher from making the next trench as close as was desired.

The contractor was requested to use a Ditch Witch Model 1500 trencher or equivalent, a 12 hp small non-riding machine less than 91 cm (36 in.) wide, because this type of machine is small enough to fit through standard yard gates and maneuver in a developed lot. The contractor began the job with a 17 year old Ditch Witch Model M-4-22, the predecessor of the 1500. He trenched about 61 m (200 ft) in 8 hours with difficulty as fist-sized rocks jammed the chain. It was not possible to make curved trenches, but the contractor was able to dig the end trenches for pipe bends with a single right-angle cross cut and some hand-cleaning of the trench.

On the second day the contractor was permitted to finish the job using a much larger riding trencher with backhoe and blade attachments, the 40 hp Ditch Witch Model R40. This machine was able to trench roughly 60 m (200 ft) per hour and easily removed large chunks of concrete footings from the ground. The backhoe was useful for digging the end trenches.

The pipe which was purchased in 76 m (250 ft) coils was unrolled, warmed in the sun, and installed without incident with only one buried joint using a nylon male fitting and four stainless steel hose clamps. Temperature sensors were placed on the outside of the pipe under heavy insulation at distances of 45 m (149 ft), 79 m (260 ft), and 108 m (355 ft). Backfilling was done using the blade on the R40 and by hand.

Indoor Hardware

The indoor system hardware, shown in Figure 2,

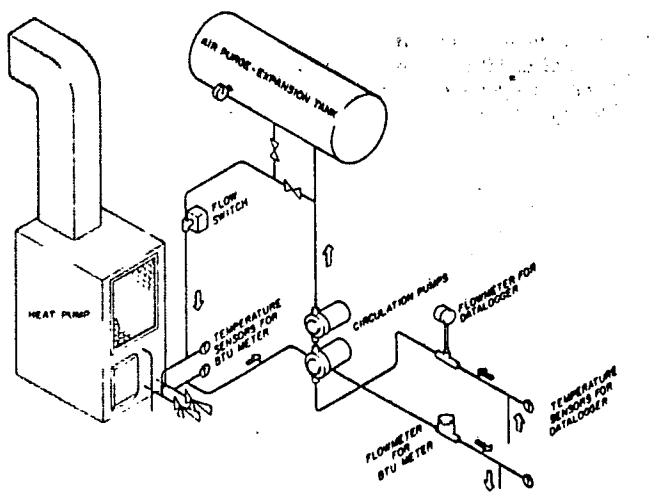

Figure 2. Indoor Hardware Layout

consists of a Command-Aire SWP 301 nominal 3 ton water-to-air heat pump, two Grundfos UP 26-64 F circulation pumps, a 0.2 m^3 (40 gal) expansion tank, and various temperature and flow sensors (which are discussed below). The heat pump selected was used because previous

operation had demonstrated adequate capacity of about 4 to 6 kW (15 to 20 X 10^3 Btu/hr) absorbed from the ground with fluid temperatures averaging as low as -7 C (20 F) without apparent damage. In order to operate the heat pump with fluid temperatures this low the following measures were taken:

1. The factory-installed freeze protection device, set at about 7 C (45 F), was disabled.
2. A fluid flow switch which shuts off the heat pump if the flow rate drops below 0.2 L/s (3 gal/min) was installed. The heat pump must be restarted manually if this switch is tripped.
3. An antifreeze solution of water and 32% ethylene glycol by volume was used. A solution containing 25% ethylene glycol has a freezing point of about -12 C (10 F) and is considered adequate. Note that the heat pump used was designed for operation with entering water temperatures of 16 to 27 C (60 to 80 F) and was not optimized for the present use.

One bedroom in the house was dedicated for the indoor heating system hardware and data acquisition equipment. A short sheet metal duct was fabricated and tapped into the existing central air distribution plenum to deliver conditioned air from the heat pump to the rest of the house. The air inlet of the unused air handler was sealed to insure adequate air flow to all the rooms.

Data Acquisition System

Electrical consumption is measured by three ordinary dial-type kilowatt-hour meters, one each for the heat pump (blower plus compressor), the circulation pumps, and the entire house. Readings are recorded daily by hand. Four running time meters are also monitored daily. These record on time for the heat pump compressor, the unused air handler, and for each of the two domestic hot water resistance elements. Two glass thermometers, one located above the heat pump thermostat in the central hall and the other outdoors under the north eave of the house are also monitored daily. Ambient temperature data, including mean daily temperatures and degree-days are provided by the BNL Meteorology Department.

Two independent data acquisition systems are used to monitor earth coil performance. A Rho Sigma RS805 Btu meter, using a 3/4 in. turbine-type fluid flow meter and special accuracy thermistors, was installed on November 20, 1980. The meter has two digital counters, one for gallons and one for Btu's. As shown in Figure 2, the Btu meter sensors are located so that the meter registers flow through the earth coil and heat absorbed by the heat pump (including heat from the circulation pumps). Both counters are monitored daily. It should be noted that this meter is not recommended for use below 0 C (32 F) by the manufacturer because its temperature sensor linearization has not been extended below about -4 C (25 F). Nevertheless, agreement with the more elaborate system described below was excellent for flow and reasonable for energy. The primary data acquisition system, completed on December 30, 1980, contains a Fluke 2240C datalogger interfaced with a Northstar Horizon microcomputer. Fluid flow is measured with a Ramapo 1-1/4 in. target-type flow meter. Temperatures are measured using special accuracy (± 0.4 C) copper-constantan thermocouple wire and matched BNL-made thermocouple junctions. Temperature sensors are located in wells at the inlet and outlet of the earth coil and on the outside of the buried pipe under heavy insulation at 45 m (149 ft), 79 m (260 ft), and 108 m (355 ft). Three sensors measure indoor temperatures at different locations, and one is located outside under the eave on the north side of the house.

OPERATION

Heating System

In operation, when the thermostat calls for heat a relay turns on the circulation pumps immediately, and then 10 seconds later the heat pump compressor and blower. The 10 second delay permits a smooth fluid flow to be established before the heat pump is turned on which is essential because of the "lock out" flow switch. When the thermostat is satisfied, the relay shuts off all equipment immediately.

The only operational problem encountered during the 1980-81 winter was a fluid flow slightly below the common design practice for the heat pump used, 0.47 L/s (7.5 gal/min). Instead, the fluid flow was about 0.43 L/s (6.7 gal/min), despite the use of two pumps. This occurred because of flow impedances from the heat pump heat exchanger [4.3 X 10^4 N/m^2 (6.2 psi) at a flow of 0.47 L/s (7.5 gal/min)] and the two flow meters, particularly the target-type meter. Additionally, a loose electrical connection caused intermittant operation with only one pump at a flow rate of approximately 0.29 L/s (4.6 gal/min) during part of the winter.

Data Acquisition System

The Btu meter runs continuously without attention. The datalogger is programmed to scan the 5 earth coil, 3 house and 1 ambient temperature sensors, and the Ramapo flow meter output every 30 seconds. The computer monitors the flow meter output channel and does nothing if the flow meter output is below a threshold value, indicating no flow or system operation. When the heating system is turned on and the flow meter output exceeds the threshold, the computer accepts and analyzes the data from the datalogger. It computes fluid flow rate and, using a trapezoidal integration routine, the amount of heat added to the earth coil during the preceding 30 second time interval, as well as the earth coil instantaneous U-value:

$$U = \frac{\dot{Q}}{L(T_{FF} - \overline{T}_c)} \qquad (9)$$

where $\dot{Q}$ is the rate of heat extraction from the earth coil, L is its length, T_{FF} is the far-field ground temperature at the earth coil depth, and $\overline{T}_c$ is the average of the earth coil inlet and outlet temperatures. All raw data plus this computed information is printed every 30 seconds. When the heating system shuts off and the flow meter outputs drops, the computer stops until the next cycle begins.

PERFORMANCE

Tables 2 through 5 contain the monthly system performance data for the period November 20, 1980 to March 2, 1981. Table 2 shows that the monthly mean far-field ground temperature at the 1.2 m (4 ft) earth coil depth was higher than the monthly mean ambient daily maximum temperature during all months shown except February, higher than the daily mean temperature in all months, and averaged about 12 C (22 F) above the mean daily minimum temperature. The temperature of the earth coil often was below freezing, confirming the need for antifreeze. The fluid temperature entering the heat pump was about 3 to 5 C (5 to 9 F) below the far-field temperature throughout the winter. The minimum average earth coil temperature observed was about -4 C (24 F). The temperature in the central hall of the house was kept between 21 and 23 C (70 and 74 F) except during a 3 day system failure caused by an electrical outage.

Table 2
Winter 1980 to 1981 Monthly Heating System Performance

Period	Monthly Ambient Temperatures (°C) Min.	Mean	Max.	Mean Ground Far-Field Temperature at 1.2 m Depth (°C)	Earth Coil Mean Fluid Temp.'s (°C) Leaving Ground	Entering Ground	House Central Hall Temperature Range (°C)
November 20 - 30, 1980	-1	+4	+9	+9	+5	+1	21 - 22
December, 1980	-7	-2	+4	+7	+2	-1	21 - 23
January, 1981	-12	-7	-2	+3	-2	-5	22 - 23*
February, 1981	-5	+1	+6	+3	0	-3	21 - 23

* Except for 3 day system failure due to electrical outage.

Table 3
Winter 1980 to 1981 Monthly Heating System Performance (cont.)

Period	Heat Removed From Ground (10^6 J) "Btu Meter"	Datalogger-Computer	Electrical Energy (kWh) Heat Pump	Circulation Pumps	System On Time (Hours)	System Fractional On Time (%)	Mean Fluid Flow Rate (10^{-2} L/s)
November 20 - 30, 1980	776	-	149	10	36.9	14	43.9
December, 1980	3126	-	735	54	201.8	27	42.5
January, 1981	3217	3795	877	51	261.3	34	36.3
February, 1981	1785	1935	482	37	147.1	22	40.8
Season November 20, 1980-March 2, 1981	8904	5730†	2243	152			

(Note: 1 kWh = 3.6 X 10^6 J)
† January-February only

(Note: 1 gal/min = 6.309 X 10^{-2} L/s)

Table 4
Winter 1980 to 1981 Monthly Heating System Performance (cont.)

Period	Mean Rate of Heat Extraction From Ground (kW) Btu Meter	Datalogger-Computer	Mean Power (kW) Heat Pump	Circulation Pumps
November 20 - 30, 1980	5.8	-	4.0	0.3
December, 1980	4.3	-	3.6	0.3
January, 1981	3.4	4.1	3.4	0.2
February, 1981	3.4	3.7	3.3	0.3

Table 5
Winter 1980 to 1981 Monthly Heating System Performance (cont.)

Period	Heat Pump COP Btu Meter	Datalogger-Computer	System COP Btu Meter	Datalogger-Computer	Monthly U-Value (W/mC) Btu Meter	Datalogger-Computer
November 20 - 30, 1980	2.5	-	2.4	-	5.9	-
December, 1980	2.3	-	2.1	-	4.8	-
January, 1981	2.1	2.3	2.0	2.2	3.8	4.3
February, 1981	2.1	2.2	2.0	2.1	5.6	5.8
Season November 20, 1980-March 2, 1981	2.2	2.2†	2.0	2.1†		

† January-February only

(Note: 1 Btu/ft-hr-F = 1.731 W/mC)

Table 3 shows the monthly earth coil heat extraction totals as computed by the Btu meter and by the datalogger-computer system (for January and February). The two systems agree reasonably well with the datalogger computer system reading higher, especially in January when earth coil temperatures were lowest.

Table 3 indicates that the highest monthly system fractional on time was 34% in January. The mean fluid flow rate data (taken from the Btu meter) shows the loss of flow which mainly occurred in January when the flow averaged 36.3 X 10^{-2} L/s (5.76 gal/min). The lowest monthly mean rate of heat extraction from the ground, according to the datalogger-microcomputer system, was about 3.7 kW (12.6 X 10^3 Btu/hr) in February. The heat pump power was highest early in the winter when the heat extraction rate was highest. The circulation pump power was flat except for a drop in January, demonstrating that the low flow then was correlated to low power, i.e. to a bad electrical connection.

The heat pump heating coefficient of performance, COP_H is given by:

$$COP_H = \frac{E_G + E_{HP} + E_P}{E_{HP}} \quad (9)$$

while the system heating coefficient of performance, COP_s is:

$$COP_s = \frac{E_G + E_{HP} + E_P}{E_{HP} + E_P} \quad (10)$$

where E_G is the energy removed from the earth coil, E_{HP} is the heat pump electrical energy consumed, and E_P is the circulation pump electrical energy consumed, with all terms in consistent units. Using the datalogger-computer system value for earth coil heat

extraction, COP_{HP} was about 2.2 for January and February combined. In view of the higher COP's observed early in the season, it is likely that the seasonal COP_{HP} was somewhat higher, perhaps 2.3 or so. Likewise, the seasonal system COP_S was about 2.2 or greater. All COP's were quite constant and very weakly related to ambient temperature. In fact, COP's were slightly higher in January than in February which was much warmer, probably because of less cycling in January.

The monthly U-values are given by (9) using the appropriate monthly average heat extraction rates, and mean far-field and earth coil temperatures. The lowest monthly mean U-value occurred in January and, using the earth coil heat extraction rate from the datalogger-computer system, was about 4.3 W/mC (2.5 Btu/ft-hr-F). The lowest instantaneous U-value observed (not shown in the table) was about 2.9 W/mC (1.7 Btu/ft-hr-F) in January. During the coldest part of January, a U-value of 3.1 W/mC (1.8 Btu-ft-hr-F) was common. In February, the U-value was frequently above 9 W/mC (5 Btu/ft-hr-F).

DISCUSSION AND CONCLUSION

The minimum mean earth coil temperature actually observed, -4 C (24 F), is slightly higher than the design minimum temperature, -7 C (20 F). Thus, the GROCS model-based earth coil design method described above has validity. The winter of 1980-81 was significantly colder than normal, but the coldest month was January while the design method conservatively assumes that the end of February is the coldest time. A slightly shorter earth coil might have been adequate.

The ground coupled heat pump system used no resistance heating during the winter of 1980-81 despite unusually cold temperatures. As can be seen from the ambient temperature data in Table 2, an air-source heat pump designed with a balance point of 0 C (32 F) would have used resistance heating most of December, virtually all of January, and much of February. The cost of the earth coil in September 1980 was about $5.00/m ($1.50/ft) installed including pipe. The indoor hardware is simple and not unusual, and should have a reasonable cost.

No insurmountable design problems were encountered. The eath coil was installed on 2 m (6 ft) centers rather than 1 m (3 ft) centers as desired because of design features of the trenchers used. Also, the smaller trencher was very slow. The ideal machine for this application would be small (< 0.91 m [36 in.] wide), powerful, contain a pipe reel and feeder to install the pipe as the trench was dug, and redeposit the soil after installing the pipe. It would be possible to cross trenches with such a machine by raising the chain a bit. Packaged heat pump (-circulation pump) units with all appropriate controls already installed would greatly reduce on site installation costs. A simpler, less expensive air purge-fluid expansion device than the 0.2 m^3 (40 gal) tank described above would be desirable. The system controls used in the test system described above appear to be adequate.

The earth coil and system performances have been measured under realistic conditions as described in detail above. A system seasonal COP of about 2.2 was obtained although no part of the system was optimized except for the earth coil. In order to improve system efficiency significantly the heat pump must be sized accurately and designed to operate optimally with source temperatures in the range of -7 to 4 C (20 to 40 F). The heat pump in the system described here never operated more than 60% of the time on even the coldest day, and thus could have been reduced in size considerably. Oversizing reduces efficiency by causing cycling and by unnecessarily reducing the earth coil temperature when the system is on while undersizing necessitates back-up heating. Thus, accurate sizing is essential. However, liquid-source heat pumps currently are rated at temperatures far above the range of interest, so that sizing for a ground coupled system is difficult. An appropriate rating standard (e.g. ARI) is essential and must be developed for the design of efficient ground coupled heat pump systems.

Current liquid-source heat pumps are designed to operate optimally with source temperatures of about 16 to 27 C (60 to 80 F) (some are optimized for space cooling). They do not have the controls or safety devices appropriate for lower source temperature operation. Recent investigations indicate that ground coupled heat pumps can be designed to operate with COP's above 3.0 using accessible technology. This requires the selection of heat pump components which are optimized for high efficiency and long life at the temperature range appropriate for ground coupled heat pumps.

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