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GROUND-COUPLED HEAT-PUMP-SYSTEM EXPERIMENTAL RESULTS *

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GROUND-COUPLED HEAT-PUMP-SYSTEM EXPERIMENTAL RESULTS*

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ABSTRACT

Since October 1980, a small house in Upton, Long Island, New York has been heated and cooled by a liquid source heat pump using a shallow serpentine earth coil as a heat source/sink. This paper, after a brief introduction and system description, presents system performance data for the winter of 1981-82 and the summer of 1982, followed by a discussion of these results. The experimental test house is a 104 m^2 (1120 ft^2) 3-bedroom ranch of energy-saving construction with a heating load of 7.8 X 10^6 J/°C-day (4.1 X 10^3 Btu/°F-day). The heat pump used during most of the period reported on here is a commercially available water-to-air unit sized to just meet the building design heating load with no auxiliary heat. The earth coil contains 155 m (507 ft) of nominal 1-1/2 in. medium density polyethylene pipe, and is buried 1.2 m (4 ft) deep. An antifreeze solution, consisting of approximately 25% ethylene glycol in water, is employed to permit subfreezing earth coil operation. Two independent data acquisition systems, a datalogger-microcomputer system backed up by a "Btu-meter," monitor the space conditioning system performance. During the winter of 1981-82, the system, which extracted 15.5 X 10^9 J (14.7 X 10^6 Btu) of heat from the ground, operated with a seasonal performance factor (SPF) of 2.46. No resistance heating was used. The minimum earth coil daily U-value observed during this season was 3.34 W/m°C (1.93 Btu/ft-hr-°F). During the summer of 1982, a total of 10.6 X 10^9 J (10.0 X 10^6 Btu) of heat was rejected to the ground. The system SPF was 1.91, with a minimum daily U-value of 3.53 W/m°C (2.04 Btu/ft-hr-°F).

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1. INTRODUCTION

Beginning in 1978, the author and colleagues have investigated the use of the earth as a heat source/sink or storage medium for various heat pump-based space conditioning systems. Between December 1978 and September 1981, eleven experiments, including six earth coils in various configurations, four buried tanks and a group of six vertical heat exchangers, were operated (1,2). Soil thermal property experiments have also been conducted. A computer model, GROCS (GRound Coupled Systems), has been developed to model the behavior of ground coupling devices (3). GROCS has been integrated with TRNSYS, the solar system simulation program, to permit the simulation of complete ground coupled heat pump systems (4). Experimental results have been compared to GROCS simulation results for model validation (5-7). The model was found to have considerable validity.

In September 1980 a small house in Upton, Long Island, New York was outfitted with an earth coil-based ground-coupled heat pump system. This system has been operated from October 1980 to the present. The goals of the project are:

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.
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.

A previous paper (8) described the design and installation of the ground-coupled heat pump system, as well as experimental results from the first winter's operation. This paper, after briefly describing the building load, the space conditioning system, and the data acquisition systems used, presents experimental results for the winter of 1981-82 and the summer of 1982. These results are discussed and evaluated. Suggestions are made for improving system performance.

2. SYSTEM DESCRIPTION

2.1 Building Load

The experimental test house is a 104 m^2 (1120 ft^2) 3-bedroom ranch of energy-saving construction with 6 in. of fiberglass insulation in walls and over an unheated crawl space, and 12 in. of insulation in the attic. The heating load of the building was determined experimentally to be 7.8 X 10^6 J/°C-day (4.1 X 10^3 Btu/°F-day) (8).

The local heating season averages about 3300°C-days (5900°F-days) per year (neglecting heating degree-days in June, July, and August) (9), leading to a total seasonal heating requirement of about 26 X 10^9 J/year. The cooling season averages only 282°C-days (508°F-days) per year (9). However, because of heat generated internally by the data acquisition system electronics, the domestic hot water heater and other appliances, the amount of space cooling required is far greater than this number of degree-days would suggest.

2.2 Ground-Coupled Heat Pump System

2.2.1. Earth Coil. The earth coil consists of 155 m (507 ft) of nominal 1-1/2 in. medium density polyethylene pipe (Caution: This grade of pipe is not pressure-rated above room temperature.) buried 1.2 m deep. As shown in Figure 1, the pipe is laid out in a serpentine pattern with straight sections about 16 m (51 ft) long, spaced about 2 m (6 ft) apart. The earth coil has been operated, for the most part, with a heat transfer fluid consisting of water and 20 to 30% ethylene glycol.

The earth coil depth selected, 1.2 m (4.0 ft), is a compromise between performance (which would favor a deeper earth coil in this climate) and installation cost (which escalates rapidly with depth). This depth is easily reachable with a chain-driven trencher, and is shallow enough to minimize trench wall collapse in the noncohesive sandy soil on Long Island.

The 155 m (507 ft) earth coil was installed by a local plumbing contractor, using pipe provided to him, for $500—or about $3/m ($1/ft). Two different chain-driven trenchers were used, as discussed previously (8). The original earth coil design called for 1 m (3 ft) pipe spacing, but this was not achievable with the equipment used, and the 2 m (6 ft) pipe spacing resulted.

Once the building heating and cooling loads and the earth coil design were determined, GROCS computer simulations were run to determine the earth coil length. These simulations, described in greater detail elsewhere (8), for the most part used earth coil heat inputs based on average prorated weekly heating and cooling degree-days. However, during periods of extreme ground temperatures (weeks 9 and 34), design operating conditions were imposed.

Earth coil fluid extreme operating temperatures of -7°C (20°F) and 40°C (105°F) were also imposed. Given these constraints and a soil thermal conductivity of 1.7 W/m°C (1.0 Btu/ft-hr-°F), a minimum earth coil length of about 150 m (490 ft) resulted.

2.2.2. Heat Pump. Several commercial water-to-air heat pumps of various sizes have been used in this experiment. The heat pump sizes and dates of operation during the period of interest for this report (fall 1981 to fall 1982) are presented in section 3. For most of this period a nominal 2-ton unit was used.

2.2.3. Other Hardware. The hardware and plumbing used in this experiment are shown in Figure 2. Because of the instrumentation required, the experimental hardware occupies a bedroom of the house. The heat pump delivers conditioned air to the house via a short sheet metal duct tapped into the existing central air distribution plenum of the house. Fluid is circulated through the earth coil and heat pump heat exchanger via one or more (depending on heat pump size) centrifugal circulation pumps. A vented air purge/expansion tank is provided to remove air from the antifreeze solution and to permit fluid expansion and contraction. It is also an aid in filling the system.

2.2.4. Controls and Operation. In order to operate a commercial water-to-air heat pump in a subfreezing earth coil system, it is necessary to defeat the heat pump freeze safety switch (if any). As shown in Figure 2, in this system the freeze safety switch has been replaced by a flow switch which shuts down the heat pump if the fluid flow drops below a preset level. If this

switch is tripped, the heat pump must be manually restarted. Both high and low fluid temperature switches are probably also desirable, although they have not been used in this experiment.

In operation, when the thermostat calls for heating or cooling, a relay immediately starts the circulation pump(s). Ten seconds later, after steady fluid flow has been established, delay terminals on the relay close, starting the heat pump. The delay permits the establishment of steady fluid flow before the heat pump is started, preventing spurious system shut down.

2.3. Data Acquisition Systems

The primary data acquisition system consists of a 60 channel datalogger interfaced with a microcomputer. Fluid flow is measured with a 1-1/4 in. target-type flow meter (shown in Figure 2). Temperatures are measured using special accuracy (± 0.4°C) copper-constantan thermocouple wire and matched 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, one located outside under the eave on the north side of the house measures outdoor temperature, and one measures far-field earth temperature at the coil depth of 1.2 m (4.0 ft). Heat pump and circulation pump power are measured separately using AC power transducers.

In operation, the datalogger scans all of the above sensors once every 30 seconds. The computer keeps running averages of all the temperatures. The computer also monitors the flow meter output channel and, if the flow meter output is below a threshold value—indicating no flow or system operation—

does nothing else. When the heat pump system is turned on and the flow meter output exceeds the threshold, the computer analyzes the data from the data-logger, recording temperatures and computing fluid and heat flows, and various measures of system performance (see section 3). At the end of each day, the computer creates a daily summary including the average value of each of the temperatures monitored, the system on-time, the ground heat extraction or rejection, the heat pump and circulation pump electric energy consumptions, the earth coil fluid flow, and system performance.

The backup data acquisition system consists of a Btu meter with a 3/4 in. turbine-type fluid flow meter and special accuracy thermistors, two dial-type electric power meters, one for the heat pump and one for the circulation pump(s), a heat pump on-time meter, a room temperature thermometer, and on-time meters for the domestic hot water heating elements. The Btu meter has two digital counters, one for gallons and one for Btu's. 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). Readings are taken by hand from all of these instruments about 3 times per week. The data generated is compared to that from the primary data acquisition system regularly.

3. SYSTEM PERFORMANCE

Table 1 summarizes the system operation during the period covered by this report (October 11, 1981 to October 2, 1982). As can be seen, a nominal 2-ton heat pump was used for 38 of the 51 weeks examined.

Figures 3 through 6 present data exploring various aspects of the weekly system performance. Figure 3 presents weekly mean temperature data, including

Table 1
System Operation

Space conditioning mode	Nominal heat pump size (tons)	Date Begin (week/year)	Date End (week/year)
Heating		41/81	22/82
	3.5	41/81	46/81
	2.0	47/81	22/82
Cooling		23/82	39/82
	2.0	23/82	32/82
	3.5	33/82	39/82

the outdoor, 1.2 m (4.0 ft) ground, earth coil inlet and outlet, and house mean weekly temperatures. The earth coil temperatures are averaged over only the periods of time during which the system was operated. Figure 4 gives the weekly totals of heat added to or removed from the ground and the house, and of electric energy used by the heat pump and circulation pump(s). Periods of system shutdown appear as dips in the weekly heat totals in November 1982, and July and August 1983.

Figure 5 gives the weekly system efficiencies and U-Values. Heat pump COP (coefficient of performance) is defined as the total amount of energy added to (heating season) or removed from (cooling season) the house divided by the heat pump energy (compressor and blower) used to provide this space conditioning. This is the usual efficiency rating method for packaged water-to-air units. However, system COP, which also takes into account the electric energy used to circulate the earth coil fluid, is the correct measure of system efficiency. Both COPs are provided in Figure 5. U-Value, also given in Figure 5, is defined as the rate of heat extraction from (heating season) or rate of heat addition to (cooling season) the ground per unit

length of earth coil, divided by the difference between the far-field and mean earth coil-temperatures. By convention, U-Values are taken as positive. Figure 6 contains the weekly fractional on-time and mean earth coil fluid flow rates.

3.1 1981-2 Heating Season Performance

Figure 3 shows that throughout the heating season the test house indoor tempearture was maintained at about 22°C (72°F). The mean weekly far-field ground temperature at the 1.2 m (4 ft) earth coil depth was higher than the mean weekly ambient temperature until about week 15 of 1982. The far-field temperature was also far more steady. Note that in Upton the mean daily minimum ambient temperature averages about 5 to 6°C (9 to 11°F) below the daily mean temperature (9).

The earth coil fluid temperature was (at least partly) below freezing between week 50 of 1981 and week 14 of 1982, confirming the need for anti-freeze. The temperature of the fluid entering the heat pump averaged about 2 to 3°C (3 to 6°F) below the far-field temperature. The lowest weekly mean earth coil temperature observed was about -2°C (29°F) during week 3 of 1982. It is assumed that some soil freezing occurred.

Figure 4 shows a great weekly variation in heat extraction from the ground and electrical energy used. Nevertheless, as shown in Figure 5, the variation in system performance is quite small throughout the heating season. The minimum mean weekly system COP for the 1981-82 heating season was about 2.3 to 2.4 during weeks 5 to 10 (February and March) of 1982. This period coincided roughly with the lowest far-field and earth coil temperatures, but

interestingly not with the coldest ambient temperatures--and highest heat demand--which occurred during weeks 1 to 4 (January) of 1982.

The U-Values dropped rapidly at the beginning of the heating season, and then stabilized at approximately 5 W/m°C (3 Btu/ft-hr-°F) from week 49 of 1981 to week 14 of 1982. The lowest weekly U-Values observed were about 4.3 W/m°C (2.5 Btu/ft-hr-°F) for weeks 10 to 14 of 1982. The lowest winter daily U-Value observed (not shown) was 3.34 W/m°C (1.93 Btu/ft-hr-°F) on January 12, when the mean outdoor temperature was -12°C (10°F).

As shown in Figure 6, system operating time is sharply peaked and correlated with the ambient temperature. The greatest system operation occurred in weeks 2 and 3 of 1982, during which the system operated 69 and 70% of the time, respectively. Earth coil fluid flow was quite smooth, averaging about 0.25 L/s (4 GPM) when the 2.0 ton heat pump was used and about 0.62 L/s (10 GPM) for the 3.5-ton unit, as per usual practice.

3.2 1982 Cooling Season Performance

As shown in Figure 3, the test house indoor temperature was maintained at approximately 22°C (72°F) throughout the 1982 cooling season. The mean outdoor temperature was higher than the far-field ground temperature until roughly week 31 (August) of 1982. Note, though, that the mean daily maximum temperature at Upton averages about 6°C (11°F) higher than the mean daily temperature. For most of the summer, i.e., from week 28 (July) on, the fluid temperature entering the heat pump averaged roughly 27°C (80°F), or about 3 to 6°C (6 to 10°F) above the far-field temperature. The fluid temperature entering the ground averaged roughly 32°C (90°F) during this time.

Figure 4 shows a great variation in the heat removed from the house throughout the cooling season. As during the winter, though, the system COP was quite constant at about 1.7 to 1.8 through most of the cooling season. Earth coil U-Values dropped steadily during the portion of the summer that the 2.0 ton heat pump was used, from about 9.3 to 5.5 W/m°C (5.4 to 3.2 Btu/ft-hr-°F). U-Values rose and were steady at about 9 to 10 W/m°C (5 to 6 Btu/ft-hr-°F) after the 3.5 ton unit was reinstalled.

A seasonal weekly minimum U-Value of 5.5 W/m°C (3.2 Btu/ft-hr-°F) was observed during weeks 31 and 32 (August). The daily minimum observed (not shown) was 3.53 W/m°C (2.04 Btu/ft-hr-°F). The fluid flow and system on-time were similar to those observed in winter.

4. DISCUSSION AND CONCLUSION

The seasonal system performance is summarized in Table 2. All temperatures shown are averaged over only those periods of time when the heat pump system was on. As can be seen from the table, the heat provided to the building during the heating season (26.0×10^9 J) is consistent with what would be expected from the measured building heating load and the average number of local heating season degree-days. The cooling load (6.9×10^9 J), however, is much higher than would be expected from the number of cooling degree days, consistent with a significant internal heat load. Although the building heating load is about 4 times as great as the cooling load, the amount of heat removed from the ground in winter is only about 50% greater than the amount added during the summer. This suggests that one need not go much further south before the cooling load begins to dominate earth coil design considerations.

Table 2
1981-82 Seasonal System Performance Summary

	Space Conditioning Mode	
	Heating	Cooling
Average Far-Field Temperature (°C)	+ 4.3	+ 20.7
Average Earth Coil Temperature (°C)	+ 0.4	+ 28.1
Heat to House (10^9 J)	+ 26.0	- 6.9
Heat to Ground (10^9 J)	- 15.5	+ 10.6
Heat Pump Energy (KWH)	2683	937
Circulation Pump Energy (KWH)	256	74
Heat Pump COP	2.70	2.05
System COP (SPF)	2.46	1.91
Minimum Daily U-Value (W/m °C)	3.34	3.53

The heating season system COP, or seasonal performance factor (SPF), was 2.46. The building was heated adequately at all times by the heat pump with no resistance heating. During the first winter of operation (1980-81), using a 3.0-ton heat pump, the SPF was 2.2 (8). Thus, the use of a smaller, more optimally sized heat pump significantly improved system performance. Nevertheless, it is felt that, given the fluid temperatures encountered, there is still considerable room for efficiency improvement.

The cooling season SPF was 1.91. This is significantly below the manufacturers' and BNL-measured steady state heat pump performance. This suggests that cycling is an important factor in system performance, reiterating the importance of proper heat pump sizing.

Table 2 also contains the minimum daily U-Values for each season. These values may provide the basis for an earth coil design methodology (see [8]). Interestingly, the summer and winter U-Value extremes are quite similar despite very different soil temperatures. This suggests that summer soil drying and winter soil freezing did not play a large role in the performance of this system.

In conclusion, while the performance reported here is a significant improvement on past results, it is felt that still better performance is possible with a closed-loop, ground-coupled heat pump system. What is needed are heat pumps optimized for this application with suitable components, controls, and industry rating guidelines.

ACKNOWLEDGMENTS

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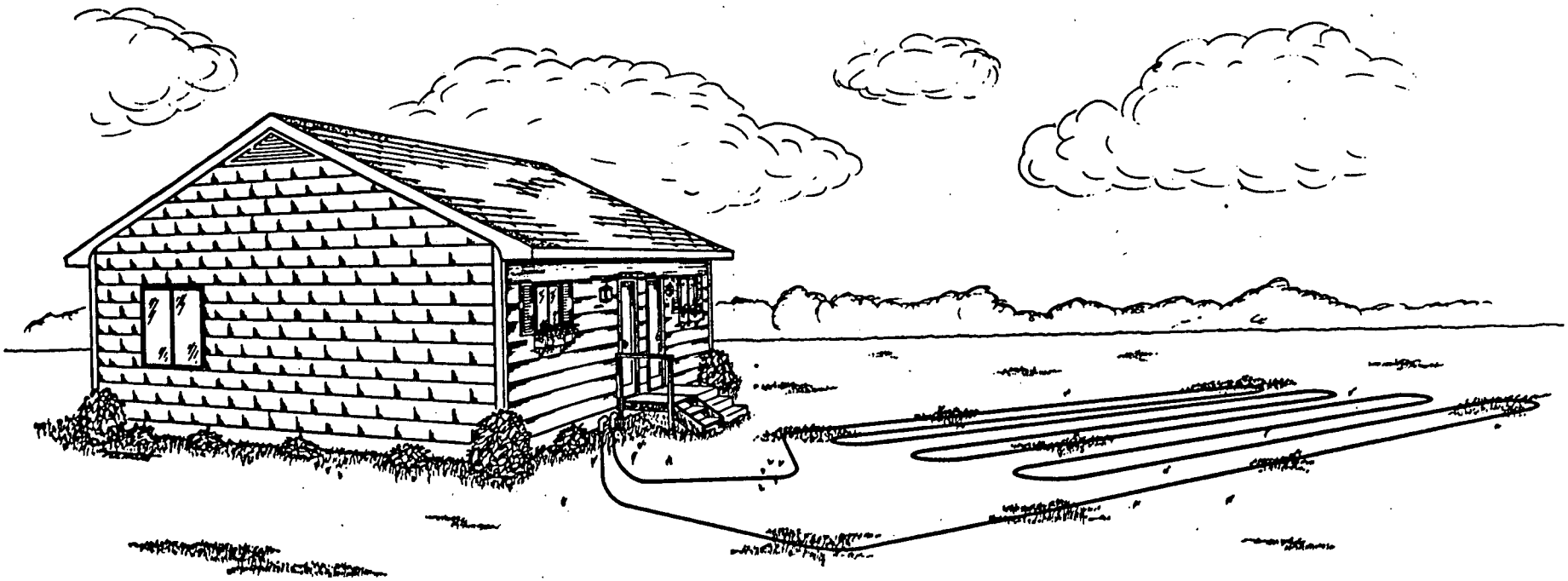

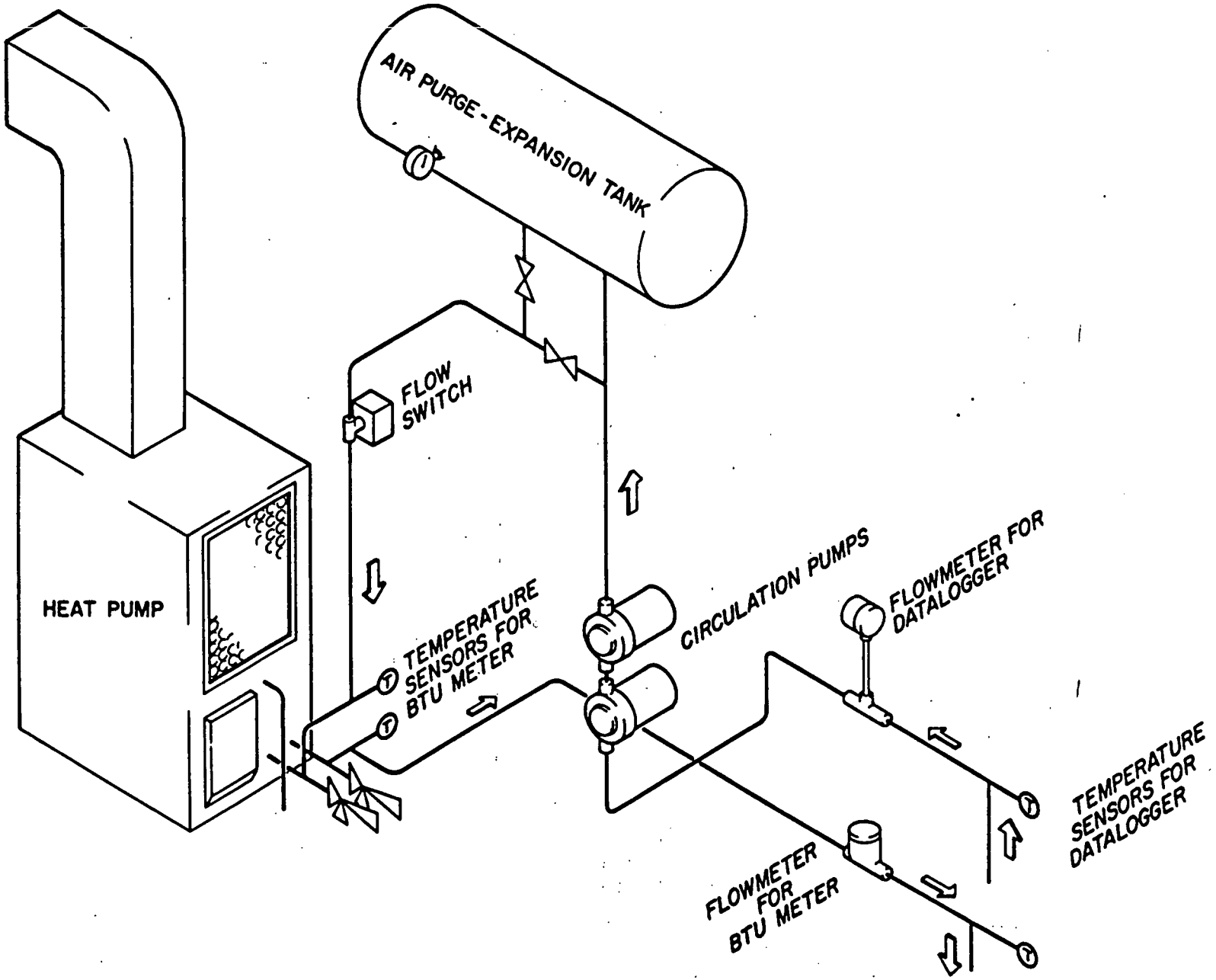
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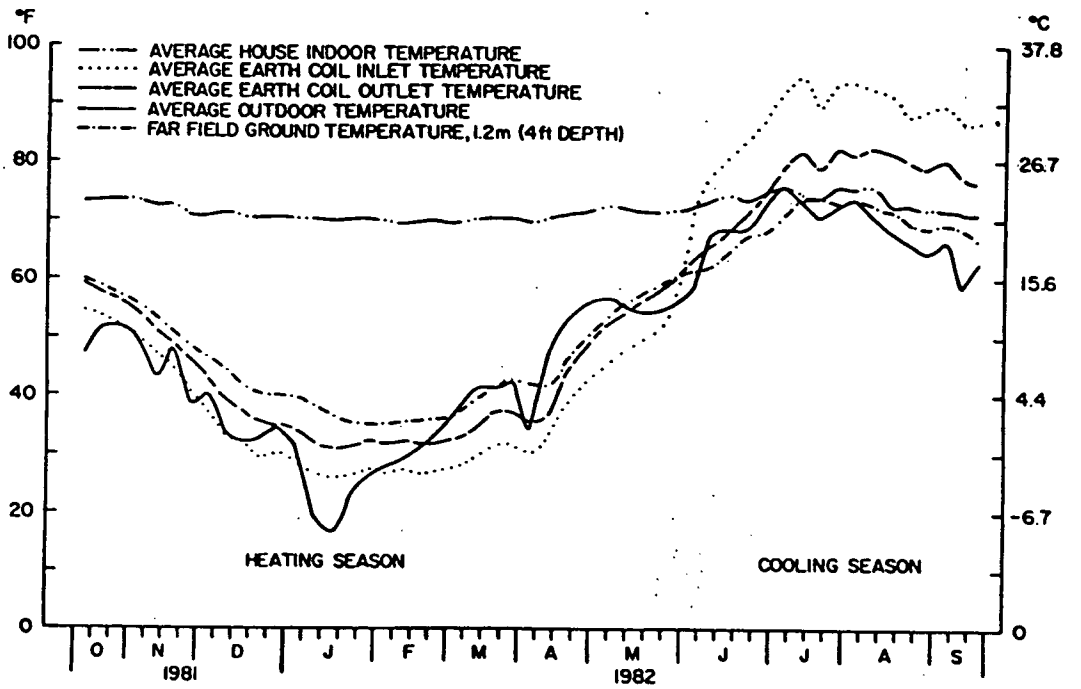
FLOWMETER FOR BTU METER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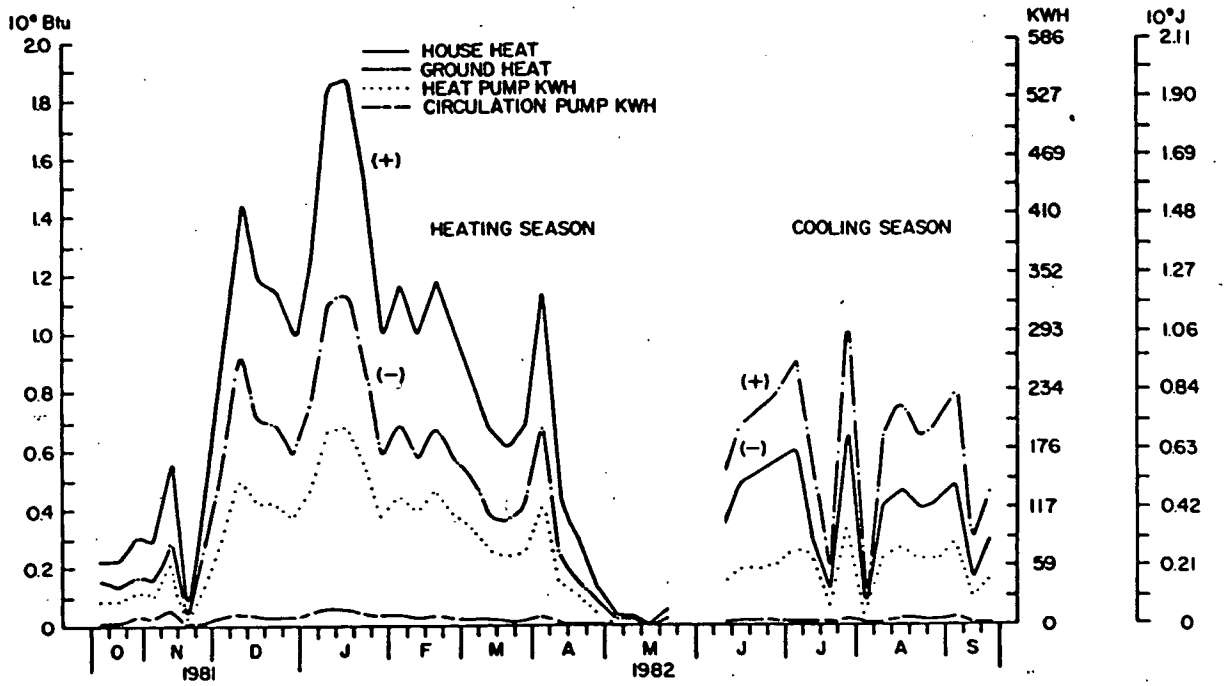
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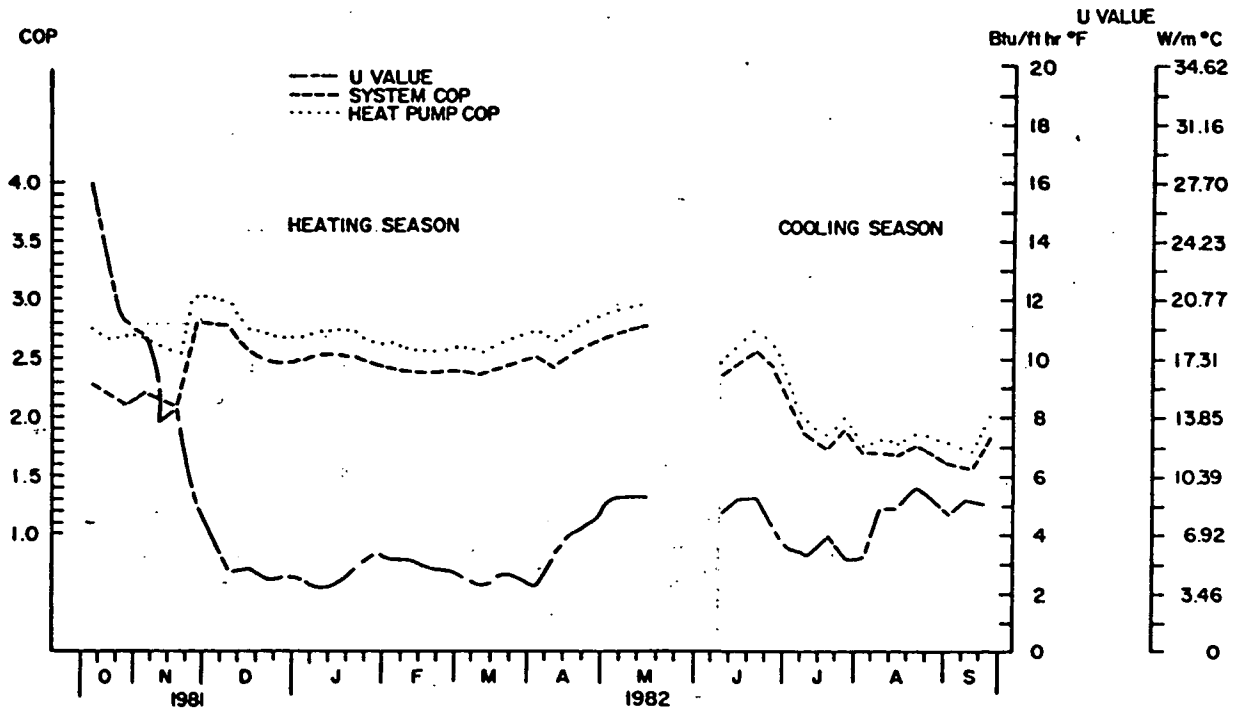
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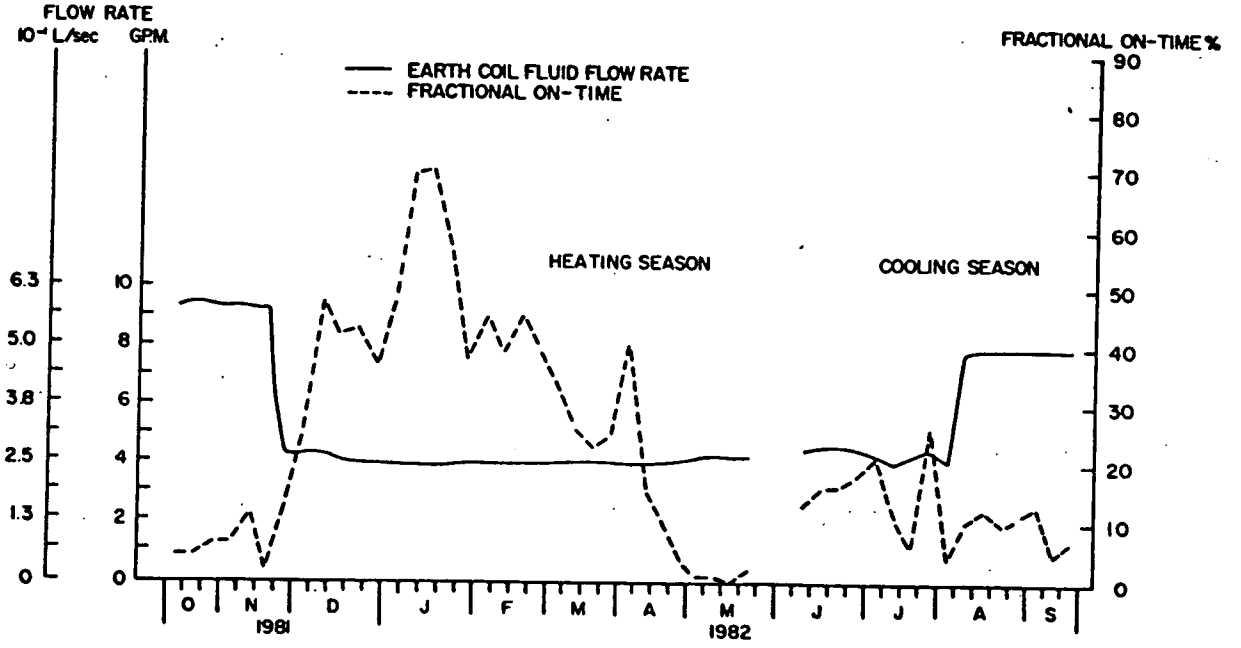
FLOW RATE
10⁻⁴ L/sec
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