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Résumé

Un échangeur à haut rendement utilisant la chaleur du sol a été mis au point en vue d'être employé avec des thermopompes à captage au sol. Il est constitué de tubes en cuivre ayant la forme d'une spirale et peut être installé dans un trou de sonde vertical remblayé avec du sable. La performance thermique d'un prototype grandeur réelle a montré que cet échangeur de chaleur permet des débits d'extraction de chaleur très élevés à des températures de service inférieures au point de congélation. Pour la plupart des types de sol, les cycles gel-dégel ne posent pas de problèmes; cependant, dans l'argile sensible Leda, dans laquelle les essais des prototypes ont été effectués, un tassement appréciable s'est produit après le premier cycle gel-dégel en raison de l'affaissement initial de l'ouvrage en sol.

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PERFORMANCE OF A SPIRAL GROUND HEAT EXCHANGER FOR HEAT PUMP APPLICATION

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SUMMARY

A high-efficiency ground heat exchanger has been developed for use with ground-source heat pumps. The exchanger is made of copper tubing, shaped in the form of a spiral, which can be installed in a vertical borehole backfilled with sand. Thermal performance of a full-scale prototype indicated that this heat exchanger can achieve very high heat extraction rates if subfreezing operating temperatures are used. For most soil types cyclic freezing and thawing is not a problem; however, for the sensitive Leda clay in which the prototype tests were conducted, substantial settlement occurred after the first freeze-thaw cycle owing to initial collapse of the soil structure.

KEY WORDS Ground-source heat pumps Heat pumps Spiral ground heat exchangers

INTRODUCTION

Current ground-source heat pump (GSHP) technology is such that GSHP installations perform well provided that the system is properly designed for the site and application. There are thousands of successful installations with many years of operating experience in a number of countries, (von Cube and Stiemle, 1981). In the past, the major impediment to more widespread application of the technology has been the inability of GSHP systems to compete economically with other heating/cooling systems (Svec, 1987). Current GSHP systems are competitive in many markets and, through a worldwide effort of research and development and of demonstration projects, GSHPs are making major inroads into the heating/cooling market.

For GSHPs a significant portion of the initial cost (30% and 40% for horizontal and vertical systems, respectively) is in the installation of the ground heat exchangers. This paper describes research aimed at reducing the relatively high initial installation costs. During the early phases of this research it was demonstrated that improved heat exchanger design and the use of lower operating temperatures had the potential to increase the heat extraction/rejection rate by a factor of two to three (Svec, 1985). The implication of these findings is that the total length of a ground heat exchanger might be reduced by a corresponding amount. Since the major cost in installing vertical system is the cost of drilling and the major cost in horizontal systems is the cost of trenching and restoration of the ground surface, any reduction in the length of heat exchanger required directly reduces the installation cost.

A field testing facility has been developed by the Institute for Research in Construction (IRC) of the National Research Council of Canada for the purpose of testing full-scale installations of ground heat exchangers. The performance characteristics of a new heat exchanger developed at IRC have been obtained and are reported below.

TEST FACILITY

The purpose of the field testing facility (described by Svec, 1985) is to subject full-scale ground heat exchangers to a series of carefully controlled tests in order to determine performance characteristics under specified operating conditions. The most important aspect of the facility is the ability to control and monitor the temperature and rate of flow of the circulating fluid with a high degree of accuracy. A specially designed

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refrigeration system is capable of maintaining a preset temperature with an accuracy of $\pm 0{\cdot}05$°C. The measurement accuracy of the rate of fluid flow is within ± 1% and that of the fluid temperature is within $\pm 0{\cdot}005$°C.

The temperature distribution in the ground is measured using thermocouples and is monitored continuously. Tests are designed to determine energy withdrawal during a test cycle and subsequent natural recharging. Because the site is underlaid by a deposit of a particular type of clay called 'Leda' clay, which is known for its open structure and high natural water content (often called highly sensitive clay), appreciable settlement was anticipated particularly at the conclusion of the first freeze-thaw cycle. Ground surface settlements have been monitored using standard surveying techniques.

GROUND HEAT EXCHANGER

Theoretical and full-scale experimental results obtained from a series of tests using various heat exchangers (Svec, 1985) led to the following conclusion. If small heat sinks or sources are evenly spaced along and as close as possible to the wall of a borehole, and if the borehole is backfilled with a relatively high-conductivity material (saturated sand) then such an arrangement will perform thermally in a way similar to that of a large-diameter tube (equal to the diameter of the hole).

One of the first full-scale heat exchanger designed to test the above conclusion consisted of four 1·25 cm diameter copper tubes symmetrically placed in a 30 cm vertical hole in Leda clay. The hole was backfilled with sand which was naturally saturated by a high groundwater table. The thermal performance of this heat exchanger was excellent (Svec, 1985). In order to improve several aspects of this design, primarily ease of construction and structural strength of the heat exchanger, it was decided to use 1·9 cm-diameter copper tubing shaped into a spiral (Figure 1). This design offers the following important advantages:

(i) The contact surface is always very close to the wall of the borehole.
(ii) The overall contact area can be adjusted easily by changing the pitch of the spiral (i.e. compressing or stretching the coil.

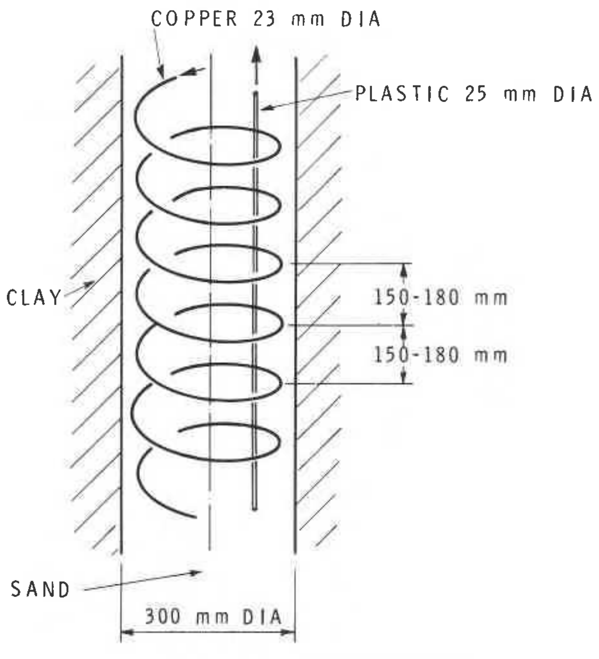


Figure 1. Copper spiral heat exchanger

(iii) The length of the tube in a spiral can be many times greater than that of the return pipe, which results in negligible thermal interaction.
(iv) A spiral is very flexible in the direction of the axis of the borehole and therefore can accommodate very large vertical deformation of the surrounding soil.
(v) Almost the entire space in the borehole remains clear so that backfilling of the borehole can proceed efficiently.
(vi) A manufacturing process to produce 25 cm-diameter (or larger) copper spirals already exists and is relatively inexpensive.
(vii) If plastic is used to manufacture the spiral, the disadvantage of lower conductivity can be partially offset by increasing the density of the spiral.

The first prototype (Figure 1) was constructed using 60 m of 1·9 cm diameter copper tubing wound tightly on a 20 cm diameter plastic cylinder. When completed, the coil resembled a compressed spring. It was installed in a 30 cm diameter predrilled vertical borehole 15 m deep, by slowly pushing the end of the coil down the hole while spreading the loops to form a spiral with a pitch of about 15–18 cm (Figure 2). A 2·5 cm diameter plastic pipe was used as the return. Commercially available copper–plastic connectors were silver soldered to the

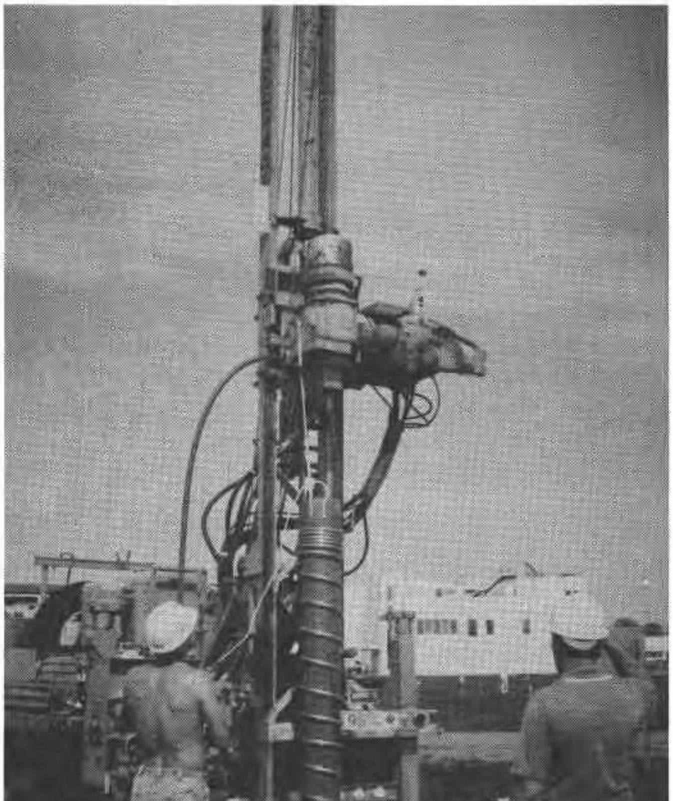


Figure 2. Installation of heat exchanger

copper spiral and fused to the plastic pipe. The hole was filled with water and was then backfilled with sand. Finally the unit was connected to a heat pump system.

The temperature of the circulating fluid was measured using a pair of thermistors at the top of each of the 'in' and 'out' pipes. The measured temperature difference and volume of fluid flow were then used to compute the total energy extracted from the ground, as well as the heat extraction rate per metre of heat exchanger (i. e., per metre of borehole).

DISCUSSION

One of the most important factors for a well balanced, optimised design of a GSHP system is a quantitative knowledge of ground heat exchanger performance under given ground thermal and hydrological conditions. In other words, a designer has to know what heat extraction rate can be expected at a particular site for a prescribed range of operating conditions. The fact that the heat extraction rate depends on the operation strategy makes the estimation of the heat extraction rates somewhat complex. The system operates in a microtransient state for any one cycle and approaches a macrosteady state in the long run.

The objectives of the test program of the first prototype were as follows:

(i) to obtain profiles of heat extraction rates up to 'steady state' at different but constant temperatures
(ii) to determine the maximum thermal energy which could be extracted from the ground by the heat exchanger
(iii) to ascertain the thermal response of the new heat exchanger system to a cyclic operation
(iv) to observe the radial extent of heat depletion from the soil surrounding a single heat exchanger
(v) to observe the process and rate of natural recharge of the surrounding soil at the completion of testing.

TESTING PROCEDURE AND RESULTS

Thermal energy was continuously extracted on a 24 h/day basis except at the end of the test program when the ground thermal response to cyclic heat withdrawal was investigated. It should be noted that the condition of continuous heat withdrawal is most unlikely to occur in the operation of a normal heat pump system where the heat is extracted cyclically according to load demand. Continuous withdrawal, however, represents the extreme operation condition to which a system might be exposed. It is also a condition more amenable to experimental control and numerical modelling than cyclic operation.

The heat extraction rates during the first 100 days of operation are shown in Figure 3. The objective of this test was to determine the heat extraction rate as a function of time due to a drop in the fluid temperature. Each curve tends to become asymptotic to the steady-state heat extraction rate at a particular exchanger input temperature. For the first test the input temperature at the top of the exchanger was maintained at 0°C. No freezing of the ground occurred under this condition. The heat extraction rate Q_o at the beginning of the test was about 100 W/m (watts per metre length of the borehole, i.e. of the installed heat exchanger). The 'steady-state' heat extraction Q_s after 12 days of operation decreased to 30 W/m. The temperature distribution in the ground in the radial direction at this time is shown in Figure 4, curve 1. Without interrupting the flow, the input temperature was decreased to −2·7°C. As soon as the input temperature was changed, the heat extraction rate increased to 110 W/m. After 24 days the most distant thermocouple in the soil (located 1·55 m from the centre of the exchanger) indicated a small temperature drop (Figure 4, curve 4). During the following 24 days, the system was run at approximately −7°C with $Q_o = 120$ W/m and $Q_s = 70$ W/m, at which time there was a system malfunction and the temperature of the input fluid increased to −6·2°C. After 16 days at this temperature the extraction rate had stabilized at 55 W/m. At this time the testing facility was inoperable for about 48 h. When the test was resumed the input temperature was stable at −6.8°C and Q_o increased again to over 100 W/m. After 20 days of continuous operation Q_s reached 60 W/m. At this time, the most distant thermocouple indicated a temperature in the ground of 6°C. This thermocouple was located at 1·55 m from the heat exchanger. It is estimated that the extent of the heat exchanger influence was about 5 m.

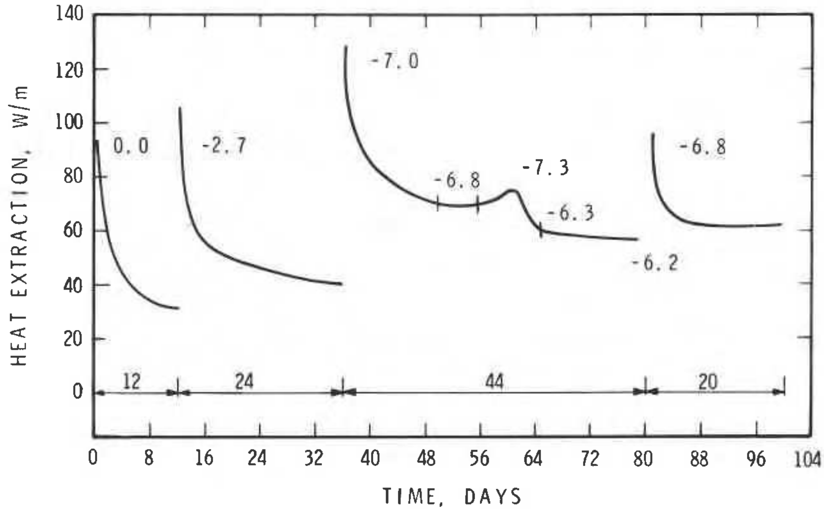
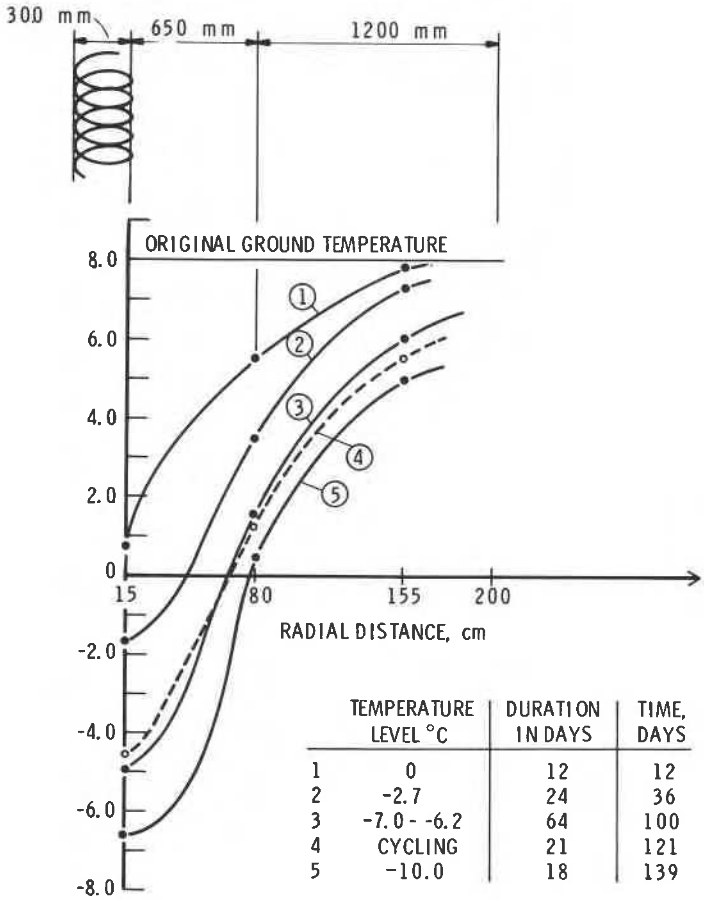


Figure 3. Heat extraction as function of fluid temperature and time



	TEMPERATURE LEVEL °C	DURATION IN DAYS	TIME, DAYS
1	0	12	12
2	-2.7	24	36
3	-7.0 - -6.2	64	100
4	CYCLING	21	121
5	-10.0	18	139

Figure 4. Ground temperature profiles

Without permitting any ground thermal recovery, a test was started to determine the thermal response of the heat exchanger to cyclical withdrawal of heat. Two operational schedules were tried: (1) 17 h withdrawal and 7 h idle for 14 days, and (2) 7 h withdrawal and 17 h idle for 14 days.

The heat extraction rates during the 17 h withdrawal period of schedule 1 were averaged over three periods, i.e., 5 h, 3 h and 9 h (Figure 5*a*). The corresponding rates fluctuated between 85 and 90 W/m, 65 and 70 W/m and 60 and 63 W/m, respectively. The heat extraction rate for schedule 2 calculated as an average for the entire 7 h of heat withdrawal fluctuated between 77 and 90 W/m (Figure 5*b*). It should be noted that the heat extraction rate Q_s at $-7\,^{\circ}C$ was about 60 W/m. By the end of the cycling tests, the soil temperature at 1·55 m from the centre of the heat exchanger had decreased to about $+5{\cdot}5\,^{\circ}C$ (Figure 4, curve 4). These results indicate that operational strategy influences the rate of heat extraction over short periods.

Many GSHP system typically cycle on/off at least once per hour. Under those conditions the rate of heat extraction is appreciably higher over the shorter period. In a recent demonstration project involving a GSHP system in a structure equivalent to a small single family house, extraction rates from the Leda clay soil ranged from 115 to 160 W/m during the 1986/87 heating season.

An integration of the results (Figures 5*a* and 5*b*) indicates that continuous operation will produce a larger (but not significantly larger) total amount of heat energy than a cycling operational strategy. The coefficient of performance (COP) however, will be slightly larger for a cyclical operation because of the higher operational temperature. From this point of view, an operational strategy which permitted cycling among a group of heat exchangers could provide a further improvement in the COP, but the benefits would have to be assessed against a probable increased capital cost.

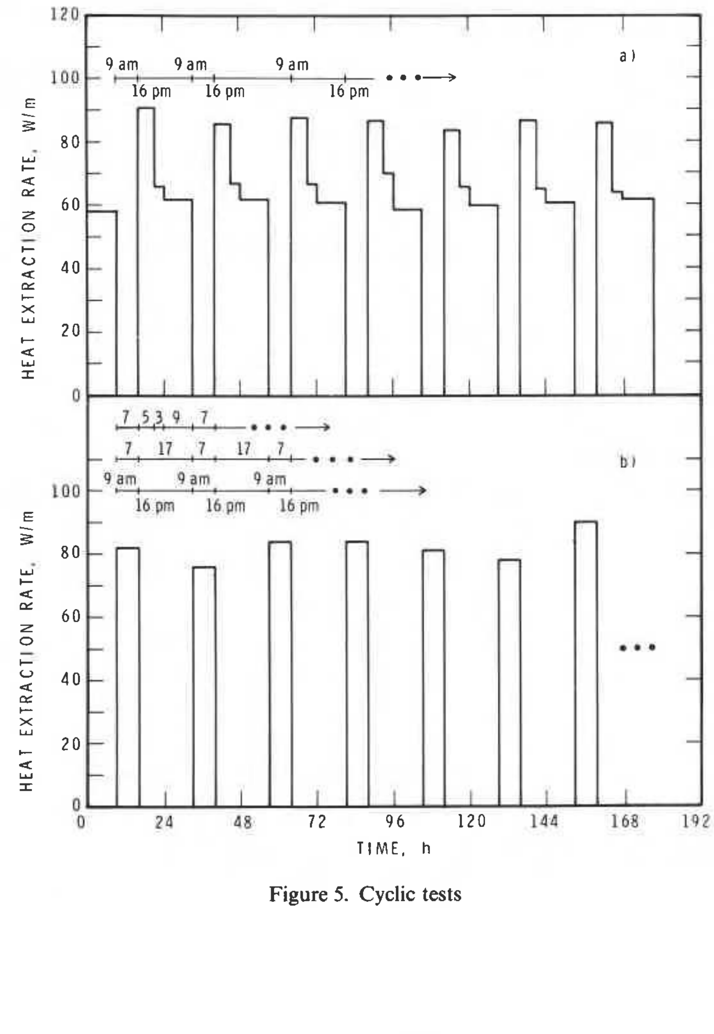


Figure 5. Cyclic tests

The test program concluded with another steady-state withdrawal test at an input fluid temperature of −10°C. Q_o was well over 100 W/m. After 18 days, Q_s was about 85 W/m. At the conclusion of this test the soil temperature at 1·55 m from the centre of the heat exchanger had decreased to about −5·0°C.

One of the most interesting results of this test program was the natural recharging of the ground (Figure 6). At the conclusion of the tests (21st April 1987), thermocouples located at a depth of 7·5 m and situated on the spiral and in the soil at 80 cm and 1·55 cm from the centre of the spiral indicated temperatures of −6·5, 0·5 and 4·7°C, respectively. These temperatures could be interpolated to indicate that a cylinder of soil 1·2 m in diameter had been frozen around the heat exchanger. The soil was Leda clay which has a natural water content of about 60%. A very significant amount of latent heat estimated at about 3·8 MWh had been removed in the course of the test as a consequence of freezing the soil.

By the 1st May, the coil temperature was about −0·3°C, and at 80 cm the temperature had increased to 1°C. There was practically no change at 155 cm. By the 10th July (after a period of 80 days), the soil mass had completely thawed, and temperatures at the three locations mentioned above were 0, 3·4 and 5·2°C, respectively. Subsequently, the thermal recovery of the soil was very rapid, especially close to the heat exchanger. By the 20th October (after a period of 182 days), the temperatures at all locations in the soil were between 5·7 and 6·4°C, which is within 2°C of the original ground temperature.

The results indicate that the frozen soil could be regarded as a cold thermal storage for air-conditioning purposes. Recharging would easily be achieved during the air-conditioning season in spite of the rather extreme heat withdrawal of the experiments. If air conditioning is not needed, a very inexpensive solar collector could serve to reestablish the original ground temperature or even create a low-grade hot thermal storage.

An important consequence of using subzero temperatures in soils such as Leda clay is that the process of freezing and consequent volume expansion destroys the natural structure of the soil. This process will lead to large settlements occurring within the cylinder of soil after thawing is complete. The largest settlements will occur after the first freeze-thaw cycle. Unless special precuations are taken, the heat exchanger or connecting plumbing may be damaged. Such settlement will not occur in most soils except those with a loose density or a collapsible structure.

One important aspect which has not been addressed in these tests is the long-term effect of the seasonally out-of-phase thermal cycles on adjacent or intercepting vegetation root systems. This subject is beyond the scope of the present study but should not be overlooked in the design of full-scale systems.

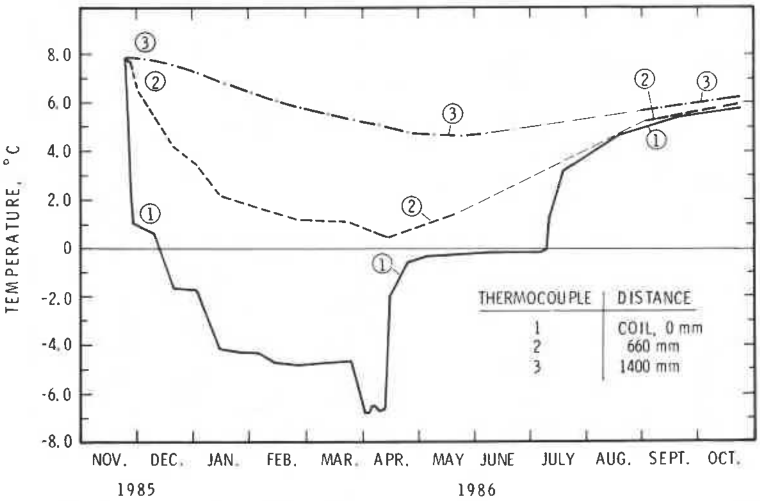


Figure 6. Test history

CONCLUSIONS

The copper spiral coil was manufactured without difficulty as a prototype, and subsequent industrial production of similar coils was considered routine. One manufacturer claimed that 150 m of 2·2 cm diameter copper tubing could be wound into a 30 cm diameter tight coil in a matter of minutes. During this process the copper is work hardened, and so some annealing is necessary to permit subsequent expansion of the coil to the desired pitch.

No major difficulty was experienced during the installation process. It was found useful to strap the coil to light lumber (2·5 × 5 cm or 2·5 × 7·5 cm) in order to maintain the desired pitch during installation.

Backfilling of the hole with sand proceeded most easily if the hole was at least partially full of water. Bulking and poor compaction of the backfill may occur in a 'dry' borehole.

In a soil such as Leda clay which has a large natural void ratio and a high natural water content, volume expansion during freezing may destroy the soil structure resulting in substantial settlements. In most other soils the freeze-thaw cycles will have relatively little effect.

The heat extraction rates achieved using the spiral heat exchanger are substantially greater than the rates obtained for plastic U-tube heat exchangers in similar soils. In fact, use of the copper spiral and lower (below freezing) operating temperatures result in a required total borehole length one half to one third of that normally required.

Natural recharging of the ground thermal regime is significant. Complete ground thermal recovery can be achieved easily during the air-conditioning season. If air conditioning is not part of the system, then a very simple solar recharging system will be adequate to fully restore the natural thermal regime.

There is some indication that system operation strategy may affect the coefficient of performance of the system. This possibility should be studied further.

ACKNOWLEDGEMENT

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