PERFORMANCE OF HORIZONTAL FIELD EARTH-COUPLED HEAT PUMPS

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ABSTRACT

An alternative to traditional methods of residential heating and cooling is the heat pump. However, heat pumps which use the outside air as a heat source/sink become inefficient during the periods of highest demand. Another possible heat source/sink is the earth, several feet below the surface. The purpose of this paper is to study the performance of horizontal pipe field, closed-loop, earth-coupled heat pump systems. The effects on system performance of variations in pipe field and soil parameters are discovered through the use of a finite element computer simulation of the system. These parametric studies use heating and cooling loads for Ohio. Total field length and pipe diameter as well as pipe material and soil thermal conductivity are varied in several different sets of simulations. The results of these simulations, summarized as yearly operating costs, are used to determine the system configuration which gives the minimum payback period in a break even economic analysis. For a 2000 square foot house in the Central Ohio area, the optimum earth-coupled heat pump system has a payback of about seven years when compared with the performance of an air-to-air heat pump. The simulation methods used in this paper are easily adapted to systems with other heating/cooling demands.

INTRODUCTION

As gas and electric rates rise, many homeowners may find themselves looking for alternatives to conventional home heating methods. One such alternative is the heat pump. However, heat pumps which use the outside air as a heat source (air-to-air) become inefficient during the coldest part of the winter when the heating demand is highest. To provide adequate heat for a home, most air-to-air heat pumps require a back-up system. Another possible heat source is the earth. Even on the coldest winter nights, subsurface soil has retained enough heat to remain above freezing making it an excellent source for efficient heat pump operation. In the summer, the earth can also be used as a cooler-than-air heat sink for air conditioning.

There are several ways to couple a heat pump to the earth. Most include burial of a device that can absorb heat from the ground and transfer it to the heat pump. Some systems are "open-loop" using readily available ground water. Other systems are "closed-loop" using a fixed, relatively small amount of secondary fluid circulated through buried pipes. The fluid absorbs heat from the ground and transfers it to the heat pump, which then delivers the heat at a higher temperature to the home.

Closed-loop systems may use buried horizontal or vertical pipe fields, or large tanks. However, they require adequate access to the earth and in some cases, large surface areas. Vertical systems do not require large land areas, but several deep holes have to be drilled. Horizontal systems need a large surface area, but can be easily installed with conventional trenching methods.

Open-loop systems are only possible if a dependable ground water source is available. Most ground water has a high mineral content which causes corrosion and scale build-up. There is also the problem of disposing of the water once heat has been removed. Although this system may be inexpensive to install and operate, ground water may not be readily available in some areas.

To examine a single topic more closely, this paper will study only horizontal, closed-loop, earth-coupled heat pump systems. Closed-loop was selected over open-loop mainly because most open loop systems require a large amount of ground water not readily available in all areas. Horizontal pipe fields need a large ground area, but are relatively easy to install. A pipe field near the surface receives more heat from the sun and rain in the spring and can sometimes recover normal temperatures faster than a vertical system. The major disadvantages of horizontal systems are the high cost of purchasing and installing the pipe and the large surface area required.

PREDICTING PIPE FIELD PERFORMANCE

The basic unknown in the design of earth-coupled heat pumps is the thermal performance of the underground heat exchanger. Mathematical models to predict performance have been developed and vary widely in complexity. Geeraert and Steffens (1) of Laborelec in Belgium have studied the relative computation times and accuracies of several models from a simple steady-state method to complex finite element methods. They noted that a steady-state method can conservatively predict actual horizontal coil performance to within 25 percent. To obtain accuracy within 5 percent or less, a non-linear finite element method must be used. Methods which account for changing soil properties and the heat of freezing which is released when soil moisture freezes are the most accurate. However, an increase in accuracy is only obtained with a corresponding increase in required computer time.

Finite element models have been used by several investigators to study earth-coupled heat pump performance. Most of these models assume that soil properties and soil moisture are constant. Nievergeld and Koppenol (2) used such a model to investigate the dependence of seasonal performance on pipe length, diameter, burial depth, and spacing for a horizontal field in the Netherlands (high ground water level). They found that length had the greatest effect on performance.

A three-dimensional finite element program called GROCS, GROund Coupled Systems, was developed and extensively verified at Brookhaven National Laboratory (BNL) (3) (4) (5) (6). The GROCS program uses up to thirty finite elements. Each element is a block of earth whose size, shape, location, and interaction with other blocks is determined from a hand-drawn model. This dimensional data is taken from the model drawing and input to the program by the user. There are two types of blocks which may be used in a model: free blocks and rigged blocks. Rigged blocks act as boundaries, and their temperatures are determined independently from climatic and soil property data. Temperatures of the free blocks are intialized by the user and determined at each time step by finite difference equations. In most models, a group of free blocks, one or more of which simulate the underground heat exchanger, are surrounded by rigged blocks. To calculate free block temperatures, GROCS requires the input of physical dimensions and soil property data (thermal conductivity, thermal diffusivity, and volume heat capacity). The user must supply constraints such as initial and final time of the simulation and the time step interval. For the free block(s) which serves as the earth-coupling device, weekly heat inputs or withdrawls must be provided. The user may also select the time interval for the temperature printout.

In the simulations to be discussed later, heating and cooling loads used in GROCS were calculated for a 2000 ft^2 frame house located in Columbus, Ohio. These loads were calculated using the ASHRAE handbooks and climatological data from the National Oceanic and Atmospheric Administration (7).

The approximations contained in GROCS which may limit its accuracy are: 1) a small number (thirty) of finite elements are used; 2) no considerations are made for soil moisture movement or soil freezing; 3) constant soil properties are assumed; 4) temperature boundary conditions are imposed by the rigged blocks at a finite distance from the heat exchanger block; 5) a relatively large time step of several hours can be used to decrease computing time. Even with these approximations, BNL has proven the validity of GROCS by comparison of simulation predictions with experiments carried out over a period of several years. In most cases, using undistributed properties of a moist soil, GROCS temperature predictions were within 6°C of experimental results (8). Because of the validation and the availability of the program, GROCS is used in the present study to simulate horizontal earth-coupled heat pump systems.

Since the GROCS program has been made publicly available, other investigators have used it for simulation of earth-coupled systems. The most important modification of GROCS for the simulation of a horizontal pipe field is the calculation of the equivalent resistance of the pipes in the soil slab representing the pipe field. The equivalent resistance concept permits the calculation of average fluid temperature in the pipe. Kutateladze (9) presents the solution for the thermal resistance of a row of pipes of equal diameter and at equal temperature in a mass bounded by two parallel planes as:

$$R_{eq} = (1/2\pi k_s L)\ \ln[(s/\pi r)\ \sinh(\pi h/s)] \qquad (1)$$

where k_s = soil conductivity
L = length of pipe
s = distance between pipe centers
r = pipe outer radius
h = width of slab

In (9) R_{eq} is specified as:

$$R_{eq} = (t_{s1} - t_{s2})/Q \qquad (2)$$

where t_{s1} = temperature at the pipe surface
t_{s2} = temperature at the slab surface
Q = heat flow between the two boundaries

To get a total equivalent resistance, the resistance of the pipe wall may be added directly to R_{eq} . It can be shown that convection resistance between the fluid and the pipe is negligible compared to these two terms .

Now, the total resistance per unit length is given by:

$$\Omega = (1/2\pi k_s)\ln[(s/\pi r_o)\sinh(\pi h/s)] + (1/2\pi k_p)\ln(r_o/r_i) \qquad (3)$$

where all terms are as defined previously except for

r_o = outer radius
r_i = inner radius
k_p = pipe conductivity

Since heat flows are input data for the program, the fluid temperatures at the end of each time step can now be calculated as:

$$T_f = T_s + Q(\Delta t/168)(\Omega/L) \qquad (4)$$

where T_f = fluid temperature
T_s = slab temperature
Q = weekly heat input
Δt = time step
L = length of pipe field

The $\Delta t/168$ in equation (4) gives the fraction of weekly heat load withdrawn from the pipe slab during each time step.

This method of approximating fluid temperatures has been used and verified by researchers at Oklahoma State University. Bose (10) has found that predicted fluid temperatures were not more than 4.4°F off from those measured experimentally. He also concluded that this error may be higher during the cooling season due to the decrease in soil moisture caused by dumping heat in the pipe field.

In most horizontal closed-loop systems in use today, the pipe field has a back-and-forth or serpentine arrangement. The two most important parameters which describe this arrangement are pipe spacing, s, and depth of burial, b.

A typical pipe spacing is 1.5 meters and typical burial depth for a system which is to provide both heating and cooling is 1.3 meters (11).

The GROCS program also requires physical property data for the soil. In GROCS, constant property values are assumed. In reality, this is not the case; soil conductivity varies with moisture content, which changes as heat is conducted through the soil, changing soil temperature. However, it has been shown that a soil conductivity value representing a moist soil, 15 percent moisture by volume, will give results which compare favorably with experimental data (12). The parametric studies to be discussed later were run for the two limiting cases of dry and saturated soil as well as the in-between case for a moist soil.

As developed at BNL, the GROCS program uses a system of blocks to model underground heat flow problems and prints the temperature of each block at time intervals specified by the user. A useful model of a horizontal pipe field can be constructed by adding several steps to the program. The field itself may be modelled as a thin block, or slab, with the equations presented above (eqn. 3,4) to calculate fluid temperature from the slab temperature and field parameters. Additions to GROCS can also be made for the calculation of heat pump COP and electrical usage and cost.

With the approximation of fluid temperature mentioned above, the heat pump COP may be calculated for each time step. Average linear functions derived from several manufacturers' data were used to determine heating and cooling COP in the GROCS program. Pure resistance heating (COP=1) is used when the source temperature drops below a certain value (T_{min}). Electrical power required can be calculated from the COP and the amount of heat transferred during each time step.

The modified GROCS program can now be used to simulate a horizontal earth-coupled heat pump system. However, there are several limitations which affect the accuracy of the simulation results:

1) The approximations and assumptions of GROCS as discussed previously contribute to an inherent inaccuracy.
2) Heating and cooling loads, while reasonably accurate, are not exact.
3) During the heating season, the cycling between pipe field and pure resistance heat can only occur at the end of each time step. This has the greatest effect for short pipe lengths and low thermal conductivities. The heat pump is simulated as being used for the entire time step, at the end of which, coil temperature may be well below T_{min}.
4) The equivalent resistance concept is most accurate for a row of a large number of pipes. For shorter lengths, where only one or two legs of pipe are used, the calculated equivalent resistance may not be accurate.

To summarize the simulation capability of the modified GROCS program, an example problem will now be solved.

Problem: For the previously discussed residence and location, determine the performance of a horizontal field, closed-loop, earth-coupled heat pump which has the following characteristics:

PIPE FIELD:	
Length	400 meters
Depth	1.3 meters
Spacing Between Pipes	1.5 meters
Pipe Material	PVC
Inner Diameter	0.0508 meters (2 inches)
Wall Thickness	0.00476 meters (3/16 inch)
Thermal Conductivity	0.167 W/mK
SOIL:	
Thermal Conductivity	2.60 W/mK (15% moisture)
Volume Heat Capacity	1699000 J/m^3K
Thermal Diffusivity	5.51×10^{-3} m^2/hr

The first step in the solution to this problem is to obtain the input data which the program requires. The problem statement gives all physical data for the pipe field and soil. The parameters which define ground temperature - T_0, T_1, and p_0 - must be found for the given location and soil conditions. These three values can be found in ASHRAE Transactions, 1965 (13), as

$T_0 = 11.67°C$

$T_1 = 12.22°C$

$p_0 = -(0.65+\pi/2)$ (14)

The remaining input data must be taken from the physical model of the buried pipe field. A cross-sectional view of one possible model is shown in Figure 1. This figure shows a series of numbered free blocks surrounded by rigged blocks (numbers underlined). This particular model was conceived by considering several factors. Where large heat flows are expected, small blocks should be used for a more accurate solution. The maximum depth was chosen approximately equal to the depth of penetration of annual temperature variations (15).

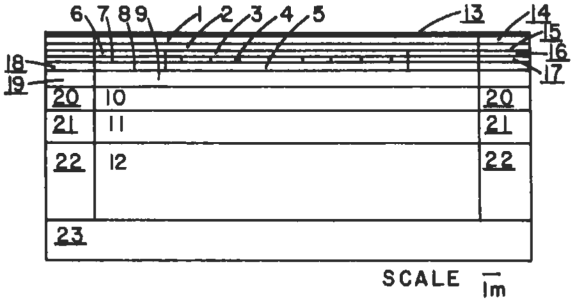
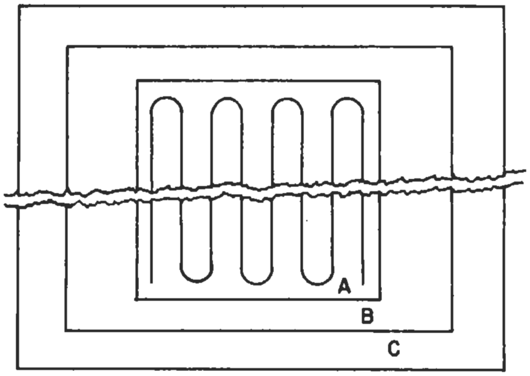


Fig. 1: Cross-sectional view of horizontal pipe field model.

Fig. 2: Plan view of a horizontal pipe field model.



Daily temperature variations are not considered since their depth of penetration is only on the order of centimeters (16). The specified field depth and pipe spacing were maintained in block four. The closer a rigged block is to the surface, the greater its seasonal temperature variation will be. Therefore, rigged blocks near the surface were kept thin for a more accurate temperature portrayal.

A better idea of the three dimensional nature of this model can be obtained with the plan view shown in Figure 2. The letters, A,B, and C, in this figure are for reference only and are not used in the program. The pipe field slab (#4) and one slab immediately above (#3) and below (#5) are represented by area A. These slabs are surrounded by slabs 6, 7, and 8, which are represented by area B. Slabs 1, 2, 9, 10, 11, and 12 are the size of areas A and B combined. Rigged blocks 14-22 are represented by area C, and the two blocks on top and bottom (#13 and #23) are the size of areas A, B, and C combined. Essentially, this model is a set of blocks within boxes.

The dimension information required by GROCS can be measured or calculated from Figures 1 and 2. Depth of center of each block can be measured from Figure 1. The volume of the free blocks can be calculated using both figures. Heat transfer area and distance between centers of each interacting pair can be measured from Figure 2.

Weekly heat inputs and withdrawals to block four are obtained from calculations of heating and cooling loads mentioned earlier. Based on the maximum heat loss occuring in week four of 32450 BTU/hr., a three ton heat pump was selected. The capacities and power requirements for a specific three ton heat pump were also used in the program. All other required data has been discussed above.

In this run of GROCS, the simulation was started in week 46 and continued until the end of the next year. A time step of six hours was used. Two graphs of example results are shown with time, in weeks, on the horizontal axis.

Figure 3 shows weekly average coil temperatures. The curve is generally sinusoidal with two discontinuities. The first occurs at week six and was caused by the use of resistance back-up heating. During week six, the simulation shows that resistance heating was used for six hours. This would imply that the coil cannot maintain at least T_{min} during this week. The GROCS program handles this situation by cycing between the back-up system and the heat pump. During a time step when the back-up system is in use, no heat is withdrawn from the coil; and it has time to recover by absorbing energy from the surrounding earth. When the coil has recovered sufficiently to give an average temperature above T_{min}, the heat pump and coil will be used during the next time step. The second discontinuity occurs when the change is made from heating mode to air conditioning mode and back. The first addition of heat to the coil from the heat pump as an air conditioner increases the coil temperature, causing the slight jump at week 21. The opposite effect is seen at week 39 when the system switches back to heating.

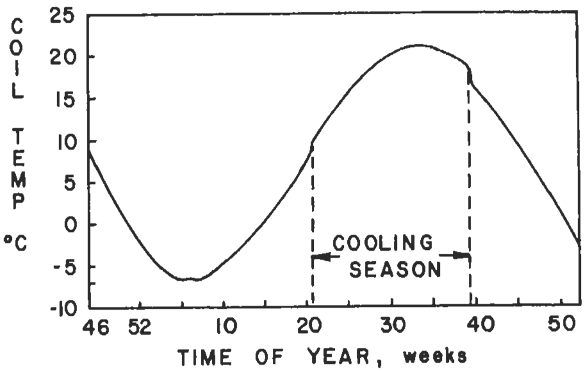


Fig. 3: Average weekly coil temperature vs. time of year.

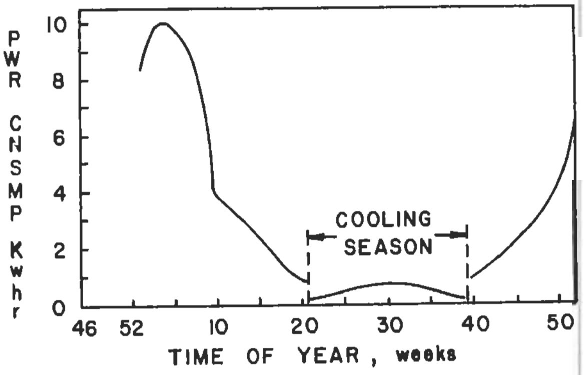


Fig. 4: Average weekly power consumption vs. time of year.

Figure 4 shows weekly power usage vs. time. During the period when resistance heating is being used, either as supplementary or back-up, power consumption increases dramatically. Also, during the cooling season, the electricity required is about 10 percent of that used during the heating season.

To determine optimum configuration, a parametric study is conducted on two important values: length of the pipe field and pipe diameter. The effect of different pipe materials is also briefly considered. GROCS runs are made for lengths from 50 to 600 meters. Using these results, an economic analysis is performed to determine an optimum length. Using this optimum length, the diameter is varied to find its influence on performance.

PIPE LENGTH VARIATION

The effect of length on several performance factors is shown in Figures 5-7. These curves all show large variations with length under 300 meters and a leveling-off trend for greater lengths.

Figure 5 shows COP vs. length for both the heating and cooling season. Both curves show an increase in seasonal COP as field length increases. With longer coils, more heat can be removed from or rejected to the earth. The cooling season curve levels off much sooner than the heating season curve, which is still increasing slowly at 600 meters. This result is most likely due to the shorter cooling season and its much smaller loads.

Operating costs are directly related to COP through power consumption. Total annual operating

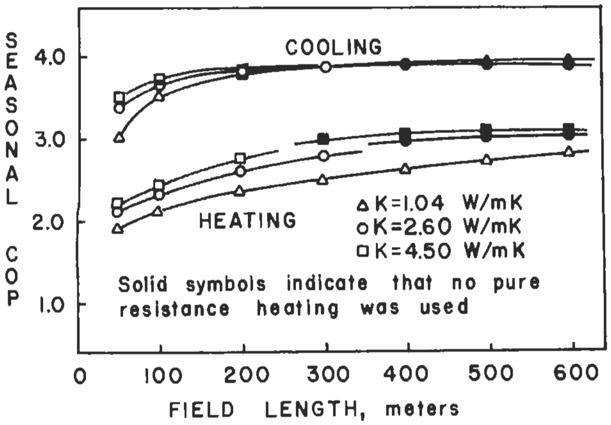


Fig. 5: Heating and cooling COP vs. pipe field length.

cost vs. length is shown in Figure 6. This curve shows cost decreasing as length increases. The cost decreases as COP increases (refer to Fig. 5), since with a higher COP less electricity is needed to run the heat pump.

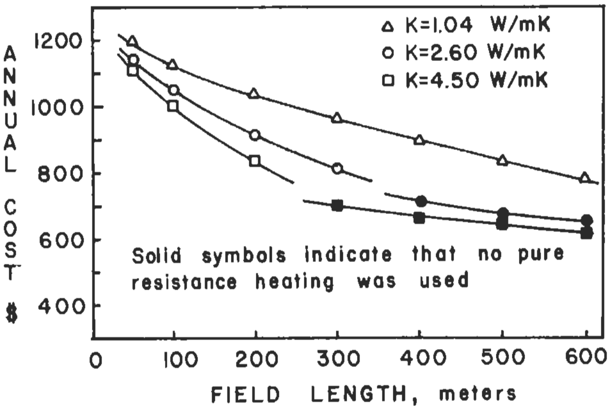


Fig. 6: Annual Operating cost vs. pipe field length.

For this study, the back-up system is assumed to be electrical resistance heating. Supplemental resistance heat is also used at low source temperatures where the capacity of the heat pump is smaller than the load. The percentage of the total heat demand which can be met by the heat pump alone is called the load fraction of the system. Figure 7 shows a graph of load fraction vs. length. For long field lengths and high thermal conductivities, the load fraction approaches 1.0. As field length decreases, load fraction decreases. The solid symbols in all three figures represent systems which required no pure resistance heat. That is, the average coil temperature of these systems was never below T_{min}. However, all of the systems studied did require some supplemental resistance heat.

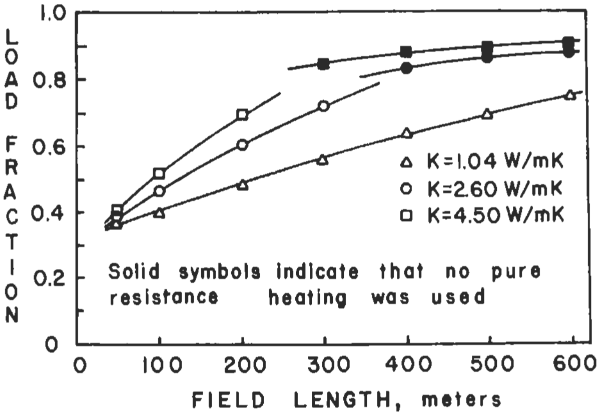


Fig. 7: System load fraction vs. pipe field length.

ECONOMIC ANALYSIS

This economic analysis will be conducted based on several assumptions about the homeowner and his/her heating system: The homeowner is currently heating with an oil furnace and a forced air system. There is no central air conditioning. The homeowner feels that it is time to replace the oil furnace, and the homeowner wants air conditioning capabilities with the new system. He/she is considering two alternatives: an air-to-air heat pump and the earth-coupled system described in previous sections of this paper. The homeowner wants to know which system will be more economical and how long it will take for the energy savings of the better system to make up for the initial investment. If the earth-coupled system is better, he/she also wants to know how much pipe is needed to bury in the yard.

A payback period or break-even analysis is a simple way of looking at the economic advantages of one particular system over another. Generally speaking, an air-to-air system will cost less, but be more expensive to operate than the earth-coupled system. In this case, the cumulative value of energy saved by the earth-coupled system is compared for each year to the current value of an alternative investment. The alternative investment is the difference in the initial cost of the two systems, and its current value is determined by inflation and interest rates. The payback period is the amount of time it takes for the cumulative energy savings to equal the current alternative investment value.

In order to calculate the value of the alternative investment in current dollars at any future time, the rate-of-return (after taxes) and the inflation rate must be estimated. Assuming that these values are constant throughout the life of the system, the value of the alternative investment is given by (17):

$$V_i = I[(1+t)^i/(1+r)^i] \qquad (5)$$

where
I = initial investment
t = after tax rate-of-return
r = inflation rate
i = a given year during the life of the system

The value of the energy saved by the earth-coupled system depends on the fuel price escalation rate (above inflation), the inflation rate, and the value of the energy saved per year. The value of cumulative energy savings after i years is given by (18):

$$X_i = E \sum_{n=1}^{i} [(1+e+r)/(1+r)]^n \qquad (6)$$

where E = value of energy saved per year
e = fuel price escalation rate

The net present value, P, of the system is defined as the cumulative energy savings minus the current alternative investment value:

$$P_i = X_i - V_i \qquad (7)$$

Since fuel savings over one year are small relative to the initial investment, P starts out negative. However, as these fuel savings accumulate, at some point the total fuel savings will be greater than the value of the investment at that same point. This break even point occurs when P becomes positive.

The annual energy consumption of the earth-coupled system is determined in the modified GROCS program. To determine the payback period, the energy consumption of an air-to-air heat pump must be known or calculated. For the heating season, this is most often done by the bin method. This method consists of calculating the rate of heat loss which occurs at many different outdoor temperatures and multiplying each rate by the number of hours of occurence of each temperature. The outdoor temperatures are usually grouped into "bins" of 5°F. The capacity and power input of the air-to-air heat pump must also be known at each bin temperature. The bin method is described in detail in the ASHRAE 1981 Systems Handbook, chapter 43. The hourly temperature occurences used are for Columbus, Ohio, and the heat pump capacity and power consumption are for a typical three-ton heat pump. Results from the bin method analysis gives a total heating power consumption of 19642.9 Kwhr.

Although it could be applied, the bin method is not generally used for cooling. Instead, the equivalent full load hours procedure is used. This procedure consists of using an estimate of the ratio of annual cooling energy requirements to rated energy input of the cooling equipment (19). For a residential air-to-air heat pump, ASHRAE gives an estimate of 1.63 Kw/ton including auxiliary components, and also gives an equivalent full load hours of operation for Columbus, Ohio of 800 hrs. So the cooling energy requirements can now be approximated by:

Cooling Kwhr = (1.63 Kw/ton)(3 ton)(800 hrs)
= 3912 Kwhr

To determine the value of the energy saved by the ground-coupled system, power consumption is divided into heating and cooling, each having different cost rates.

Several other costs and parameters are needed to procede with the economic analysis. Costs for three ton air-to-air and water-to-air heat pumps have been provided as $2510 and $4150, respectively (20). The water-to-air heat pump is more expensive mainly because it has some higher cost components and because the demand for water-to-air heat pumps is lower than for air-to-air heat pumps. The cost of excavation and burial of the pipe field is estimated to be $1.25/ft(21). Electricity is assumed to be supplied by utilities at 4.5¢/Kwhr during the heating season and 6.5¢/Kwhr during the cooling season (22). Inflation rate, fuel price escalation rate, and rate-of-return are estimated as 0.06, 0.02, and 0.075, respectively (23). Operating and maintenance costs and life of 20 years are assumed to be the same for both systems.

For the example problem given above, the payback period is calculated to be 7.74 years.

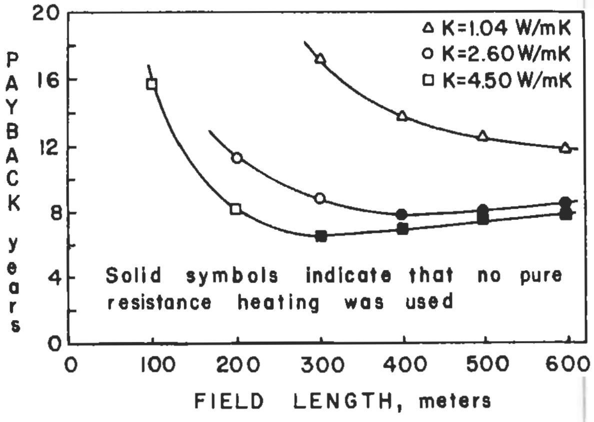


Fig. 8: Payback period vs. pipe field length.

Figure 8 is a graph of payback period vs. length for the three soil conductivities. In this figure, the two higher thermal conductivities show a minimum payback period of 6.57 years for k = 4.50 W/mK, and 7.74 years for k = 2.60 W/mK. The payback curve for k = 1.04 W/mK is still decreasing at 600 meters, and shows no minimum. As mentioned earlier, k = 2.60 W/mK should give results closest to those to be expected from an actual installation. On that basis, it can be concluded that a length of 400 meters will give the minimum payback period of 7.74 years. It also appears from Figure 8 that this minimum payback occurs at the shortest length which requires no pure resistance heat.

The effect of assumptions made about the rates can be seen by examining simple payback for the optimum system. Simple payback is found by assuming that e=0.00, and that t=r. The optimum system for the intermediate conductivity has an initial expenditure of $5790, and annual fuel savings of $435.16. This leads to a simple payback period of 13.3 years.

Another way of looking at the economic feasibility of the earth-coupled system is to examine the life cycle savings (the total energy savings over the life of the system). This data has already been calculated as part of the payback analysis and is shown graphically in Fig. 9. Over the 20-year life of the system, the optimum length will save the homeowner $10,652. Even though there is a minimum payback at an intermediate length, the life cycle savings continue to increase with increasing lengths.

PIPE DIAMETER VARIATION

The economic analysis of the last section gave optimum lengths for the two higher soil conduc-

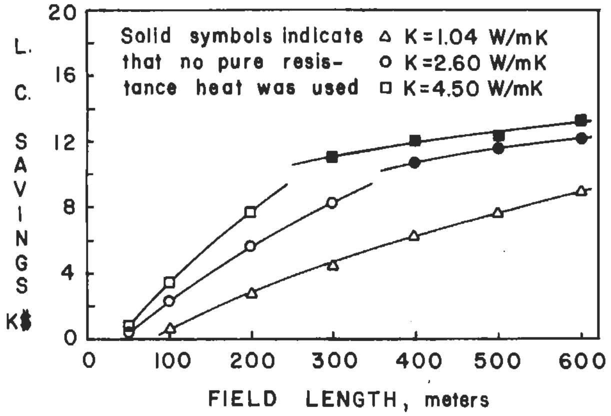


Fig. 9: Life cycle savings vs. pipe field length.

tivities. With these lengths, several GROCS runs were made to determine the diameter which gives the best thermal performance.

There are several factors which limit the pipe diameter that can be used in a ground-coupled system. Diameter is physically limited by the excavation method used. Most pipe is only manufactured in discrete, standard sizes such as 1", 1½", 2", or 3". In the modified GROCS program, the pipe field is represented by a thin slab. The diameter that can be simulated is restricted in the vertical direction by the thickness of this slab. The spacing between pipes restricts simulated diameter in the horizontal direction. To determine the effect on performance of diameter, three pipe sizes will be simulated: 1½", 2", and 3".

Figure 10 shows heating and cooling COP vs. diameter for three standard pipe sizes. Pipe diameter has very little effect on cooling season COP. Heating season COP increases slightly with increasing diameter. This is probably due to the fact that a larger pipe has a greater surface area that can absorb heat from the ground.

The annual cost curve is shown in Figure 11. Electrical costs increase as diameter decreases, because more electricity is needed by the heat pump to extract the required heat from the ground with the smaller available surface area.

The load fraction curve of Figure 12 shows that a decrease in diameter causes a decrease in load fraction. In the last section, it was determined that the shortest pipe field which required no pure resistance heat was the optimum length. By that same reasoning (smallest diameter which requires no pure resistance heat), the two inch pipe appears to be the optimum diameter. In all three Figures, the solid symbols represent systems which do not use pure resistance heat.

PIPE THERMAL CONDUCTIVITY VARIATION

To examine the effect of pipe material on system performance, a GROCS run was made for the optimum configuration (400 m pipe length, 2 in. diameter, soil conductivity of 2.60 W/mK) using a pipe conductivity for polyethylene of 0.391 W/mK. These results are compared to those for PVC pipe (k = 0.167 W/mK) in Table 1. As can be seen from this table there is a noticeable improvement in performance when a pipe with a higher thermal conductivity is used. Heat can be transferred through the pipe walls quicker if the thermal resistance is smaller.

SUMMARY OF OPTIMUM SYSTEM

A technically and economically feasible method for increasing the performance of a heat pump for residential space heating has been studied in this paper. This method consists of extracting heat from the earth with a fluid that is circulated through an underground pipe field. Of several general computer simulation methods that were reviewed, one was chosen and modified to predict the performance of a horizontal, closed-loop, earth-coupled heat pump system. This computer simulation was used in conjunction with a specific house (2000 ft^2) and climate (Columbus, Ohio). Pipe lengths of 50 to 600 meters were simulated and an optimum length was determined by an economic analysis. With pipe length fixed at this optimum value, several pipe diameters were simulated, and an optimum diameter was selected. It was also shown that an

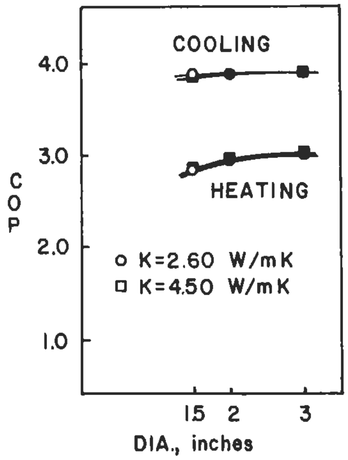


Fig. 10: Heating and cooling COP vs. pipe diameter.

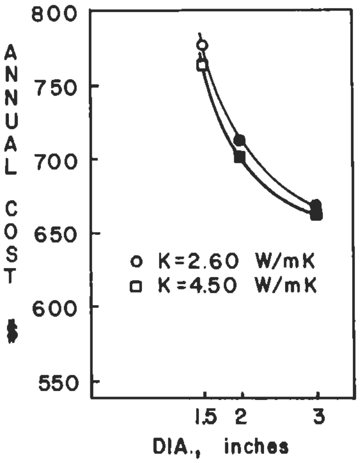


Fig. 11: Annual operating cost vs. pipe diameter.

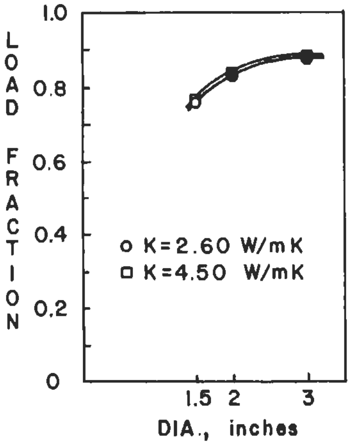


Fig. 12: System load fraction vs. pipe diameter.

Table 1: Comparison of results for two different pipe materials.

	R13 (PVC)	R33	%Impr. R33-R13 / R13
Heating COP	2.69	2.76	2.6
Cooling COP	3.83	3.85	0.5
Heat Pump Kwhr (Heating)	10154	9473	6.7
Suppl.Res.Heat (Kwhr)	5009	3801	24.1
Pure Res.Heat (Kwhr)	54	0	--
Heat Pump Kwhr (Cooling)	911	906	0.5
Total Cost, $	713.51	656.24	8.0
Load Fraction	0.833	0.874	4.9
Payback, yrs.	7.74	6.96	10.1
LCS, $	10652	11798	10.7

increase in pipe thermal conductivity had a slight beneficial effect on performance.

The optimum configuration for an earth-coupled heat pump for the residence has been determined to be as follows:

Length	400 m (1312 ft)
Pipe diameter	2 inches
Spacing	1.5 m (4.9 ft)
Depth	1.3 m (4.2 ft)
Pipe Material	polyethylene

This system will have a payback period of 6.96 years, and a life cycle savings of $11,798.

CONCLUSION

The main purpose of this paper has been to describe a method of simulating an earth-coupled heat pump system. These systems, generally more efficient than air-to-air heat pumps, are in limited use today. This is mainly because of high initial cost and the lack of a method to accurately predict performance. Most of the methods presented in this paper are based on previously documented work. In order to develop these methods into a useful design tool, they would have to be used in conjunction with data from actual installations in different climates and modified, if necessary, to accurately model real systems. The author invites contact from readers of this paper who may possess performance data from horizontal or vertical closed-loop, earth-coupled heat pump systems in order to develop design tools.

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