THE DESIGN OF GROUND-COUPLED HEAT PUMP SYSTEMS

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ABSTRACT

Ground-coupled heat pumps are being installed in increasing numbers due to proven performance and economy.

The overall thermal resistance between the ground coupling fluid and a given type of surrounding soil is affected by pipe material, wall thickness, diameter and length, the spacing and depth of burial, and the resistance of the flowing fluid. An important variable affecting performance is the thermal conductivity of the soil in which the ground coupling device is buried.

The optimum ground-coupled system considers initial investment and operating costs on a discounted basis. The large number of variables affecting both first cost and performance makes the optimum difficult to determine. This paper discusses design tradeoffs and significant factors which determine performance.

NOMENCLATURE

A_s = Annual surface swing, °C (F)

D = horizontal pipe depth, m (ft)

I(X) = values of integral at $X = \frac{r}{2\sqrt{\alpha t_1}}$, see Table 1.

L = coil length, m (ft)

Q′ = heat rate, W/m (Btu/h·ft)

T = temperature at a distance r, °C (F)

T_m = Mean earth temperature °C (F)

T_o = normal or undisturbed earth temperature, °C (F)

U_s = soil thermal conductance per unit length W/m·°C (Btu/h·ft·F)

$\dot{q}$ = heat rate, W (Btu/h)

r = radial distance from line source, m (ft)

r = pipe radius - m (ft)

t = Time, days, s or hrs

t_o = Phase constant or day of minimum surface temp, days

x = Soil depth, m (ft)

α = thermal diffusivity of soil, m^2/s (ft^2/hr) or m^2/day (ft^2/day)

β = variable of integration

INTRODUCTION AND OVERVIEW

THE GROUND COUPLED HEAT PUMP CONCEPT

Ground coupled heat pumps are closed-loop systems designed to use the earth as a heat source and/or sink. Thermal contact with the earth is usually accomplished with a long piece or several pieces of plastic pipe, buried horizontally or vertically in the ground. Water or a brine is circulated through the pipe, transferring thermal energy to or from a heat exchanger in the heat pump. This heat exchanger serves as the condenser or the evaporator, depending upon whether the heat pump is in a cooling or a heating mode. A very good history of ground coupled devices and systems up through 1981 is given by Ball, Fischer and Talbert (1).

Ground-coupled heat pump systems may be placed horizontally or vertically, as shown in Figure 1 and may be of the series type or of the parallel multiple type, Figure 2.

Advantages over the use of air as a source or sink include:

1. The ground is usually at a more favorable temperature than the air.
2. The liquid-refrigerant exchanger permits a closer approach than an air-refrigerant exchanger.
3. There is no concern with frost removal.

The ground coupled system usually shows improved seasonal performance factors in heating and improved seasonal energy efficiency ratios in cooling when compared to air source systems. The usual interest is in evaluating the energy savings versus the extra initial investment.

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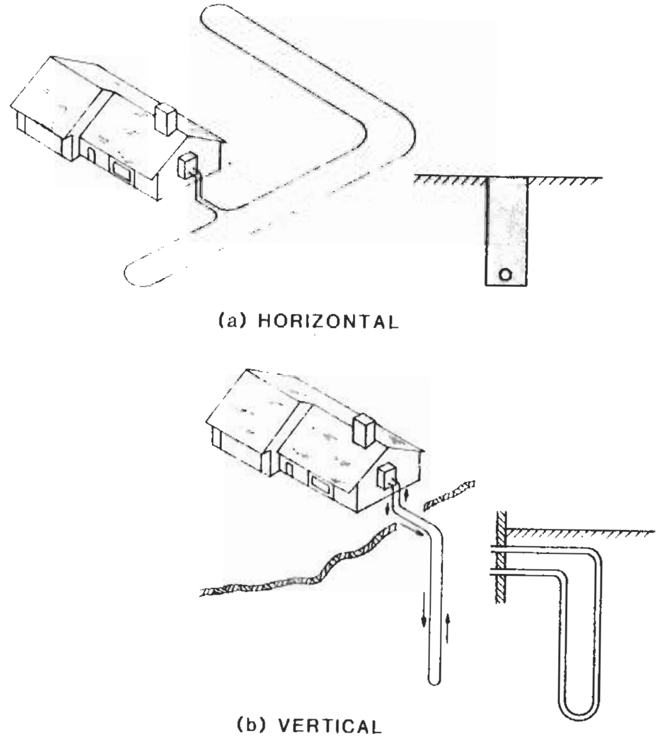

Figure 1. Types of Closed Loop Systems

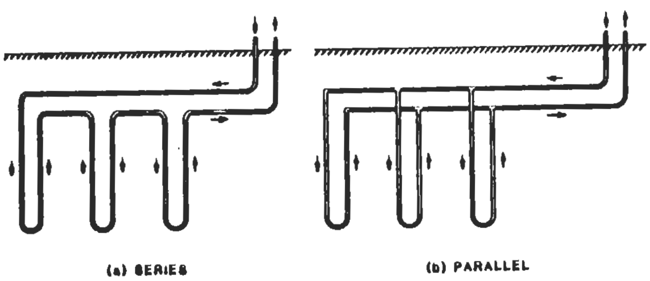

Figure 2. Multiple Closed Loop Vertical Coupling Systems

EARTH TEMPERATURE VARIATIONS

Earth temperatures have a significant effect on the performance of ground coupled systems. The yearly average of the daily ambient temperatures at a specific location is approximately the same as the deep ground temperature at that location. The temperature of the earth at a given depth is not only dependent on average ambient air temperature and the annual earth temperature swing but is greatly affected by the type of soil. As the depth is increased, the temperature variations decrease and the phase lag compared to the surface temperature is increased. The annual temperature remains constant at a value T_m at increased depth. Equation 1 can be used to calculate the earth's undisturbed temperature at a given depth for a specific location and time of year (2).

$$T(x,t) = T_m - A_s \exp\left(-x\left(\frac{\pi}{365\alpha}\right)^{1/2}\right) \cos\left\{\frac{2\pi}{365}\left(t - t_o - \frac{x}{2}\left(\frac{365}{\pi\alpha}\right)^{1/2}\right)\right\} \quad (1)$$

In the heating mode, as heat is removed by the ground exchanger, the local earth temperature decreases with time. For a given system, the decrease in temperature will depend on soil type and moisture content. In the cooling mode, where heat is added to the ground, local soil temperatures increase above normal values with time of operation.

THERMAL BEHAVIOR OF GROUND-COUPLED SYSTEMS

Because of the changes in local ground temperature, the average temperature of the fluid circulating in the ground exchanger continually increases in the cooling mode and continually decreases in the heating mode as the system continues to operate. The main concern in design is that the circulating fluid temperatures be kept within some limits to prevent wear or damage to the heat pump and to ensure efficient operation. The long term effect of ground coupling is also of interest. If there is a net removal or addition of energy over an annual cycle then the ground temperature will continue to change yearly. In the northern climates, where only heating occurs, the ground may freeze around the earth coil. If there is not sufficient heat addition to the ground exchanger during the summer, either from the sun-warmed surface soil or other means, then the soil may not thaw before the beginning of the next heating season. If this continues each year the ice formed around the ground exchanger will continue to increase in size and the heating performance of the system will decrease each year. A similar opposite situation could exist in areas where the cooling cycle dominates.

DETERMINATION OF SOIL RESISTANCE

The operation of a ground-coupled heat pump system depends on the heat transfer between the ground coupling device and the surrounding soil. This heat transfer determines how closely the circulating fluid, returning to the heat pump, can approach the local ground temperature. This heat transfer is conveniently described in terms of a time dependent thermal resistance between the circulating fluid in the buried pipe and the undisturbed soil. This concept of resistance simplifies the description of the entire subground system - the fluid, the coupling device and the soil surrounding that device. This resistance involves the makeup of the pipe system as well as the characteristics of the soil.

The resistance of the soil is usually a dominant factor in this overall thermal resistance and the effect is sometimes referred to as the "soil resistance". A better description for the apparent thermal resistance between the outer exchanger surface and the undisturbed ground might be "field resistance". To account for the transient behavior of the system, this field resistance in the soil is considered to change with time, even though all soil properties might be constant. The field resistance in the soil should not be confused with soil resistivity which is a true property of the soil. The reciprocal of resistivity is the thermal conductivity, which is also a property.

The thermal conductivity of most soils is highly dependent upon the moisture content of the soil and may undergo a seasonal change depending on the climate and the history of heating and cooling that the ground coupling device has undergone. When a pipe is transferring heat to the soil, moisture tends to be driven away from the vicinity of the pipe. When the pipe is cooling, soil moisture is drawn toward the pipe. Thus, one might expect soil dryout and increased resistance to heat transfer to be a definite possibility near the end of a dry cooling season, but to be of no concern to heating only heat pump systems.

A method for estimating soil resistance will now be developed. Ingersoll and Plass (3) have shown that the Kelvin line source theory can be used to estimate the change in temperature of a buried pipe in which heat is being absorbed or rejected. The theory has been widely used in ground-coupling design, and when used properly appears to give useful results. It is especially useful for showing trends. The equation is usually expressed as

$$T - T_o = \frac{Q'}{2\pi k_s} \int_{\frac{r}{2\sqrt{\alpha t_1}}}^{\infty} \frac{e^{-\beta^2}}{\beta}\, d\beta \qquad (2)$$

or

$$= \frac{Q'}{2\pi k}\ I(X) \qquad (3)$$

Values of I(X) for X < 0.2 are given at the top of Table 1. The soil thermal diffusivity (α) is a defined property and is the ratio of the thermal conductivity (k_s) and the heat capacity (ρc). Therefore the three soil properties thermal conductivity (k_s), density (ρ), and specific heat (c) must be known or estimated to predict the thermal behavior of ground heat exchangers.

Equations 2 or 3 may be used to give an estimate of the temperature at the buried pipe outer surface at a given time for a known heat flow rate. The specific assumptions used in Equations 2 and 3 are:

1. Soil properties are uniform and constant, i.e., soil thermal conductivity, density and specific heat remain constant for all depths and time. This assumption is limited by whether significant changes in moisture may occur and whether the soil may be non-uniform.

2. The heat flow rate per unit of pipe length is constant over the time period (t_1). This is not the usual condition in heat pump operation, since most units cycle on and off in an irregular manner.

3. The heat sink/source is considered to be a line source, i.e., very long and of extremely small diameter. This assumption can be met to a good approximation by most systems.

Table 1. Values of the Integral I(X) for Various Values of X

(For X < 0.2, $I(X) = 2.303 \log_{10} 1/X + X^2/2 - X^4/8 - 0.2886$.)

X	I(X)	X	I(X)	X	I(X)
0.0001	8.9217	0.16	1.5567	0.62	0.3646
0.0002	8.2286	0.17	1.4977	0.64	0.3433
0.0003	7.8231	0.18	1.4423	0.66	0.3231
0.0004	75354	0.19	1.3900	0.68	0.3041
0.0005	7.3123	0.20	1.3406	0.70	0.2860
0.0006	7.1300	0.21	1.2938	0.72	0.2690
0.0007	6.9758	0.22	1.2494	0.74	0.2529
0.0008	6.8423	0.23	1.2072	0.76	0.2377
0.0009	6.7245	0.24	1.1669	0.78	0.2234
0.0010	6.6191	0.25	1.1285	0.80	0.2098
0.001	6.6191	0.26	1.0917	0.82	0.1970
0.002	5.9260	0.27	1.0565	0.84	0.1849
0.003	5.5205	0.28	1.0228	0.86	0.1735
0.004	5.2329	0.29	0.9904	0.88	0.1627
0.005	5.0097	0.30	0.9594	0.90	0.1525
0.006	4.8274	0.31	0.9295	0.92	0.1429
0.007	4.6733	0.32	0.9007	0.94	0.1339
0.008	4.5397	0.33	0.8731	0.96	0.1253
0.009	4.4220	0.34	0.8464	0.98	0.1173
0.010	4.3166	0.35	0.8206	1.00	0.1097
0.01	4.3166	0.36	0.7958	1.02	0.1026
0.02	3.6236	0.37	0.7718	1.04	0.0958
0.03	3.2184	0.38	0.7487	1.06	0.0895
0.04	2.9311	0.39	0.7263	1.08	0.0836
0.05	2.7084	0.40	0.7046	1.10	0.0780
0.06	2.5266	0.42	0.6634	1.20	0.0547
0.07	2.3731	0.44	0.6247	1.30	0.0379
0.08	2.2403	0.46	0.5884	1.40	0.0259
0.09	2.1234	0.48	0.5543	1.50	0.0174
0.10	2.0190	0.50	0.5221	1.60	0.0115
0.11	1.9247	0.52	0.4919	1.70	0.0075
0.12	1.8388	0.54	0.4634	1.80	0.0048
0.13	1.7600	0.56	0.4365	1.90	0.0030
0.14	1.6873	0.58	0.4112	2.00	0.0019
0.15	1.6197	0.60	0.3872	2.20	0.0007

In addition to how well the above assumptions fit and how well the heat flow rate is known, the accuracy of the solution will depend upon the reliability of the available thermal conductivity, density, and specific heat data. The extreme soil conditions (minimum moisture content, etc.), heat pump characteristics, temperature limitations and building loads will determine the required ground exchanger length.

The time (t_1) in Equations 2 or 3 is measured from the beginning of the heating/cooling season to the time where "design conditions" occur, presumably the hottest or coldest day anticipated late in the season when soil conditions are at their worst due to the cumulative effects of operation. The best estimate would be the time to the last "maximum" daily demand of the seasons, obtained from a daily estimation of the building heat gain/loss.

Equations 2 and 3 assume a uniform heat flow rate per unit of pipe length (see assumption #2 above). Since this is rarely true in an actual heat pump system one would naturally question how the equations might be used and whether any results obtained could be meaningful. It has been found through a large number of computations using Equations 2 and 3 that long term buildup effects of heating can be closely approximated by assuming that all of the heat input (or removal) occurring during the previous part of the season has occurred at a uniform rate, with the total input (or removal) equal to the actual total. The following operational conditions also affect the temperature cycle:

1. The heat rejected during the cooling season consists of the building load plus the heat energy required to drive the heat pump system.
2. During heating cycles, the heat energy supplied to the building is the energy from the ground plus the heat energy required to drive the heat pump system.

The short term effects of cycling can be superimposed on the long term solutions to give temperature predictions that are accurate enough for design purposes. Thus the Kelvin line source theory has been found to be a useful tool for determining the temperature difference between the outer surface of a ground coupling device and the undisturbed earth temperature as the season progresses.

Because it is the circulating (return) water temperature that is of interest, and not the pipe outer surface temperature, one must also consider the temperature changes in the fluid and across the pipe wall. It will be convenient to introduce the concept of resistance to make these calculations. Equation 3 can be rearranged in the following form:

$$Q' = \frac{2\pi k_s}{I(X)} (T - T_o) \qquad (4)$$

Letting $\dot{q} = Q'L$ and $U_s = \frac{2\pi k_s}{I(X)}$

$$\dot{q} = \frac{2\pi k_s L(T - T_o)}{I(X)} = U_s L(T - T_o) \qquad (5)$$

Soil resistance R_s is defined as the reciprocal of the conductance, U_s, or

$$R_s = \frac{1}{U_s} = \frac{I(X)}{2\pi k_s} \qquad (6)$$

R_s is the soil's resistance to heat flow, which, like U_s, is dependent upon operating time, soil type, and moisture content. Once the soil resistance is determined the pipe resistance and convective resistance of the fluid flowing in pipe can be added to give an overall resistance to heat transfer between the fluid and the undisturbed ground.

The Kelvin line source method assumes that the source or sink is in an infinite homogeneous conducting medium. The method gives the temperature distribution with time in the soil around a pipe with acceptable accuracy when the pipe is far from the ground surface or other pipes that may be heating or cooling. Vertical ground coupling devices usually require only minor corrections due to ground surface effects. The nearby presence of the ground surface for horizontal systems, and the presence of nearby pipes for both horizontal and vertical systems requires that the line source method be modified.

If one assumes that the buried pipe is near an adiabatic surface, that is a surface across which there is no heat flow, then one has a semi-infinite medium instead of the infinite medium which was assumed for the line source method. The solution for this case is obtained by imagining that an image or mirror source of the same strength as the original source exists in a matching semi-infinite medium and is at an equal distance on the other side of the adiabatic surface. The two systems together then consist of two parallel line sources of equal strength in an infinite medium with an adiabatic surface an equal distance from each source. Since the line sources are of equal strength it can be seen that the plane which is equal distance from each must be adiabatic because of symmetry.

The temperature distribution (and thus the resistance) at any time can be obtained by solving for the temperature around each source assuming it is in an infinite medium and ignoring the other source. The two solutions are then added to give an approximation for the temperature distribution for a single pipe near an adiabatic surface.

The above method could be used to determine the temperature distribution and the soil thermal resistance around a buried horizontal pipe. The assumption that the surface of the ground is adiabatic is not exactly true in every case but appears close to the actual condition in the critical seasons of heating and cooling. During the cooling season for example, the effect of the hot ambient air and soil temperatures near the surface is to make much of the heat flow from the pipe into the ground.

Solutions also exist for heat transfer from a pipe or pipes to a plane isothermal surface. This condition exists with buried pipes that are gaining or losing heat with the surface of the ground (which is assumed to be at some constant temperature). This situation would be more likely to exist when the pipe and deep soil temperature is greatly different from the surface or ambient temperature.

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Solutions for the isothermal surface case are also obtained by using the line integral method and the method of images. In the isothermal case however the image or mirror is assumed to be a sink, with equal strength but of opposite sign to the original line source. The adiabatic assumption gives decreasing thermal resistance values as the pipe is buried more deeply whereas the isothermal assumption gives thermal resistance values that get larger with increasing depth of burial.

In most horizontal ground coupled systems there is substantial heat transfer downward into the earth as well as some heat flow upward to the surface. The ignoring of heat transfer downward or to the surface is likely to lead to some oversizing ground coupling systems. A conservative calculation would assume that the ground surface is adiabatic. The ground surface effects would be obtained by using the mirror image pipe of the same strength and the same sign as the buried pipe. Thus the presence of a ground surface would make the soil resistance larger than that for a pipe buried infinitely deep. This soil resistance will decrease as the pipe is buried more deeply.

Using superposition for horizontal exchangers, Equation 3 is modified to give:

$$T - T_o = \frac{Q}{2\pi k_s} [I(X_r) \pm I(X_{2D})] \qquad (7)$$

For the buried pipe use of the plus or minus sign depends upon whether the adiabatic or isothermal assumptions is used. Values of soil resistance for various piping arrangements are given in references (2) and (4).

MULTIPLE PIPE SYSTEMS

The placing of multiple pipes in a single trench decreases the length of trench required compared to a single pipe system. Because of thermal interference between pipes in near proximity, the total length of pipe required for the multiple pipe system is greater for the same earth coil load. The length of pipe required will vary with the diameter of the pipe spacing and soil properties. The resistance of multiple pipes can also be determined by using the superposition of line source solutions. The equations are of the same form as Eq. 7, using the adiabatic assumption, and are applied consecutively to a pipe for each surrounding pipe. Symmetry usually reduces the work somewhat. The result is an increased pipe temperature for a given heat flux from multiple pipes. This can be related to increased soil or field resistance for the ground coupled array. When compared to the soil resistance of a single pipe buried at the same depth in the same soil a reduction ratio can be determined. The reduction ratio is a ratio of the trench length required for a multiple pipe system compared to a single pipe system for the same load. If a single pipe system required 1000 feet of trench and the reduction ratio for two pipes in a trench is 0.57, the trench length for a two pipe system would be 1000 x 0.57 = 570 feet. The pipe length required is 1140 feet.

Drier, less conductive soil will result in lower performance of single pipe in comparison to multiple pipe systems. This is a result of greater thermal isolation by the less conductive soil between the pipes. In general, as the soil becomes drier, larger diameter pipe and multiple pipes in the same trench indicate improved thermal performance. Based on thermal analysis, economic analysis that considers costs associated with trenching, pipe and labor costs will dictate the earth exchanger configuration.

VERTICAL SYSTEMS

The vertical ground coupled system sometimes shows an advantage over the horizontal systems because ground surface effects are less. In addition the vertical system often has a large portion of its length below the water table, giving low soil resistance effects, and is often helped by ground water movement.

It is difficult to construct a vertical system that is free of pipe interference effects (thermal short circuiting) since both return and delivery pipes must be placed in the same hole. Heat transferring between the descending and ascending pipes reduced performance, and this effect increases with length of hole. The short circuiting effect is usually small enough, compared to total heat exchange, to make this system performance acceptable.

Vertical ground heat exchanger piping configurations can be classified as U-tubes, divided tubes, and concentric tubes, Figure 3. The heat exchanger was fabricated from PVC with interconnecting piping of polyethylene. Divided vertical tubes are subject to relatively high short circuit heat loss when used in parallel flow arrangements. In series flow patterns the temperature difference between the up and down tubes is smaller than in the parallel arrangement and short circuiting is less significant. PVC (k = 0.08 Btu/hr-ft ^{o}F) is a better material for a flow divider than Polyethylene (k = 0.23).

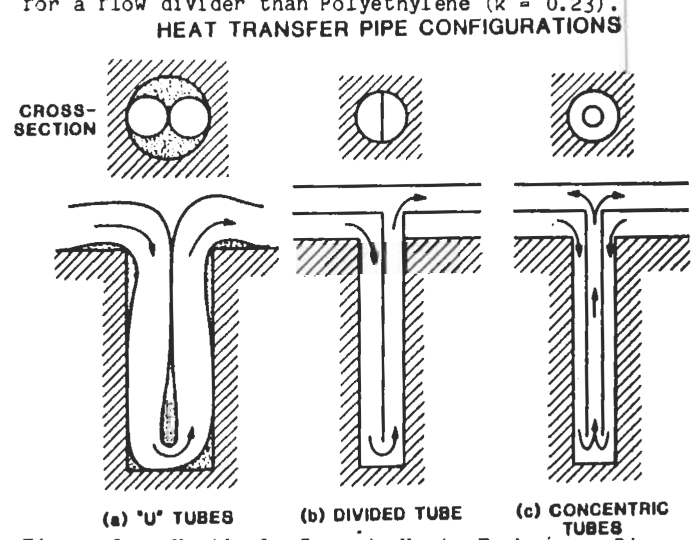

Figure 3. Vertical Ground Heat Exchanger Pipe Configuration

U-tube configurations have been fabricated from pipe sizes ranging from 3/4 to 2 inches, and depth range from 50 to 600 feet in both series and parallel systems. Heat exchanger bore length range from 150 to 200 feet of wetted bore hole per ton of heat pump capacity. Figure 4 describes several U-tube and concentric-type heat exchangers studied by Kavanaugh at Oklahoma State University (5). Concentric type heat exchangers are generally of larger outside diameter and will have a larger liquid volume. The larger diameter pipe will result in lower field resistance and the larger water volume will result in smoothing the transient peaks when cycling.

SOIL PROPERTIES

Solutions to the Kelvin equations show the soil thermal conductivity to be the single most significant factor in determining soil thermal resistance. Figure 5 shows that the thermal conductivity of several soils is relatively constant (flat portion) for a range of moisture levels down to a critical amount (6). Below this moisture level, soil resistivity increases rapidly for small decreases in moisture content. Therefore, for a given dry density, the effects on thermal conductivity of the ground heat exchanger are small for a range of moisture contents down to a critical point. For a given dry density, adding significant amounts of water above the critical moisture content will have little effect on its thermal resistivity. Thermal diffusivity is also affected by changes in density, however ground exchanger performance is affected more strongly by thermal conductivity than by thermal diffusivity.

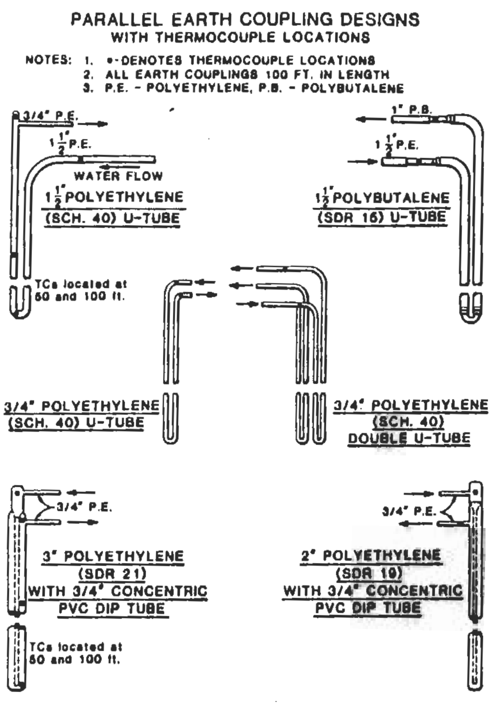

Figure 4. Vertical Ground-Exchangers Studied by Kavanaugh (5).

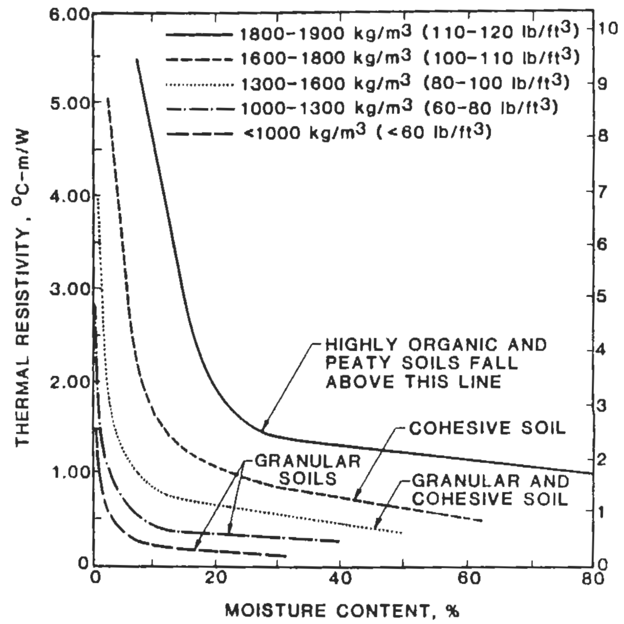

Figure 5. The Effect of Moisture Content and Dry Density on the Thermal Resistance of Soils, Salomone (6).

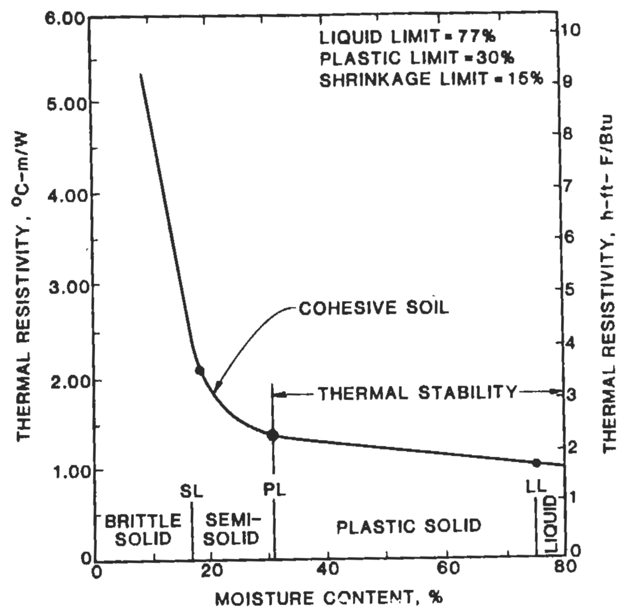

Figure 6. Thermal Resistance and Thermal Stability in Terms of the Atterberg Limits (7).

In Figure 6, Salomone defines the thermal stability range as that portion of the moisture-density curve where small changes in moisture content result in small changes in soil thermal resistivity (7). The determination of soil thermal stability limits is important in the design of ground heat exchangers for summer cooling load in

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regions with low moisture contents in the upper soil layers.

Salomone defined the critical moisture content for both fine-grained and coarse-grained soils in terms of their respective index (engineering) properties (8).

He defined the approximate critical moisture content for various soil types, in Table 2.

Table 2. Approximate Critical Moisture Content (8)

Soil Description	Approximate Standard Maximum Dry Unit Weight (ASTM D698-78)		Approximate Critical Moisture Content*
	lb/ft³	Mg/m³	%
Granular	120 to 135	1.92 to 2.16	< 12
Silts	110 to 120	1.76 to 1.92	12 to 16
Clays	100 to 110	1.60 to 1.76	16 to 22
Organic Silts and Expansive Clays	100	1.60	> 22

* Note: Critical moisture content is defined for a dry density that is 100 percent of standard maximum density (ASTM D698-78).

Thermal probe methods, developed to quantify soil thermal stability limits for underground electric power cables, is accomplished by inserting a thermal probe into the soil and determining if highly thermal resistive soils are present (10). While the work considered cable systems with much higher heat rates than normally found in heat pump ground loops, their approach and conclusions are directly applicable.

The thermal stability was shown to be independent of cable operating temperatures but is dependent upon initial moisture content, soil density, cable diameter, and the heat rate per unit length.

CLIMATE FACTORS

The climate is important since it influences loads on the building and the heating and cooling requirements. In many locations only heating is required, whereas in others, only cooling may be required. Water may be used as the heat transfer fluid in the ground where there is no concern about freezing. In cold climates a brine (antifreeze) must be used for winter operation. The soil may be an important factor in freezing and in the possible effects of heaving.

Some heat pumps are designed primarily for cooling, others primarily for heating. Selection would likely be fixed by the relative ratio of heating and cooling loads.

In cold climates with long periods of low temperatures, the heat pump may run a large percentage of the time. In hot, humid climates, the loads may also be fairly continuous, and the unit may cycle off for only short periods.

ECONOMIC CONSIDERATIONS

Economic factors are important in considering the ground-coupled heat pump. The price of alternative fuels such as oil, propane or natural gas must be considered. The local costs for drilling and ditching are quite variable and may determine the economic feasibility of any proposed system. These costs tend to decrease sharply with contractor experience and with large scale installations, such as in housing developments. Competition between contractors have already brought the costs of ground coupled systems down significantly.

The energy requirements of the building is significant. Small, well-insulated buildings have low heating and/or cooling costs and there is often little justification for any front-end investments to reduce these costs further. Ground-coupled devices tend to be more economically feasible for large homes and buildings, and where favorable electric rates exist.

As with many energy systems there is the usual tradeoff between first cost and operating cost. First cost will usually be dominated by cost of the ground exchanger, therefore once the heating and cooling loads have been calculated and before a model of heat pump has been selected, an important decision involves the sizing and layout of the earth coupling device. The choice of vertical or horizontal, series or parallel, small diameter versus large diameter, and type of pipe, all depend upon cost. Many contractors and designers have their own rules for choosing the "best" or lowest cost system. Costs vary with time and location, and because of variation in load, climates, and soil conditions, no single optimum design or set of designs can be specified. Once a particular design has been selected to fit local conditions a suitable length of pipe can be specified which will permit operation of the heat pump within some specified maximum and minimum entering water temperature (EWT).

CONCLUDING REMARKS

It is difficult to design a least cost system because it involves almost an infinite number of choices, and it requires prediction of performance at every condition under which it will operate. The latter prediction requires more skill and much more computation than the more easily obtained prediction of performance of a given system at the imposed extreme conditions.

Optimization in terms of lowest life cycle cost, requires that the performance of the system be simulated under realistic operating conditions. This in turn implies the use of numerical methods and digital computers. It also requires that good weather data be available, that the dynamic performance of the entire system (building, heat pump and ground exchanger) can be simulated, and that both present and future electrical costs be available or predicted with some reasonable reliability.

Programs of this type have been written and used by several investigators. Ball, et al., have compiled an excellent summary of computer models and design methodologies for the period up through 1981 (1).

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