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THE APPLICABILITY OF EARTH COUPLED HEAT PUMPS AND FACTORS AFFECTING THEIR PERFORMANCE*

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ABSTRACT

Earth-coupled heat pumps are closed-loop systems placed underground to take advantage of favorable thermal characteristics of the subsurface. Design concepts have been divided into three categories: shallow horizontal coils, multiple shallow wells, and single deep wells. In some areas earth-coupled heat pumps offer the potential of more efficient heating and cooling of buildings than conventional heat pumps, and they may be applicable in places where groundwater heat pumps and conventional geothermal development are not. Heat transfer occurs primarily by conduction making the thermal conductivity of the subsurface a critical factor in determining the performance of earth-coupled heat pumps. Thermal conductivity is dependent on porosity, moisture content, and the mineralogy of the solid phase. The cost of drilling or excavating into the subsurface and installing the system is an important element of the overall cost. Combining these factors with the annual range and distribution of temperature at the surface and the building's heating and cooling demand, the overall economic and technical performance of different designs can be evaluated.

1. INTRODUCTION

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1. INTRODUCTION

Earth-coupled heat pumps are closed systems in which a heat exchanger is placed below the surface of the earth. The heat exchanger, which can be the evaporator coil itself or a loop containing a secondary fluid, is usually simple metal or plastic piping. When a secondary fluid is used, it exchanges heat with the subsurface at one end of the loop while exchanging heat with the evaporator coil of the heat pump at the other end. Fluid that is circulated through the heat exchanger in a closed loop withdraws heat from or rejects heat to the subsurface. Unlike conventional air-source heat pumps, earth-coupled heat pumps use the subsurface rather than the air as a heat source or sink. Unlike groundwater heat pumps which are open systems, earth-coupled heat pumps withdraw heat from or reject heat to the subsurface without the withdrawal and circulation of any groundwater. These fundamental differences of earth-coupled heat pumps from both air source and groundwater heat pumps indicate that independent investigation of their potential utility is required. One of the principal reasons for using an earth-coupled heat pump instead of an air source heat pump is to take advantage of the fact that temperature variations are more moderate below the surface than they are above the surface. Annual variability in temperature decreases with depth from the surface until temperatures become relatively constant. In addition, an earth-coupled heat pump can be used in situations where groundwater is either unavailable or unusable.

Earth-coupled heat pumps are not a new concept. Extensive research exploring the concept was conducted in the late 1940s and the 1950s in both the U.S. and Europe. Installation of earth-coupled heat pumps used exclusively for heating became common in Europe after the 1973 increase in oil prices. Most of these heat pumps use a horizontal configuration. Current research is concentrating on the applicability of horizontal designs for both heating and cooling as well as the applicability of vertical designs. The vertical designs can be divided into two categories: multiple shallow wells connected together and single deep wells.

In the horizontal configuration, trenches are excavated to a depth of about 0.5 to 2.5 m. Plastic or metal piping with 20 to 40 mm external diameter is placed in the trenches and they are backfilled. Initially, trenches were arranged in a grid pattern and metal piping was used, but the introduction of flexible plastic tubing and reduced trenching costs have made a serpentine arrangement of trenches more common. The horizontal configuration is shown in Figure 1. A recent development consists of placing two layers of piping in the trench, one above the other, separated by about 1 m of backfill.

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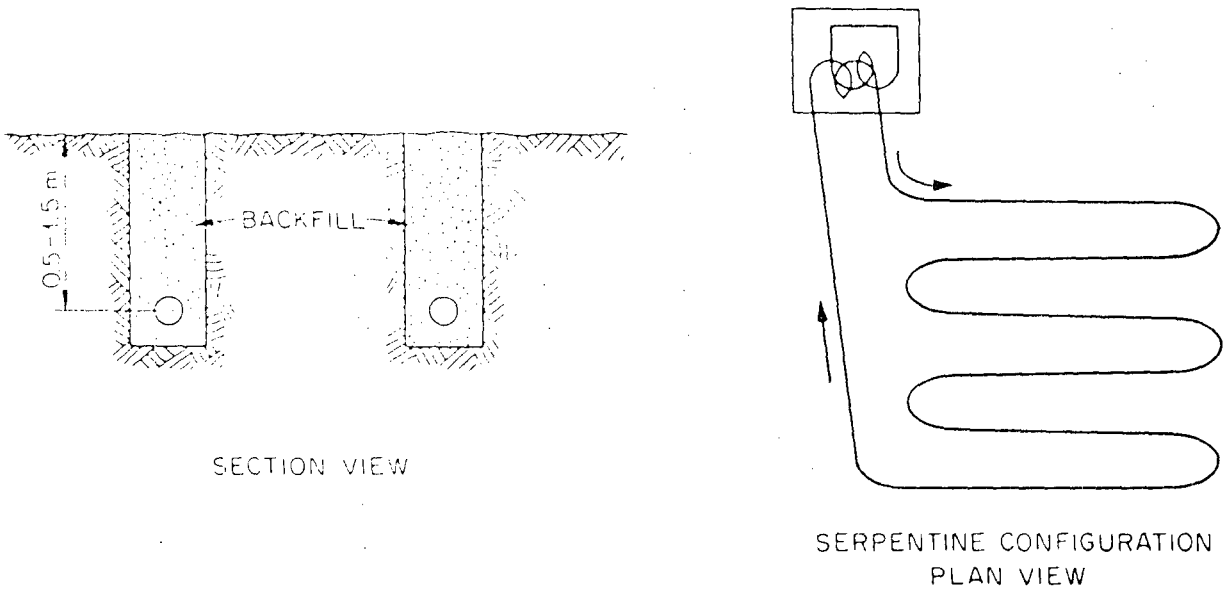

Figure 1. Horizontal configuration of earth-coupled heat pump, from David A. Ball, et al., State of the Art Survey of Existing Knowledge for the Design of Ground Source Heat Pumps, Battelle Columbus Laboratories, 1982.

In the vertical designs holes are either driven or drilled, and metal or plastic piping is installed. The piping may either have a coaxial or U-shape configuration as shown in Figure 2. Packing around the pipe may be necessary. In a multiple shallow well system the wells, which are generally less than 20 m deep, are placed 2 to 9 m from each other in a cylindrical or grid pattern and are connected together by horizontal piping. The alternative vertical design is a single, deep well typically exceeding a depth of 50 m. A coaxial design is most commonly used in this alternative. Generally, water or an antifreeze

solution is circulated through the piping, although sometimes the expansion fluid itself, freon or ammonia, is circulated in very small systems.[1]

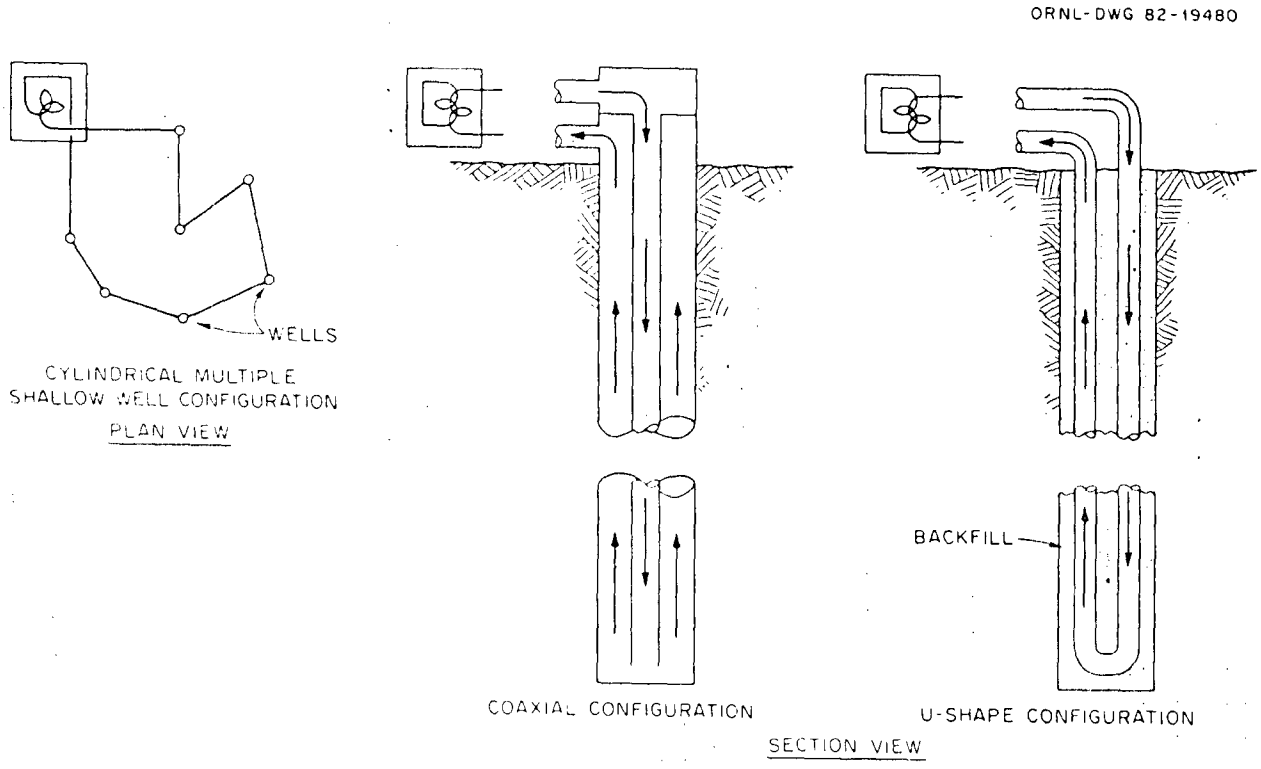

Figure 2. Vertical configuration of earth-coupled heat, from David A. Ball, et al., State of the Art Survey of Existing Knowledge for the Design of Ground Source Heat Pumps, Battelle Columbus Laboratories, 1982.

2. SUBSURFACE THERMAL REGIME

Earth-coupled heat pumps use the thermal energy of the subsurface as a heat source during the winter heating season and as a heat sink during the summer cooling season. Therefore, a preliminary understanding of the thermal regime in the subsurface is necessary to determine the performance of earth-coupled heat pumps. Heat flows from the warmer interior of the earth to the cooler surface principally by conduction at a rate that is relatively constant. This heat flow can be expressed by a geothermal gradient which is typically between 10 and 50°C/km at most locations in the U.S. Heat flow from the atmosphere to the earth's surface varies periodically on both a diurnal and an annual basis. The annual cycle of temperature change at the surface can be represented by a simple harmonic wave function.[2] The maximum surface temperature variation at a particular location is twice the wave amplitude and can be estimated as the difference between the normal daily mean earth temperatures of the warmest month and the coldest month.

Conductive heat flow below the subsurface can be explained by the one dimensional heat diffusion equation

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \qquad (1)$$

where T = temperature
t = time
α = thermal diffusivity
x = depth from surface.

A solution to the equation must fit the surface boundary conditions

$$T = \frac{1}{2} Tr_0 \sin \omega t + Tm \quad \text{at } x = 0 \qquad (2)$$

where Tr_0 = maximun surface temperature variation
Tm = mean temperature

The appropriate solution solving for temperature is

$$T = \frac{1}{2} Tr_0 \, e^{-x\sqrt{\omega/2\alpha}} \sin\left(\omega t - x\sqrt{\frac{\omega}{2\alpha}}\right) + Tm \qquad (3)$$

From this equation, numerous characteristics of heat flow below the surface can be approximated. The maximum variation in temperature at a certain depth, defined as the annual range, Tr_x, is

$$Tr_x = Tr_0 \, e^{-x\sqrt{\omega/2\alpha}} = Tr_0 \, e^{-x\sqrt{\pi/\alpha P}} \qquad (4)$$

where P is the annual period.[3] The damping effect of the exponential term causes the maximum temperature variation to decrease very rapidly with depth. The depth at which a certain range occurs is

$$x = \frac{-\ln\left(\frac{Tr_x}{Tr_0}\right)}{\sqrt{\pi/\alpha P}} \qquad (5)$$

The depth at which the maximum temperature variation is only 1°C can be estimated using climatic data and appropriate values for α. Using a low thermal diffusivity of 0.0045 cm^2/s typical of some soils in Atlanta, Georgia, where Tr_0 = 19.8°C, the depth at which Tr_x = 1°C is estimated to be 7.6 m. Using a high thermal diffusivity of 0.009 cm^2/s typical of some soil in Portland, Maine, where Tr_0 = 25.8°C, the depth at which Tr_x = 1°C is estimated to be 11.5 m. Figure 3 shows how temperature variability decreases with depth for the Portland example. These values are only simple approximations because other processes such as rain infiltration and moisture vaporization are significant near the surface and because diffusivity varies significantly over time as a function of moisture content. However, such calculations explain why temperatures 15 m below the surface are relatively constant and approximate the annual normal daily mean temperature at the surface. Below the depth at which the effect of surface variability is negligible, temperature increases very gradually with increasing depth according to the local geothermal gradient. In a limited number of areas temperatures increase rapidly with depth due to large geothermal gradients leading to the occurrence of conventional geothermal resources. However, in most regions these resources must be considered exceptions to the typical subsurface thermal regime.

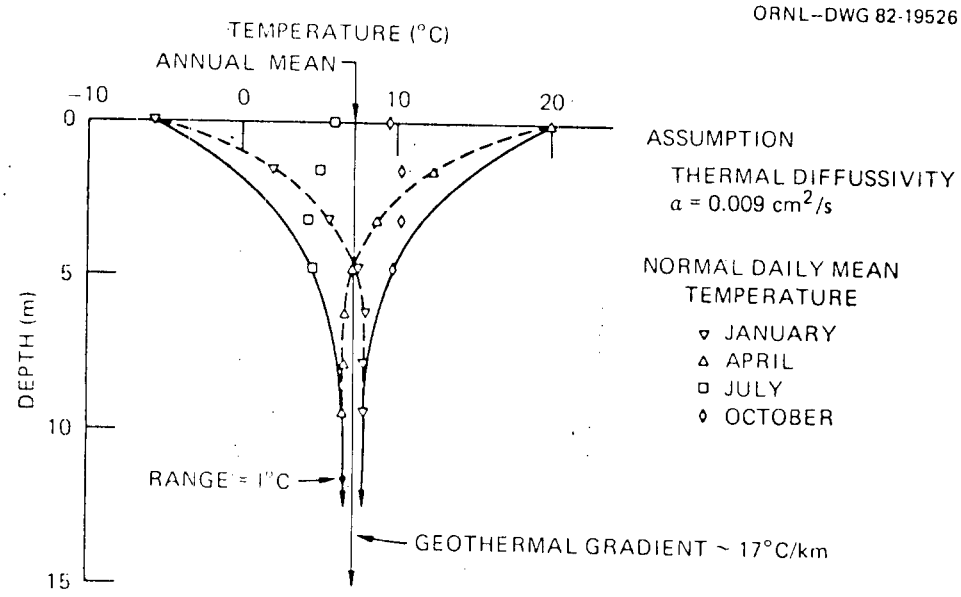

Figure 3. Schematic temperature regime of the subsurface in Portland, Maine.

3. APPLICABILITY

Earth-coupled heat pumps can be considered a means of expanding the geothermal resource base to the much more extensive areas where geothermal gradients are normal and areas where groundwater cannot be used effectively. Earth-coupled heat pumps can operate above as well as below the water table. By taking advantage of subsurface thermal properties and reduced temperature variability, earth-coupled heat pumps offer the possibility of better heat pump performance in comparison to conventional air source heat pumps. A logical hypothesis is that this advantage is likely to be greatest where the climate produces the greatest extremes in temperatures. Despite significant advances in air source heat pump technology, performance still deteriorates significantly when air temperatures are very low. One of the primary reasons renewed attention is being given to earth-coupled heat pump systems is their ability to overcome this limitation. Preliminary modeling of horizontal, multiple shallow vertical, and deep vertical designs in nine cities throughout the U.S. indicates that their performance is significantly better than an air source heat pump's performance in most cases.

Groundwater heat pumps are an alternative to earth-coupled heat pumps as an approach to utilizing the thermal energy of the subsurface in conjunction with heat pumps. Their capabilities are well understood, and they are already used in significant numbers in the U.S. As a result, the applicability of earth-coupled heat pumps must be compared to groundwater heat pumps as well as air source heat pumps. At least three situations can be identified in which groundwater heat pumps are not an alternative or are likely to be an inferior alternative to earth-coupled heat pumps. The first case is when the subsurface is so impermeable that adequate groundwater cannot be extracted. There are many areas in the U.S. where this is the case. A deep water table is the second situation that may preclude the use of a groundwater heat pump. The third limitation to the use of groundwater heat pumps is the chemical quality of the groundwater. High concentrations of some dissolved solids, most

notably calcium and magnesium, can cause the formation of scale wherever groundwater circulates. This scale can clog the system and therefore seriously impair its effective operation. High concentrations of other dissolved solids, notably chloride and sulfate, and some dissolved gases including oxygen, carbon dioxide, and hydrogen sulfide can cause significant amounts of corrosion that ultimately lead to the failure of elements of the system.[4] Groundwater of poor quality that causes these problems is not uncommon.

4. FACTORS AFFECTING PERFORMANCE

4.1 Technical Performance

The technical performance of earth-coupled heat pumps depends critically on the thermal properties of the subsurface and the design of the heat pump components. It has already been noted that earth-coupled heat pumps are closed systems that withdraw or reject heat to the subsurface by means of conduction. The thermal properties of the subsurface that must be investigated are therefore temperature, heat capacity, thermal conductivity, and thermal diffusivity. Temperature has already been considered in Section 2. To determine the other properties, the complexity of the subsurface must first be recognized. Below the water table the subsurface is a two phase system of water and solid material. Its characteristics vary spatially but remain constant over time. Above the water table in the unsaturated zone, the subsurface is a three phase system of air, water, and solid material with large spatial and temporal variation of the relative proportions of air and water. The thermal properties of each phase are very different, in most cases varying by orders of magnitude. Although much is known about heat transfer in multi-phase systems, there are still many practical and theoretical difficulties which prevent exact solutions.

The proportion of each phase is an important factor in determining the bulk thermal of the overall system. Porosity is the ratio of the volume of void space to the total volume. Void space is occupied by water under saturated conditions and by some combination of air and water under unsaturated conditions. Porosity varies from 70 percent in some clays and organic soils to a very small fraction of one percent for some igneous rocks. Porosity eventually decreases with increasing depth although local deviation from this trend is common. Dry bulk density is the product of porosity and the density of the solid phase. Permeability is not a significant factor in considering earth-coupled heat pumps since they are closed systems.

Volumetric moisture content is the proportion of total volume occupied by the water phase. Below the water table the volumetric moisture content and porosity are equal. Above the water table moisture content is less than the porosity by the proportion of void space occupied by air. The ice phase is generally included in the moisture content. The relative proportions of air and water above the water table vary continually due to the processes of rain infiltration, evaporation, and transpiration by plants. As a result, the bulk thermal properties are also changing. How much moisture content changes depends on both the climate and the type of subsurface materials at a particular location. Because the subsurface systems above and below the water table are basically different, depth to the seasonally low water table itself is an important factor that should be determined.

Thermal conductivity, volumetric heat capacity, and their ratio, thermal diffusivity, are bulk thermal properties that affect the performance of earth-coupled heat pumps. Among these properties, volumetric heat capacity is the simplest to evaluate if the proportions of each phase are known. For water the volumetric heat capacity is 4.2 J/cm^3K, for ice it is 1.9 J/cm^3K, and for air it is 0.001 J/cm^3K. Volumetric heat capacity for common minerals within the temperature range of the shallow subsurface is only slightly variable, typically ranging between 2.1 and 2.6 J/cm^3K.

Determining bulk thermal conductivity is much more difficult. For water thermal conductivity is 0.6 W/mK, for ice it is 2.2 W/mK, and for air it is 0.02 W/mK. However, the thermal conductivities of minerals and the solid phase of rocks are highly variable. Many of the common rock and soil forming minerals have thermal conductivity between 1 and 4 W/mK. However, the thermal conductivity of quartz, one of the most common minerals in rock and soil, is particularly high, ranging from 7 to 12 W/mK depending on the crystal orientation to heat flow. The thermal conductivity of the solid phase of rock is less than that of single minerals because of structural discontinuities. For instance, the average thermal conductivity of a quartzitic sandstone is only two thirds that of a quartz crystal.[5]

The thermal conductivities of soils have been thoroughly investigated by Kersten.[6] Based on a large set of measurements, Kersten developed empirical equations for the the bulk thermal conductivities of soils with different textures using bulk density and moisture content as the independent variables. The thermal conductivities of rocks have been studied extensively by Robertson.[7] His research indicates that, for a standard rock composition, increase in bulk thermal conductivity at a constant temperature is directly proportional to the square of the solidity. Solidity is the volumetric proportion of the solid phase equal to one minus the porosity. Robertson has developed tables illustrating this relationship for different types of rock with either air or water in the void spaces. The tables for non-carbonate sediments with water in the void spaces (Figure 4) shows a value of approximately 1.0 W/mK for clay sediments and a value of about 7.0 W/mK for quartzite. The trend is towards increasing values with depth because of decreasing porosity. Typically, values range from 1.5 to 3.0 W/mK.

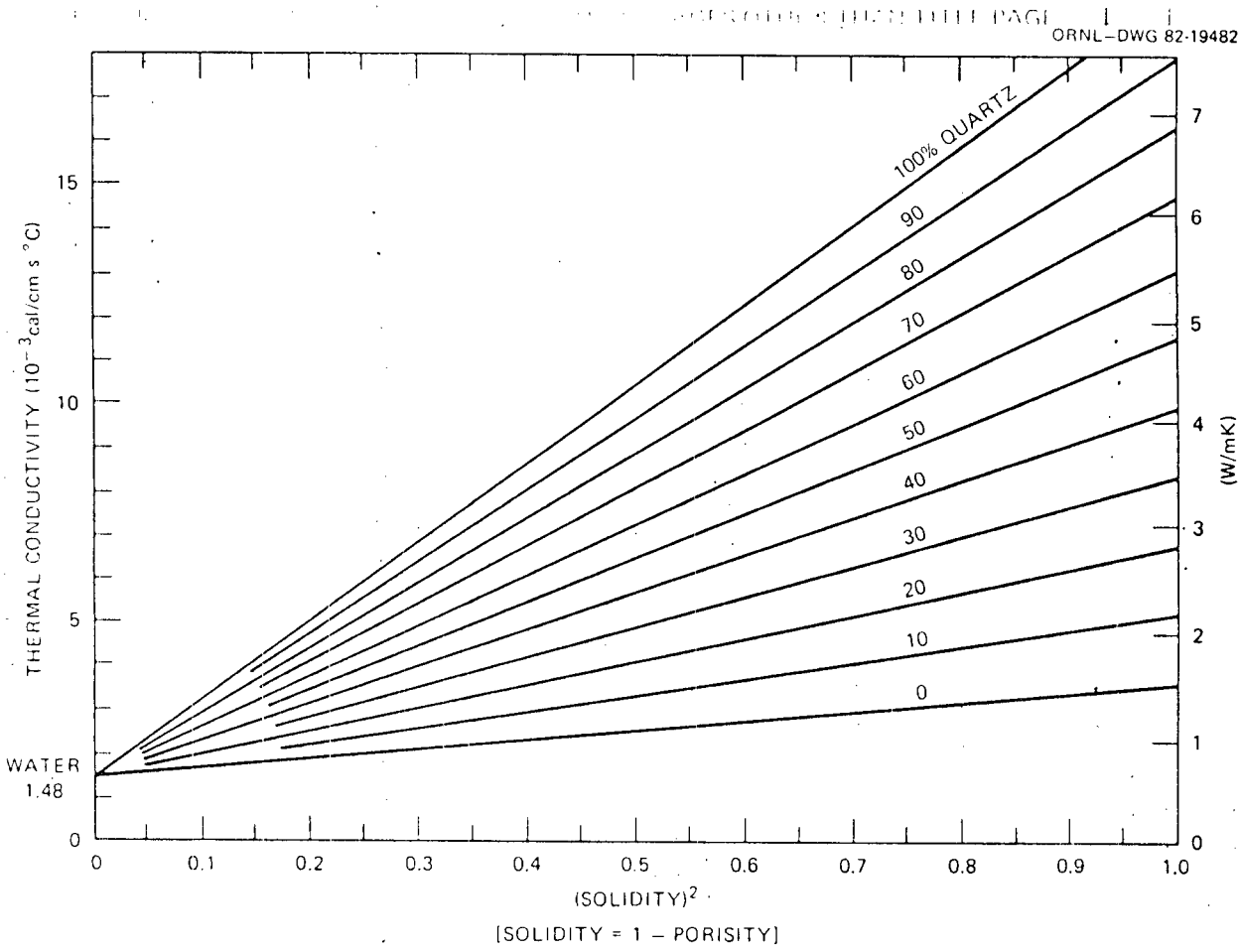

Figure 4. Thermal conductivity of noncarbonate sedimentary rocks with water in pores, from E. C. Robertson, Thermal Conductivity of Rocks, U.S. Geol. Survey Open-File Report 79-356, 1979.

Bulk thermal diffusivity in the subsurface can be determined several ways. Laboratory measurement of core samples is not very common. An alternative is to measure temperatures at various depths and various times in the field and then calculate the diffusivity using the equations discussed in Section 2. The least precise but easiest method is to estimate the bulk thermal diffusivity from values for the bulk thermal conductivity and bulk volumetric heat capacity based on known characteristics of the subsurface. Even though the thermal diffusivity of air is high, the air phase above the water table is usually neglected when this third method is used because the thermal conductivity is so low. When no terms for the air phase are included in the calculation, the results agree reasonably well with those found by the second method using temperatures.

A value of 0.01 cm^2/s is often used as an average for bulk thermal diffusivity in the subsurface. Although this value is probably quite close to the average over a large area its use is not adequate for calculating the performance of earth-coupled heat pumps at a specific location. Because thermal diffusivity is such a critical variable in determining heat transfer, technical and economic performance can be expected to be sensitive to marginal differences in its value. Approximations based on conductivity and heat capacity indicate that where the subsurface is interbedded it is not uncommon to find a stratum with diffusivity three times greater than the diffusivity of

the stratum immediately above it. Thermal conductivity of the solid phase and porosity are the most important factors affecting the value of thermal diffusivity which commonly ranges from 0.005 to 0.02 cm^2/s. Above the water table, moisture content is another important factor. Figure 5 shows a theoretical relation between thermal conductivity and thermal diffusivity with varying porosity assuming saturated conditions. The uppermost line represents rock with porosity of almost zero while the lowermost line represent rock and soil with porosity of 50%. Points corresponding to clays and shale occur on the left side while those corresponding to sands and sandstones occur on the right side.

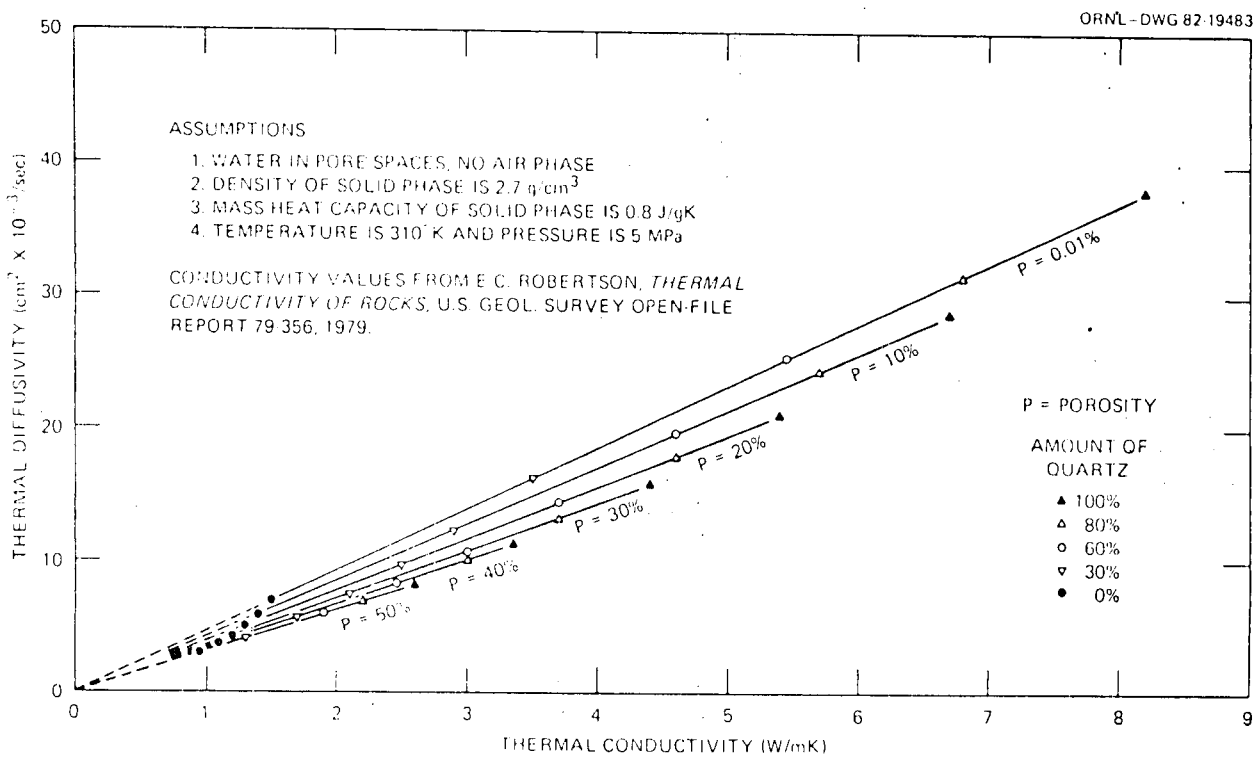

Figure 5. Theoretical relation between thermal diffusivity and thermal conductivity below the water table.

Once thermal properties of the subsurface at a particular location have been estimated, the technical performance of an earth-coupled heat pump can be modeled given a certain heating and cooling demand and initial assumptions about system design. Modeling below the water table is a relatively simple and straightforward task since temperature is the only thermal property that changes and heat transfer in the subsurface occurs almost entirely by conduction. Modeling above the subsurface is much more complicated. Both natural changes in moisture content and artificial changes due to the operation of the heat pump result in continual variation of the bulk thermal properties. Heat transfer mechanisms in addition to conduction is significant. Above the water table the subsurface temperature gradients produced by operation of the heat pump create moisture gradients. Moisture flows according to these gradients from the warmer to the cooler area. The effect of this mass transfer or moisture migration process on the overall heat transfer needs to be evaluated. The energy involved when moisture changes phase during both vaporization and freezing also needs to be considered.

Numerous models have been developed in North America and Europe for both horizontal and vertical designs and they are comprehensively reviewed by Ball et al.[8] The most sophisticated but also the most expensive of these are two and three dimensional transient models. Few of the models currently in use are able to consider moisture migration, and model development is still an active and fertile area of research. After an initial modeling effort has been conducted, additional runs are desirable in order to determine the sensitive parameters and to eventually optimize system design.

The moisture migration and phase changes caused by operation of earth-coupled heat pumps above the water table may temporarily or permanently alter the subsurface so that both the general environment and the efficiency of the heat pump are affected. These phenomena are likely to be most significant near the surface in unconsolidated sediments with a large percentage of clay. In winter where horizontal systems are used, moisture migration towards the heat pump followed by freezing may result in frost heave and related problems. In summer if vaporization and moisture migration from the heat pump is sufficiently great, desiccation of clay rich sediments may result in shrinkage and alteration of the sediment's physical properties. One effect of shrinkage is the creation of an air space around the piping that drastically reduces the heat pump's efficiency. Desiccation may also cause sediment consolidation eventually leading to subsidence at the surface. Moisture migration may also affect patterns of vegetation growth near the piping. It can be postulated that the impact of horizontal systems may be severe in areas with a considerable demand for cooling. Current research is investigating the extent to which moisture migration is caused in both the heating and cooling mode of operation and the significance of its effects on the performance of different configurations .

4.2 Economic Performance

The economic performance of earth-coupled heat pumps is the combination of its capital and operating costs. Operating costs depend on the technical performance of the heat pump. The results of modeling will lead to the most energy efficient design at a particular location as measured by the coefficients of performance for heating and cooling. These coefficients determine the amount of electricity required to meet a particular heating and cooling demand. The operating cost is basically this amount times the price of electricity. An assumption must be made about changes in the real price of electricity in the future, and it is an important factor affecting the total operating cost.

Installation of the earth-coil heat exchanger in the subsurface is a major capital expense for earth-coupled heat pumps which does not exist for air source heat pumps. To determine the total economic performance of earth-coupled heat pumps, this increased capital outlay must be considered in addition to reduced operating costs. If the increase in capital cost is too great, it may exceed the reduction in operating cost making the system uneconomical. The effect of increased capital costs and reduced operating costs can be evaluated by the payback period, the amount of time required to recover the increase in invested capital. Another way is to calculate the life cycle cost, the sum of capital and operating expenses over the operating lifetime of the system. Assumptions made regarding discount rates will have an important effect on these values.

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The costs of installing an earth-coupled heat pump depends on a number of factors that makes it quite variable. The most important factors are the thermal and physical properties of the subsurface because they determine how much piping must be installed and the ease with which trenches can be excavated for horizontal designs and wells can be drilled for vertical designs. Cost per unit length or depth is based primarily on the rate at which drilling or trenching occurs and the rate of wear on the equipment being used. These rates depend on porosity, hardness, the degree of cementation, and the degree of weathering. As a general trend these properties change in the direction of increasing costs with increasing depth. Where bedrock is very shallow, this trend may be strongly evident within a few meters or even a few centimeters from the surface. Where deep unconsolidated sediments have accumulated this trend may not become strongly evident for hundreds of meters. Except for areas where bedrock is very near the surface, drilling is considerably more expensive than trenching. Accurate estimates of local costs are desirable as the basis for estimating the cost of installation.

5. DISCUSSION

In addition to technical performance, preliminary modeling is underway to estimate total economic performance of each design used for both heating and cooling in nine cities throughout the U.S. These cities represent a broad variety of both geologic and climatic conditions. Initial results which are currently being evaluated appear to be favorable enough to warrant further investigation of all three systems. Continued research will concentrate on providing more accurate and precise input and optimizing the system designs.

Certain conditions related to both the general environment and the systems performance may make one type of design preferable to another. Some of the environmental considerations were already considered in Section 3.1. An additional factor is simply the availability of land. The scarcity of land in some locations, particularly in Europe, is one of the reasons why renewed attention is being given to vertical designs. The formation of ice around a horizontal system in a cold climate may result in its improved performance. As a crystalline solid, ice instead of water increases both the bulk thermal conductivity and diffusivity. Under certain conditions this improvement may exceed the deleterious effect of lower temperature. In favor of vertical systems is their potential to take advantage of especially good thermal properties of certain strata. The trend in general is towards improved thermal properties with depth, and a particular stratum with high thermal properties may be economically worth additional drilling to penetrate. A sandstone rich in quartz below the water table and insulated by a clay stratum above it might be a good example of such a situation. Optimizing design is predicated on a knowledge of the subsurface and the earth-coupled heat pump's interaction with it. As knowledge increases, efficiency can be expected to improve.

Current research at Oak Ridge National Laboratory is concentrating on the use of earth-coupled heat pumps for the heating and cooling of single-family detached residences. Multi-family residential and commercial uses represent other potential applications which may be more cost effective than single family residential. Futher evaluation is necessary to determine if and how economies of scale might affect the overall economic performance of alternative earth-coupled heat pump concepts.

If earth-coupled heat pumps are used widely throughout an electric utility's service area, their use may result in lower total and peak demand on the utility. Their potential to reduce total demand has already been

considered. The improvement in efficiency of an earth-coupled heat pump over an air source heat pump is likely to be greatest when atmospheric temperatures are most extreme and demand for power is at its peak. The result of the improvement in efficiency is to lower the peak power demand. Quantitative analysis is necessary to provide a more satisfactory answer to this issue.

Although earth-coupled heat pumps can operate as independent systems, they can also be combined with solar collection at the point of use. In this case the subsurface can be used as a means of storing solar energy and as a means of upgrading the efficiency of the solar collectors. Heat from the solar collectors is rejected to the subsurface during the summer and other times when it exceeds heating demand. In northern Europe where there is virtually no cooling demand, rejection of heat from solar collectors to the subsurface is necessary for some vertical designs in order to suitably increase the earth temperature between heating seasons. Hybrid systems of this type are commercially marketed in Europe. Nevertheless, the cost effectiveness of these types of systems has been questioned as a result of several investigations.[9] It must be recognized that the thermal properties desirable for heat storage are generally the opposite of those desirable for heat diffusion, and, therefore, different subsurface characteristics and different design responses to these characteristics may be desirable for a hybrid versus an independent system. While earth-coupled heat pumps are well suited to supply of electricity from typical centralized power plants using conventional sources of energy, they may also be suited to certain centralized and decentralized alternatives of unconventional power generation and may even make these alternatives more attractive.

6. CONCLUSION

Earth-coupled heat pumps are one of several promising types of subsurface thermal energy systems. Far from being homogeneous, the subsurface is highly heterogeneous with large differences in physical and thermal properties from location to location and from one depth to another. It is likely that the technical and economic performance of earth-coupled heat pumps will make it the most favorable alternative in certain situations, while elsewhere it will be a less favorable alternative. Likewise, certain design configurations are likely to be most efficient for certain conditions. If the use of earth-coupled heat pumps is to become widespread, it is necessary to greatly simplify the process involved in development of optimal design and performance. Additional experience and research will lead to improved design procedures as well as improved performance and will help to determine how significant the contribution of earth-coupled heat pumps will be in the future.

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