A SIMPLIFIED PROCEDURE FOR SIZING VERTICAL GROUND COUPLED HEAT PUMP HEAT EXCHANGERS FOR RESIDENCES IN TEXAS

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ABSTRACT

A simplified technique for the sizing of vertical U-tube ground coupled heat pump (GCHP) heat exchangers for Texas climates was developed utilizing a transient simulation model of a ground coupled heat pump and weather and soil data for Texas. The simulation model discretized the ground heat exchanger into elements and computed the temperature distribution surrounding the heat exchanger on a minute-by-minute basis. Hundreds of runs were made with the model for a wide range of ground temperatures, ground thermal properties (density, thermal conductivity, and specific heat), and outdoor weather.

A set of sizing charts were developed from the model runs that could provide quick reference on the size of the ground heat exchanger. Corrections for ground temperature, ground density, ground thermal conductivity, and indoor air temperature were presented. Soil temperature and thermal conductivity were found to be the most important parameters for sizing GCHP heat exchangers.

Results from the simplified method were compared to two available heat exchanger sizing methods: the National Water Well Association (NWWA) and the International Ground Source Heat Pump Association (IGSHPA). The simplified method predicted shorter lengths than those from either of these two methods.

INTRODUCTION

Ground coupled heat pumps (GCHP) show promise of being an efficient and cost effective residential heating, and air conditioning system. GCHPs use ground water or buried loops containing a circulating fluid to take advantage of stable earth temperatures to provide both heating and cooling. A recent study estimated that a GCHP can be as much as 30% more efficient than a high efficiency air source heat pump (ASHPs) [Kavanaugh, Woodhouse, and Carter, 1991].

GCHPs circulate a fluid such as water or a water-ethylene glycol mixture, through pipes buried in the ground to exchange heat with the soil. One advantage of using the ground as a sink/source is that ground temperatures are more stable than outdoor air temperatures and are not subject to large daily or annual fluctuations. Residences typically require maximum cooling when the outdoor temperature is greatest and require the most heating when the outdoor temperature is lowest. With an ASHP, the unit's lowest cooling efficiency and capacity coincide with the maximum cooling requirements on the residence. Similarly, the units lowest heating efficiency and capacity coincide with the maximum heating requirement.

Three potential impediments to increased market penetration of GCHPs in Texas include: (1) the added cost of installing the ground coupled heat exchanger, (2) the lack of important soil thermal properties, and (3) the lack of an "easy-to-use" sizing procedure for ground heat exchangers. For vertical heat exchangers, additional costs of $11.48 per meter ($3.50 per foot) are not unusual. For a 183 m (600 ft.) heat exchanger, this would contribute $2100 to the installed cost of a 10.6 kW (3 ton) cooling capacity GCHP. This extra cost includes: drilling the well, pipe material, and installation. Besides the costs, there are little data available on the ground temperatures and thermal properties of soils throughout the state. These data are critical for correctly estimating heat transfer from a ground heat exchanger. It is important to accurately size the heat exchanger to provide acceptable performance and optimize the heat pump's performance. Oversizing the heat exchanger is costly and undersizing the heat exchanger will provide unfavorable performance. Two of the most popular sizing procedures (Hart 1986 and IGSHPA 1986) are based on a simplified model of the heat transfer from the heat exchanger to the ground. Discussions with several Texas utilities have shown that current sizing procedures have not provided acceptable results in some parts of the state. Current methods of sizing the ground loops can give

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lengths that vary by up to 90% [Cane and Forgas, 1991].

Modeling of GCHPs is not straight forward. Long cooling or heating cycles may not allow the soil to adequately recover for the next cycle. One study showed that after a few years, a void developed between the pipe and the soil which decreased the heat transfer to unsatisfactory levels [Ball, Fischer and Hodgett, 1983]. This void apparently occurred because the heat rejected during the cooling season increased the temperature of the soil adjacent to the pipe which helps drive moisture away from the soil surrounding the pipe.

The purpose of this study is to (1) provide relevant soil temperature and thermal property data for GCHP applications in Texas and (2) develop a simplified procedure for sizing the ground coupled heat exchanger. The simplified procedure is based on a transient simulation model of a ground coupled heat pump and weather and solid data for Texas. The sizing procedure is presented in the form of sizing charts that can provide quick reference to the user.

MODELING BACKGROUND

The sizing procedure developed in this paper utilizes the ground coupled heat pump simulation (GSIM) model written by Dobson [1991] and updated by Margo [1992]. This model was verified in the heating mode [Margo, 1992] and the cooling mode [Dobson, 1991] as part of a four year GCHP study at Texas A&M University. GSIM accurately followed monitored results from field installations of GCHPs located in Abilene, Texas [Dobson, 1991] and Lorena, Texas [Margo, 1992]. These studies provided a means to calculate the annual performance of a ground coupled heat pump that included the effect of cyclic operation. Data that were collected at these sites and used to verify GSIM included :

a) soil conductivity,
b) soil density,
c) soil temperatures at various depths and radial distance from the ground loops,
d) entering and exiting water temperatures,
e) indoor return and supply air temperatures,
f) indoor return and supply air humidities and
g) power consumption of the supply air fan, ground loop pump, and compressor.

GSIM uses the analytical solution of a constant heat flux cylindrical source emitting into an infinite cylindrical region to predict the soil temperatures at radial distances from the source. This method was presented by Carslaw and Jaeger [1940] and supplies the temperature at the pipe wall, which is needed to couple the soil temperatures to the fluid temperatures. Energy balances are used to derive the partial differential equations that describe the heat transfer from coil to soil. These partial differential equations are modeled by a set of implicit finite difference equations (Dobson 1991).

Because the heat flux varies with distance along the coil and with time, the coil is divided into a number of user specified elements with an assumed uniform heat flux. A fully implicit scheme is then applied to each element. Each element has two nodes, with the second element of the first node being the first node of the second element. Then a solution is found for each element. Superposition is used to find the effect of thermal short circuiting provided by the adjacent leg. The temperature rise from the far field to the pipe wall is represented as the sum of temperature rises caused by heat inputs for each prior time increment. GSIM makes the following assumptions for each element along the coil:

a) thermal interference from adjacent legs of the U-tube can be handled by superposition,
b) heat is moved only by conduction with the soil,
c) heat transfer in the soil is one dimensional in the plane parallel to the surface,
d) the thermal storage capacity of the pipe wall is negligible,
e) axial conduction inside the fluid is negligible,
f) radial temperature gradients inside the fluid are negligible,
g) complete contact between the outer pipe wall and the soil,
h) the convection coefficient and all thermal properties are constant, and
i) equal specific heats at constant pressure and constant volume for water,

Input data in GSIM includes soil thermal conductivity, soil diffusivity, soil temperature, number of ground loops, loop length, indoor air temperature, indoor air humidity, balance point temperature, hourly outdoor temperature, pipe thermal resistivity, heat exchanger fluid flow rate, pipe diameter, heat pump COP and capacity as a function of entering water temperature, and the number of elements in the ground heat exchanger. The model can be run on a 486 class PC in approximately 15 minutes.

The primary factor in predicting GCHP performance is the entering water temperatures (EWT) to the condenser in cooling mode (or evaporator in heating mode). It affects the COP and capacity of a GCHP. Figure 1 shows a comparison of simulated results from GSIM and experimental results for cooling at a test site from Abilene, Texas [Dobson, 1991]. The EWT results predicted by GSIM were within 0.8°C (1.5°F) of the experimental results.

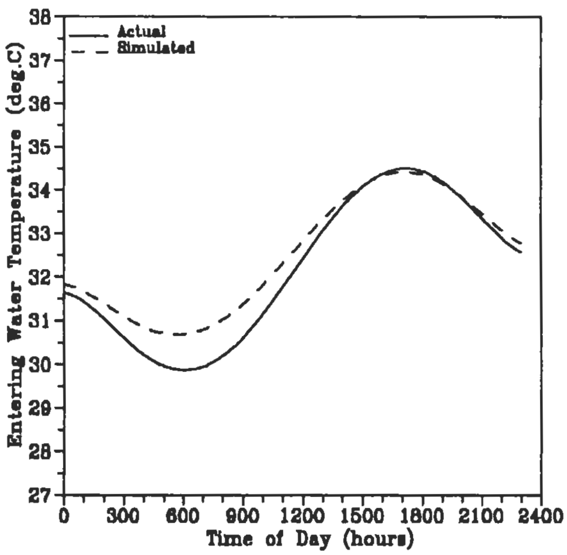

Figure 1 - Comparison of Simulated and Experimental EWT Values on September 4, 1990

The data in Figure 1 are useful for verifying that the model is representative of the data over long time periods, but offers little insight as to how it tracks start-up data. Figures 2 shows how GSIM track transient values of the EWT over a 22 minute on-time which began at approximately 11 a.m. on September 4, 1990. The prediction of the minimum EWT by the model following the off-cycle was always within 1.1°C (2°F) of the measured value.

SOIL AND WEATHER DATA

One of the primary difficulties in sizing the ground loops of GCHPs is the lack of accurate soil and thermal property data. Thermal soil property and weather data for Texas are presented along with accompanying charts.

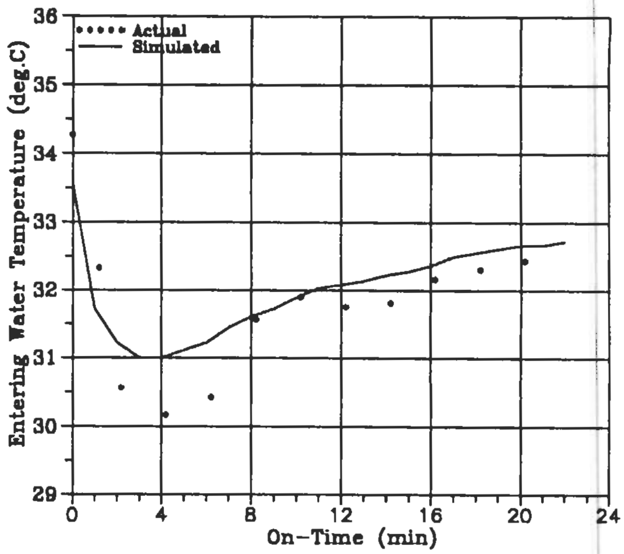

Figure 2- Comparison of GSIM and experimental EWT for Abilene, Texas on September 3,1991 for cooling

Soil Property Data

The values for soil thermal conductivity and soil density contain significant uncertainty because neither consistent nor complete data exists for geotechnical classification of the soils [EPRI, 1989]. EPRI [1989] found that the uncertainty in the choice of thermal conductivity could vary by a factor of two depending on the moisture content of the soils. In this study, the soil thermal conductivity and soil density are given for saturated moisture conditions. ASHRAE [1986] found that soil thermal conductivity values are stable down to a critical moisture level of about 20 percent.

Two of the most important underground parameters for sizing the ground loops of GCHPs are soil thermal conductivity and undisturbed soil temperature. Moisture content is also an important factor because thermal conductivity is a function of stable moisture content. The thermal conductivities of Texas soils presented in Figure 3 are derived from geological data provided by the Bureau of Economic Geology at the University of Texas [A.S.P.G, 1974]. This information was based on data provided by 21 oil companies and four universities. In this paper, only depths down to 91.4 m (300 ft.) were considered because most GCHPs loops are placed at depths less than this. At a given location, the geological formation and soils vary with depth. A weighted average value for thermal conductivity was used which included the geological formations for different depths at a given location.

Values for thermal conductivity ranged from about 0.865 W/m-°C (0.5 Btu/ft.-h-°F) for sandy soil in East Texas to 3.3 W/m-°C (1.9 Btu/ft.-h-°F) for areas with shale deposits in south central Texas. The values presented here are intended for use when a detailed well log analysis is not available.

It is recommended that the thermal conductivity values in Figure 3 be reduced by 10 to 20% when estimating the length of ground heat exchanger needed for an installation. There are two important reasons for doing this. First, many vertical U-tube installations use a bentonite mixture for backfilling the holes where the ground heat exchanger resides. A recent study (Remund and Lund 1993) of six different bentonite mixtures showed an average thermal conductivity of 0.74 W/m-°C (0.43 Btu/ft.-h-°F), which is significantly lower than the thermal conductivities of most of the soils in Texas. The first few inches of backfill (or soil) have a large impact on the total thermal resistance around the heat exchanger. If the hole radius for the U-tube is 2 inches (5 cm), the U-tube holes are separated by 20 ft (6 m) and the thermal conductivity of the bentonite is 0.74 W/m-°C (0.43 Btu/ft.-h-°F) and that of the surrounding soil is 1.72 W/m-°C (1.0 Btu/ft.-h-°F), then the bentonite accounts for 34% of the total thermal resistance to heat flow. If the hole were filled with native soil, the backfill would only account for 25% of the total resistance. A second reason for reducing the thermal conductivity relates to the source of the values in Figure 3. These values assumed that the soils were saturated with moisture. This may be a safe assumption in Texas coastal areas where water is found in shallow depths. However, if the soil is less that saturated, then the thermal conductivity will be less that those presented in Figure 3.

Soil temperature values shown in Figure 4 represent the results of analyzing data from over 14,000 water wells. Values for underground soil temperature were assumed to closely mimic those of the well water found in that area. Temperatures range from 15.6°C (60°F) in the panhandle to 15.7°C (80°F) for south Texas. Ground temperatures below 9.1 m (30 ft) were considered constant.

Density values are presented in Table 1. These were also derived from information provided by geological maps and data provided by the Bureau of Economic Geology at the university of Texas [A.S.P.G., 1974].

Table 1 - Saturated Density Values for Major Metropolitan Areas of Texas

CITY	DENSITY(lb/ft^3)	DENSITY(kg/m^3)
ABILENE	146	2335
AMARILLO	112	1800
AUSTIN	155	2475
BEAUMONT	96	1530
BRYAN	124	1980
BROWNSVILLE	96	1530
CORPUS CHRISTI	101	1620
DALLAS	125	2007
EL PASO	107	1710
FT. WORTH	132	2115
HOUSTON	101	1620
HUNTSVILLE	107	1710
KILLEEN	124	1980
LAREDO	135	2160
LONGVIEW	129	2070
LUBBOCK	129	2070
MARSHALL	129	2070
McALLEN	112	1800
MIDLAND	129	2070
ODESSA	129	2070
PLANO	120	1917
SAN ANGELO	155	2475
SAN ANTONIO	149	2385
TEMPLE	137	2194
TEXARKANA	118	1890
TYLER	121	1935
VICTORIA	94	1506
WACO	120	1922
WICHITA FALLS	140	2250

Weighted averages were taken for the area down to 91.4 m (300 ft.) below the surface. The densities for metroploitan areas with populations 100,000 are provided in Table 1. Work done by Margo[1992] showed that density was only a small contributor to the overall performance of a GCHP. For average on-times over 10 minutes, the effects of density were less than 5% on seasonal efficiency.

Air Temperatures

Table 2 presents the average summer air temperatures and the average day/night air temperature swings found in Texas. The average temperature swings are important because of their effect on the load of the residence on the heat pump run-time.

BASELINE ASSUMPTIONS

The procedure for sizing the ground loop requires the use of hundreds of runs of the GSIM model. The size of the ground loop is dependent on many variables that, at first, may seem unrelated to

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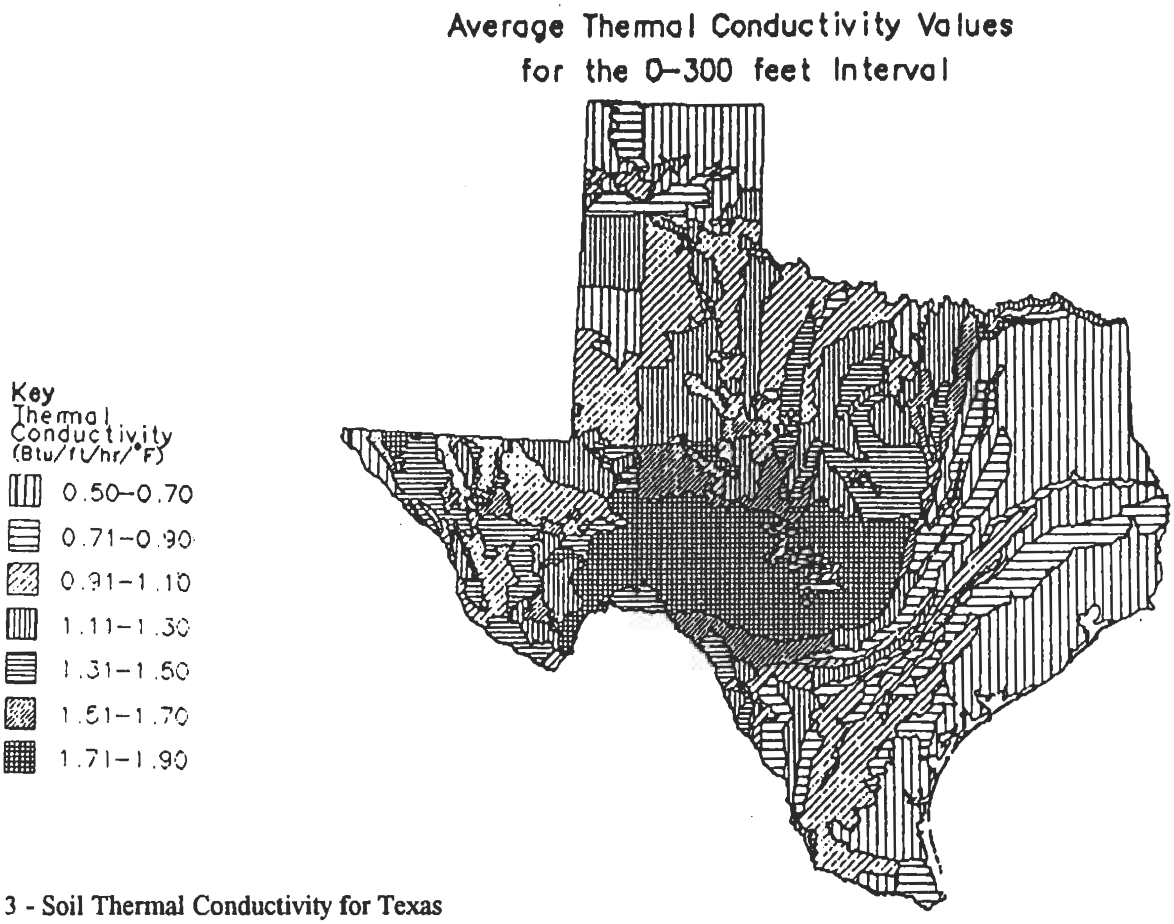

Figure 3 - Soil Thermal Conductivity for Texas

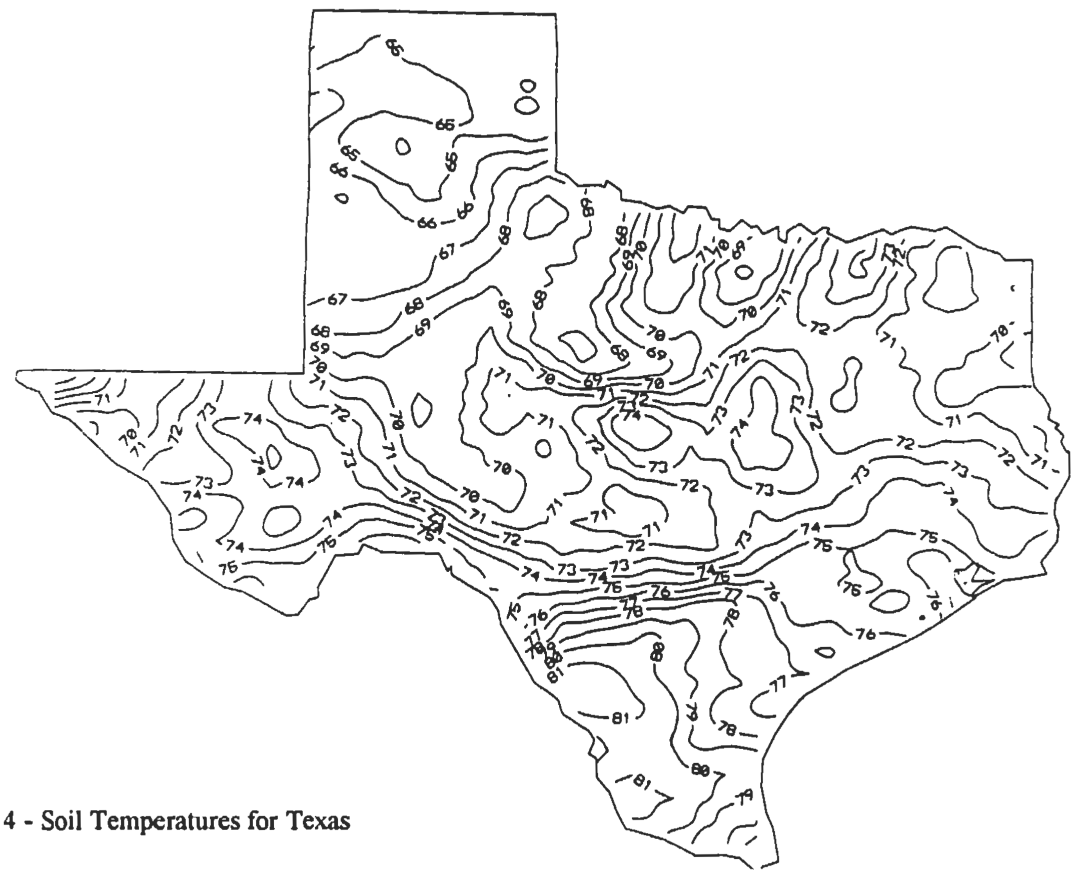

Figure 4 - Soil Temperatures for Texas

Table 2 - Average Summer Air Temperatures and Day/Night Air Temperature Swings for Major Metropolitan Areas of Texas.

CITY	Avg. Air Temp. (°F)	Avg. Air Temp (°C)	Avg. Temp. Swing (°F)	Avg. Temp Swing (°C)
ABILENE	83	28	23	13
AMARILLO	77	25	26	14
AUSTIN	84	29	20	11
BEAUMONT	82	28	19	11
BRYAN/COLLEGE STATION	83	28	21	12
BROWNSVILLE	84	29	16	9
CORPUS CHRISTI	84	29	11	6
DALLAS	85	29	23	13
EL PASO	81	27	27	15
FT. WORTH	85	29	23	13
HOUSTON/GALVESTON	82	28	16	9
HUNTSVILLE	82	28	19	11
KILLEEN	83	28	22	12
LAREDO	87	31	24	13
LONGVIEW	81	27	23	13
LUBBOCK	78	26	25	14
MARSHALL	81	27	23	13
McALLEN	84	29	22	12
MIDLAND	81	27	26	14
ODESSA	81	27	26	14
PLANO	85	29	23	13
SAN ANGELO	81	27	24	13
SAN ANTONIO	84	29	20	11
TEMPLE	83	28	22	12
TEXARKANA	81	27	23	13
TYLER	81	27	22	12
VICTORIA	84	29	18	10
WACO	84	29	21	12
WICHITA FALLS	84	29	26	14

the loop size. For instance the efficiency of the heat pump affects the amount of heat that must be rejected to the ground. The outdoor weather, and the thermal performance of the residence also affect the sizing of the loop. The sizing methodology proposed in this paper attempts to quantify the most important variables affecting the sizing of the loop. These variables are put in the form of charts that can easily be used. To develop these charts, a number of baseline assumptions had to made. These assumptions were used in GSIM. The sensitivity of Table 2 - Average Summer Air Temperatures and Day/Night Air Temperature Swings for Major Metropolitan Areas of Texas the results to some of these assumptions is discussed in a later section of the paper.

Residence Thermal Load

GSIM approximates the cooling load on a residence as a linear relationship with outdoor temperature. A linear relationship should be a reasonable approximation for thermally light buildings, such as residences. More sophisticated relationships or hourly outputs from programs such as DOE-2 could be used if the purpose were to calculate the load on a specific residence at a specific hour. However, a linearly relationship should be adequate for estimating the thermal loads over the course of a cooling season for a residence.

The model baseline residence has 185m^2 (2000 ft^2) of floor area with four bedrooms, kitchen, living-dining area and four bathrooms. The cooling load (Btu/h) on the home represents a best fit of monitored data taken from a residence in Abilene, Texas [Margo, 1992] and is presented below:

$$Q_{load} = 8970 - 879 * \Delta T \qquad (1)$$

where DT = outdoor temperature - indoor temperature (°F).

For an indoor temperature of 24°C (75°F), this cooling load equation yields a balance point of 18.2° C (64.8°F) for a zero load and an indoor temperature of 24°C (75°F). The indoor air temperature was chosen to provide a balance between comfort and economy of operation.

For developing the sizing procedures, weather files were created that simulated the range in temperatures found throughout Texas. Hourly air temperatures were created with a weather program called WETHRGEN written by Degelman (1991). The temperature patterns in these weather files simulate the sinusoidal curves associated with annual temperatures. Six different files containing air temperature, air humidity, sunrise and sunset, were created. Files for average summer temperatures of 23.9, 26.7 and 29.4°C (75,80 and 85 °F) were created, both for the small temperature swings associated with the Texas gulf coast and for the larger temperature swings encountered in west Texas. Because HVAC systems in Texas are usually sized for cooling requirements, only the summer cooling cycle was evaluated.

Indoor Air Temperature

Indoor air temperatures of 21.1, 23.9 and 29.4° C (70, 75 and 80°F) dry bulb were utilized. Wet bulb temperatures were chosen to provide fifty percent indoor air humidity. Each change in temperature produces a corresponding change in the cooling load and unit performance equations.

Heat Pump

The baseline heat pump used for this simulation was assumed to have a nominal cooling capacity of 35,000 Btu/h and coefficient of performance (COP) of 3.69. The unit had an assumed water flow rate of 0.03 m^3/min (9.0 gallons per minute) and airflow of 34 m^3/min (1200 cfm). The unit was assumed to have been installed outside the conditioned space. Installing it in the conditioned space would allow heat rejected from the compressor shell which would have increased the cooling load in summer.

Equations relating the heat rejection rate, capacity, and power demand to the EWT and return air enthalpy as the independent variables in cooling operation were developed from manufacturer's data. Return air enthalpy was chosen because the capacity of the evaporator varied with the moisture content in the air flowing over it. Return air enthalpy was chosen since the capacity of a wet evaporator is primarily a function of enthalpy difference [McQuiston and Parker, 1988].

Lower EWTs in cooling benefit performance by lowering the condensing pressure in the system. This lower pressure means an increase in capacity and a drop in power consumption. GSIM needs the heat pump cooling capacity, power and heat rejection as a function of return air enthalpy and entering water temperature. The relationships between these variables for the baseline unit is shown in Figure 5 through 7.

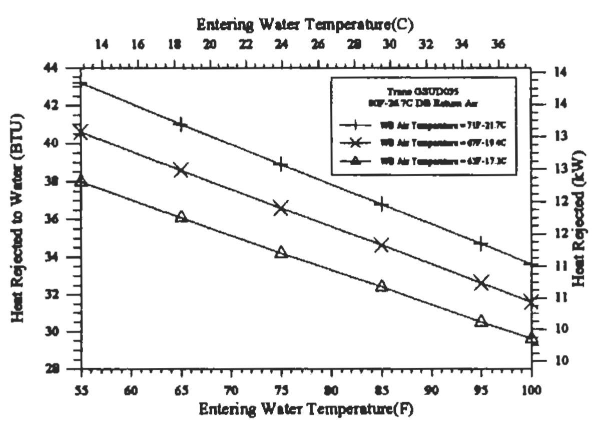

Figure 5 - Heat rejection with entering water temperature for cooling operation

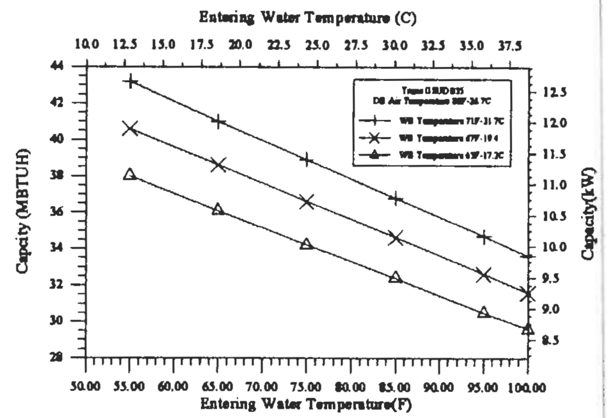

Figure 6 - Capacity variation with entering water temperature for cooling operation

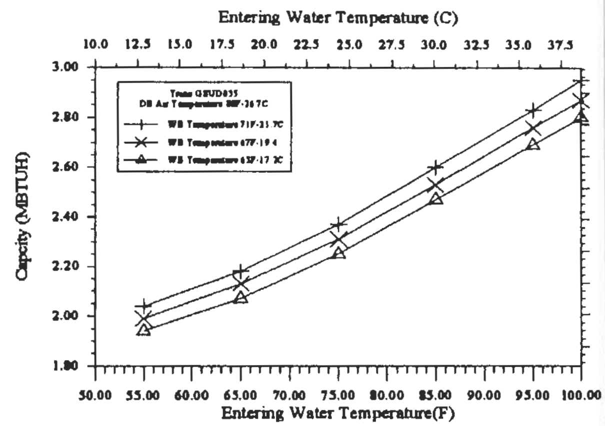

Figure 7 - Variation of power with entering water temperature for cooling operation.

Heat Exchanger Configuration

Many configurations exist for ground coupled heat pumps. This sizing procedure is limited to vertical U-tube heat exchangers. One U-tube per ton of rated cooling capacity (one U-tube per 3.52 kWh) was used. For a three loop heat exchanger, it was assumed that the flow divides equally among the three loops. The tubing material was assumed to be polyethylene. This assumption should have minimal effect on the results because most of the thermal resistance to heat transfer is in the soil surrounding the tubing. Other assumptions relating to the tubing are shown in Table 3.

Table 3- Polyethylene Pipe Characteristics

Pipe Thermal Conductivity (Btu/h-ft.-°F)	Inner Radius (in)	Outer Radius(in)
0.225	0.43	0.525

Entering Water Temperature

Probably the most critical assumption in the sizing procedure relates to the criteria associated with the entering water temperature (EWT). GSIM, estimates the EWT throughout an annual simulation of the performance of a unit. For cooling operation, it is desirable to maintain as low an EWT as possible. Lower EWTs produce higher efficiencies and higher capacities. However, lower EWTs require larger heat exchanger lengths. Determining the maximum acceptable EWT for the unit is ultimately a question of economic tradeoff. A maximum average EWT of 35°C (95°F) for any on-cycle during the cooling season was chosen as the criteria for sizing the heat exchanger. The maximum average cycle EWT is given by:

$$T_{max} = \frac{1}{t_{cycle}} \int_{t_{cycles}} EWT dt \qquad (2)$$

This means that the highest average entering water temperature for any cycle during the cooling season was 35°C (95°F). Satisfying this criteria required making many runs of GSIM at different heat exchanger lengths to finally have a length that would just satisfy the criteria. This criteria was chosen because it appears to provide a system with acceptable performance without producing excessively long lengths of heat exchanger. Higher ground coil temperatures would lead to a significant degradation in the efficiency of the ground coupled heat exchanger. The effect of this assumption is investigated in the sensitivity section (Part II) of this paper.

SIMPLIFIED SIZING PROCEDURE

The following must be identified to use the simplified sizing procedure:

1) soil thermal conductivity, temperature and density,

2) average summer air temperature and daily range in air temperature, and

3) desired indoor set air temperature.

GSIM was run with a wide range of weather, cooling load, heat pump performance, soil and heat exchanger information. The results obtained from GSIM were combined into a form of simple charts that allow for estimation of coil length needed. The general methodology procedure for using the charts is to first calculate a "base" length, L_b, of heat exchanger needed given the average summer air temperature, soil thermal conductivity and average daily temperature swing. This length is then "corrected" for indoor air temperature, ground temperature, and soil density:

$$L_{ground\ coil} = L_b * C_{it} * C_{gt} * C_{density} \qquad (3)$$

where, L_b = base chart value (Fig. 10 or 11)
C_{it}= indoor temperature correction (Fig. 12)
C_{gt}= ground temperature (Fig. 13)
$C_{density}$ = soil density correction (Fig. 14)

$L_{ground\ coil}$ signifies the bore hole depth in feet per ton of cooling.

Each of the charts used to estimate the variables in the above equation is discussed below. This procedure assumes proper sizing of the heat pump to peak cooling load on the house.

Base Length, L_b

Figures 8 and 9 depict the base chart for the sizing of ground coupled heat pumps. The "base" conditions are: an indoor air temperature of 24°C (75°F), ground temperature of 21.1C (70°F), ground density of 1766 kg/m^3 (110 lb/ft^3), and a daily air temperature range of 6.7 to 10°C (12 to 18°F). These base conditions are presented in Table 4. The curves on the chart represent different values (0.5, 1.0, 1.25, and 1.5 Btu/h-ft-°F) of thermal conductivity. GSIM runs were made using a wide range of weather files with average summer air temperatures of 23.9,26.7 and 29.4 °C (75,80 and 85 °F). Average summer air temperature files were created to simulate a 2160 hour cooling season. Loop lengths were chosen to provide a maximum average heat pump EWT for any cycle of 35 °C (95 °F).

Table 4 - Base Conditions Utilized in Figure 8.

Indoor Temp	Ground Temp	Soil Density	Daily Air Temp Range	Coil Loops	Max Cycle Loop Temp	Cool. COP
75°F	70°F	110 lb/ft^3	12 to 18°F	1/ton	95°F	3.69
24°C	21°C	1766 kg/m^3	7 to 10° C	1/3.5 kW	35°C	3.69

Figure 9 is similar to the previous chart but the daily range in air temperature has been changed to 12.2 to 14.4°C (22 to 26°F). The assumptions used for this chart are listed in Table 5. Applications subjected to large temperature swings needed longer coil lengths to provide the same EWTs as applications with the same average air temperature and smaller temperature swings. Large temperature

Table 5 -Base Condition Utilized in Figure 9.

Indoor Temp	Ground Temp	Soil Density	Daily Air Temp Range	Coil Loops	Max Cycle Loop Temp	Cool. COP
75°F	70°F	110 lb/ft^3	22 to 26°F	1/ton	95°F	3.69
24°C	21°C	1766 kg/m^3	12 to 14°C	1/3.5 kW	35°C	3.69

swings produced higher peak temperatures. High peak air temperatures resulted in larger cooling loads. This meant that for the same size ground coil, the heat pump had longer on-times and higher EWTs than a similar site with a smaller temperature swing. During the peak portions of the day, there is little time for the ground surrounding the heat exchanger to recover between cycles. Thus, to maintain the requirement of a maximum average cycle EWT of 95°F (35°F), the ground heat exchanger length must be longer in the climates with the larger daily temperature swings.

Indoor Air Correction, C_{it}

The base charts accounted for only a fraction of possible applications. Correction factors were needed for applications throughout Texas. GSIM runs were made holding all variables constant except the one being investigated. An example is the indoor air correction factor. Computer simulations were made with conditions duplicating those in the base chart except that indoor air temperature was varied between 21.6 and 26.7 °C (70 and 80 °F) to produce the values found in Figure 10. This had the effect of changing the thermal load on the residence. As the indoor to outdoor temperature difference was increased the thermal load increased, necessitating longer heat exchanger lengths to produce acceptable heat pump inlet water temperatures.

Ground Temperature Correction, C_{gt}

The effect of ground temperature on the required length of the ground coil is shown in Figure 11. For this chart, 21.1°C (70°F) was taken as the base condition(C_{gt}=1). The data presented in Figure 11 shows the dramatic impact of higher ground temperatures on the increase in length of the ground heat exchanger. For example, having to install a system at a location where the ground temperatures are 80°F rather than 70°F increases the heat exchanger length by over 75%.

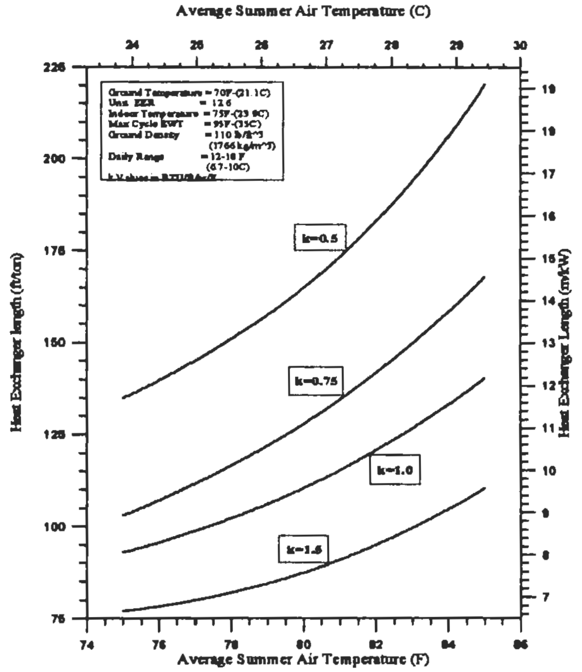

Figure 8- Base Sizing Chart for Small Temperature Swings.

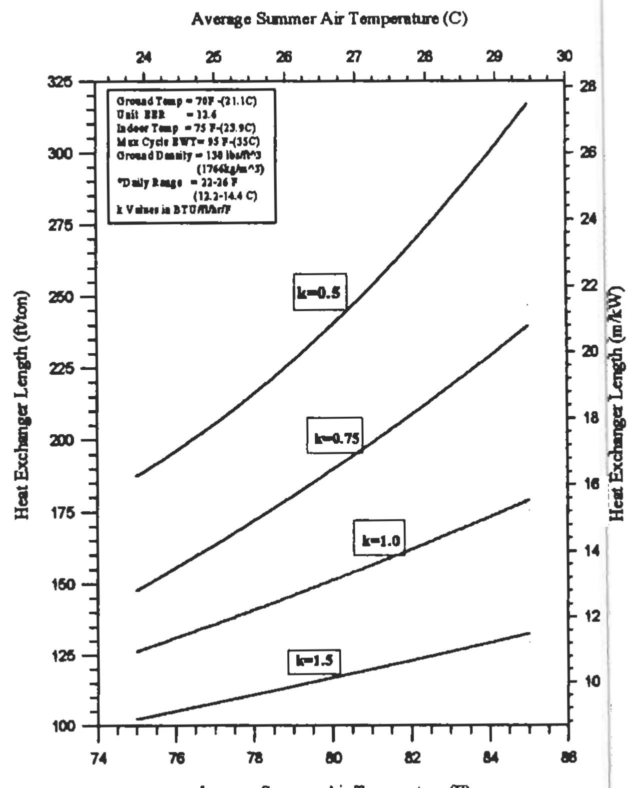

Figure 9 - Base Sizing Chart for Large Temperature Swing

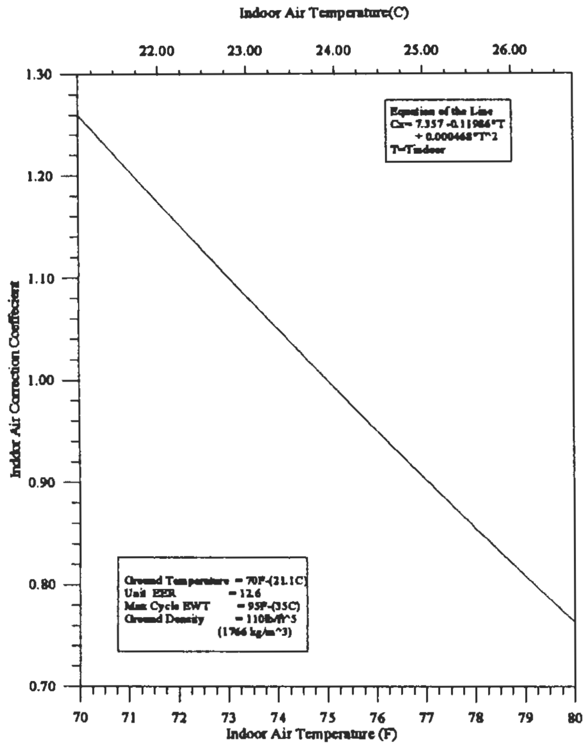

Figure 10 - Indoor Set Air Temperature Correction Chart

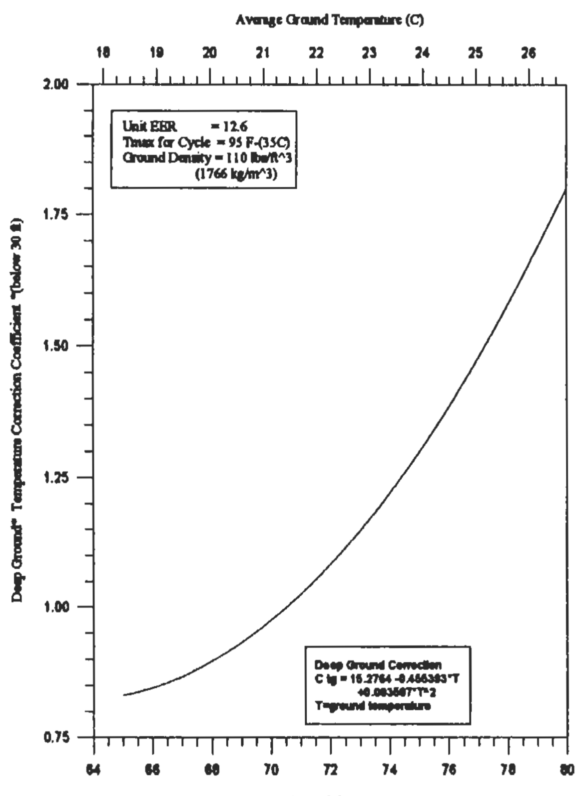

Figure 11 - Ground Temperature Correction Chart

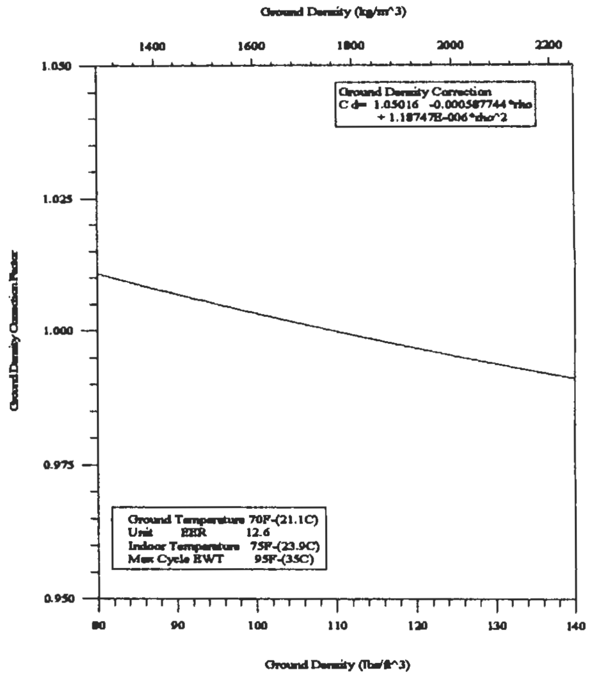

Figure 12 - Density Correction Chart

Density Correction, $C_{density}$

Density was shown by Margo [1992] to have only a small effect on heat exchanger performance. GSIM runs were made using all six weather files and all four of the soil thermal conductivity values mentioned earlier. Figure 12 provides a correction for the density values encountered throughout Texas. The chart shows that the effect of density is small (less than 2 percent) in the range of soil densities that would be expected in Texas applications.

EXAMPLE: HOUSTON

To illustrate the use of the method, sample calculations for a GCHP installation in Houston are detailed. The charts in Figures 8 through 12 require that the following information be specified: average summer air temperature, soil thermal conductivity, indoor air temperature, ground temperature and soil density. Table 6 lists the assumed values for this example:

Because Houston in located in coastal region of Texas, it's daily range of temperatures would fall in the 12 to 18 °F range. Therefore, Figure 10 would be more appropriate for sizing the heat exchanger loops in that city. The values of the coefficients in

Table 6 - Value of variables used for this example.

Item	Value
Location	Houston/Galveston
Average Outdoor Air Temp	82°F
Soil Thermal Conductivity	0.65 Btu/ft/hr/F
Indoor Air Temp	75°F
Ground Temp	80°F
Soil Density	94 lb/ft^3

Table 7 - Values of coefficients in Equation (3) and length of ground heat exchanger needed in Houston.

Item	Value
L_h	160 ft/ton
C_{it}	1.0
C_{gt}	1.8
$C_{density}$	1.01
Lground coil	290 ft/ton

Equation (3) along with the estimated length for a Houston application are shown in Table 7. For Houston, the estimated length of heat exchanger needed for a ground coupled heat pump would be approximately 290 ft/ton.

RESULTS FOR SOME CITIES IN TEXAS

The simplified technique was used to estimate the ground heat exchanger lengths of residential GCHP applications in major cities in Texas. The values for soil density and soil temperature were estimated from Table 1 and Figure 4, respectively. The soil thermal conductivities were estimated from some of the detailed soil data used to construct Figure 3. The results are listed in Table 7. The values for indoor temperature, soil density, soil thermal conductivity, indoor air temperature and ground temperature are listed for each of the cities.

As can be seen in Table 8, the estimated ground heat exchanger lengths vary from 175 feet in Amarillo to 373 feet in Brownsville. Both locations have relatively poor soil thermal conductivities. However, the ground temperature in Amarillo is 63° F versus 80°F in Brownsville. In addition, Amarillo has an average summer air temperature of 77°F versus 84°F in Brownsville. Both factors would require a much larger heat exchanger length in Brownsville.

It is important to note that the heat exchanger lengths in Table 8 depend on thermal conductivity data estimated at a specific location in each city. It is highly recommended, when possible, that soil samples be taken at a given location to determine the thermal conductivity for a GCHP installation.. A different thermal conductivity value could make a significant difference in the amount of heat exchanger needed. For example, if a unit were to be installed in the Rio Grande Valley at a location where the thermal conductivity was 0.75 Btu/(h-ft-°) rather than the 0.49 Btu/(h-ft-°F) used in Table 8, the length of heat exchanger would drop from 370 to 290 feet.

SENSITIVITY OF THE TECHNIQUE

The simplified method for sizing the ground heat exchanger of a ground coupled heat pump utilized a number of important assumptions. The sensitivity of the results to changes in the maximum entering water temperature and over/undersizing of the heat pump is examined below.

Maximum EWT Criteria

GSIM was used to quantify how the change in the maximum entering water temperature (EWT) criteria would affect the coil length. In the base case, it was assumed that the maximum EWT for a cycle was 35°C (95°F). This value was chosen because it provides reasonable performance for a GCHP. However, a GCHP purchaser may wish to reduce the initial cost of installation by allowing the maximum EWT to be higher than assumed here and thus requiring a smaller ground loop. Table 9 and Figure 13 show how the maximum cycle EWT criteria affects the heat exchanger length for an application in the Houston area. Because GSIM is a transient program, it can provides estimates of the Seasonal Energy Efficiency Ratio (SEER) of the heat pump and average on-times during the cooling season. These are also provided in Table 9.

Increasing the EWT above the 95°F criteria decreases the heat exchanger length. The shorter heat exchanger lengths decreases the SEER and increases the average on-time for the heat pump. For Houston, the estimated SEER dropped from 12.2 to 12.0 as the maximum cycle EWT was increased from 95.3 °F to 96.6°F. However, the estimated loop length dropped from 300 to 250 ft for this small change in EWT criteria. This would suggest that a Houston application could install loop lengths from 250 to 300 feet/ton without a significant degradation

Table 8- Sample Estimate of Heat Exchanger Lengths for Some Texas Cities Assuming an indoor temperature of 75 °F.

Location	Design Heat Exchanger Length (ft/ton)	Thermal Conductivity (Btu/h/ft/°F)	Soil Density (lb/ft^3)	Ground Temp (°F)	Design Temp (°F)	Average Summer Temp (°F)	Average Temp Swing (°F)
Amarillo	175	0.48	112	63	95	77	26
Austin	205	0.77	155	72	98	84	20
Brownsville	370	0.49	124	80	93	84	16
Bryan/College Station	220	0.71	120	73	96	83	21
Corpus Christi	210	0.89	101	77	94	84	11
Dallas	250	0.72	110	71	100	85	23
El Paso	270	0.48	107	71	98	81	27
Houston/Galveston	290	0.65	94	80	94	82	16
San Antonio	200	1.00	127	75	97	84	20
Waco	190	0.80	130	71	99	84	21

in performance. The results from the sensitivity analysis in Houston would suggest that the values calculated with Figures 8 through 12 could be reduced by 10% without a significant drop in performance.

Oversizing and Undersizing the Heat Pump

The effects of oversizing and undersizing the heat pump were studied using Houston weather data and GSIM. The performance (capacity and power) curves of the three ton heat pump were shifted up or down to produce a 8.78, 10.98 and 13.19 kW (2.5, 3.0 and 3.5 tons) cooling capacity units. The load on the residence was kept at a peak of 13.19 kW (35,000 Btu/h) at an outdoor air temperature of 40.6 °C (105 °F) and an indoor temperature of 23.9°C (75 °F). The coil length was maintained at a constant 315 feet/ton. The results are presented below in Table 10.

The results show that oversized systems provide the highest SEER values, shortest on-times and lowest maximum cycle EWTs. The undersized unit provided the lowest SEER values, longest on times and highest maximum cycle EWTs. The oversized unit required less time to satisfy the home cooling load than undersized units.

COMPARISON WITH OTHER SIZING METHODS

A comparison was made between the results of this method and those of two other published methods for sizing ground heat exchangers. For these comparisons, all parameters were held constant to find the coil length predicted by each method.

Table 9 - Effect of Varying EWT on Coil Length for Houston Using GSIM.

Max Cycle EWT (°F)	Loop Length (ft/ton)	SEER (Btu/W-h)	Avg On-Time (min)
117.2	100	9.0	26.6
115.1	125	9.9	23.9
105.3	150	10.6	22.5
102.0	175	11.1	21.6
99.5	200	11.4	20.8
97.6	225	11.7	20.1
96.6	250	12.0	19.7
95.9	275	12.2	19.4
95.3	300	12.2	19.2
94.8	325	12.3	19.2

*experimental conditions: soil thermal conductivity 0.64 Btu/h-ft-°F, indoor temperature 75°F, ground temperature 80°F, soil density 110 lb/ft^3, three loop system

Table 10- Results of Varying Heat Pump Size for Houston, TX.

Coil Length (ft/ton)	Cooling Capacity (Btu)	Max cycle EWT (°F)	Avg On-Time (min)	Circulating Time (min)	SEER (Btu/W-h)
315	30,000	98.4	30.5	16	11.6
315	36,000	95.6	18.1	16	12.4
315	42,000	90.7	14.0	16	12.9

The methods used in this comparison were the International Ground Source Heat Pump Association method presented by ASHRAE (1986) and the National Water Well Association method presented by Hart [1986]. The procedure for sizing the ground loops for each method are presented below. It is assumed that the heat pump has been correctly sized for the application. Soil, building and heat pump

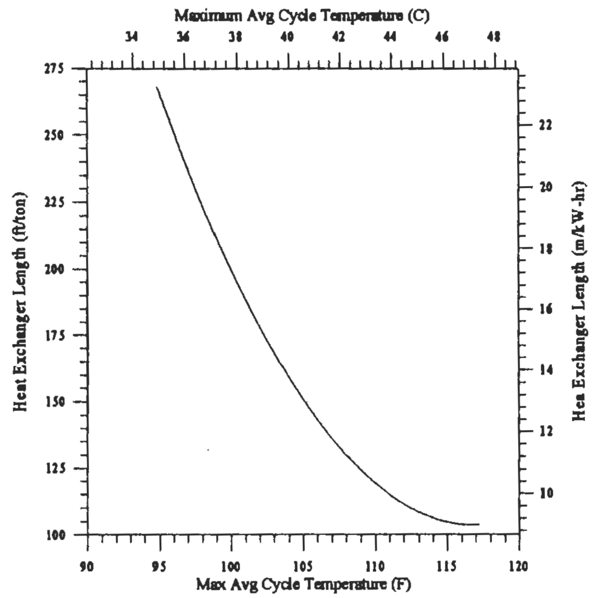

Figure 13- Effect of Varying EWT on Coil Length for Houston

characteristics were held constant for all three methods. A more detailed discussion of comparison of sizing techniques can be found in Gonzalez (1993).

For Houston, IGSHPA required a heat exchanger length of 465 feet, the NWWA required a length of 370 feet, while the current method would require a length of 290 feet. Obviously, there are large differences between the techniques and more detailed investigation would have to be conducted to ascertain why there are such large differences.

SUMMARY AND CONCLUSIONS

This paper presented a "first attempt" at a simplified technique for sizing the ground heat exchangers for ground coupled heat pumps in Texas. While other sizing procedures are available, the technique developed here was meant to be as simple to use as possible without sacrificing accuracy. As a part of the method, relevant soil temperature, thermal conductivity and density data for Texas were also presented. The results presented in this paper focused on a residential applications. With the assumption that the building load was primarily driven by weather, this procedure would not be applicable to commercial or industrial buildings. Likewise the application is limited to vertical U-tube installations where only one loop is placed in each bore hole.

While the data presented in the soil charts are useful for a "first cut" analysis of the heat exchanger lengths needed in a given location in the state, the authors warn the users that soil properties vary dramatically within a given city. In some locations, hot springs can be found in shallow depths, which could produce ground temperatures 10 to 30 °F above those presented here. Thermal conductivity is dependent on the type of soil. On one side a city, the soils may be clay and on the other, they may be predominately limestone. Thus, the user must take caution in blindly applying the results in this paper.

The basis of this technique is the computer program GSIM. While this program has proven to provide reasonable results for three applications where data were available, it has not been tested enough to say that it can handle as wide a range in conditions as found throughout the state. Thus, there may be changes to the model in future years that would require changes in the sizing procedure presented here.

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