

ENHANCEMENTS TO A GROUND LOOP
HEAT EXCHANGER DESIGN
PROGRAM

By

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Scope and Method of Study: The objective of this study was to enhance a ground loop heat exchanger(GLHE) design program.

1. Develop an algorithm for automatic selection of the borehole configuration based on the user-defined physical constraints.
2. Develop an optimization routine to minimize the life cycle cost of ground loop heat pump systems.
3. Allow the program to size GLHE based on the peak fluid temperatures entering the heat pump.
4. Provide a series of input checks and appropriate advice.

Finding and Conclusions: The following conclusions were found in this study.

1. Automatic selection of the borehole configuration (SELECT) has been implemented. SELECT helps the user to choose from the many possible configurations according to the field constraints.
2. A FORTRAN program, OPTIMIZE, has been written to minimize the life cycle cost of the ground-loop heat pump system with borehole depth as the independent variable. For the cases evaluated, the results show that the minimum life cycle cost is always coincident with the minimum borehole depth. The much higher first cost offsets the benefit from the lower annual operating cost with longer borehole depth.
3. Some checking and advising have been implemented in the program:
 - Fluid flow rate checking
 - Temperature setting checking
 - Peak load information checking

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CHAPTER I

INTRODUCTION

1.1 Overview

Ground source heat pump systems are increasingly popular in both residential and commercial applications. There are a number of reasons for this. They include: energy conservation, lower operating costs, and more balanced demand on the electric utilities.

Heat pumps have been identified as an efficient and economical alternative to the conventional heating and cooling systems. They have attracted a lot of attention and interest in recent years. A heat pump is a device which transfers heat from a low-temperature medium (source) to high-temperature one, or transfers heat from a low-temperature medium to a high-temperature one (sink). When operated to provide heat (e.g., for space or water heating), the heat pump is said to operate in the heating mode; when operated to remove heat (e.g., for air-conditioning), it is said to operate in the cooling mode. Heat pumps are attractive because the total energy output is greater than the energy used to drive it.

The ground is an attractive heat source and heat sink, since its temperature retains near constant throughout the year except for the upper 20 to 30 feet. It is a thermally more stable heat exchange medium than air, essentially unlimited and always available. Therefore, it has been utilized as the heat source or heat sink in HVAC systems for air conditioning, space heating, and water heating for both residential and commercial

buildings. The high initial cost of the ground-coupled heat pump system and the large land requirement are the major drawbacks, and have moderated the acceptance of these systems. However, as the price of electricity, and concerns over global environmental pollution have increased, more intensive interest has been shown in the ground-coupled heat pump system. Moreover, advancing technology in drilling and fabrications of ground-loop heat exchanger components, makes geothermal heat pump systems more and more cost effective. Also, because these systems are protected from harsh outdoor weather conditions, they tend to be more durable with lower maintenance requirements than conventional heat pump systems with exposed compressor units.

The ground loop heat exchanger used in conjunction with a closed-loop ground-source heat pump system consists of a system of long plastic pipes buried vertically or horizontally in the ground. The heat is extracted from or rejected into the ground along the buried pipes. A fluid, such as water or a brine, is circulated through the pipes, transferring thermal energy to or from the ground and the building.

1.2 Literature Review

Several models have been developed for the analysis and sizing of the ground-loop heat exchangers. The models are mainly based on the Kelvin's line source theory, cylindrical source theory, or numerical methods. Four major models are reviewed, and briefly summarized from section 1.2.1 to section 1.2.4 below. The models are: (1) Eskilson's

model (1987); (2) simple line source model (1948); (3) Hart and Couvillion's model (1986), and (4) Kavanaugh's model (1991).

1.2.1 Eskilson's Model

This model (Eskilson, 1987) is intended for sizing the vertical ground-loop heat exchanger. The mathematical formulation of Eskilson's model is governed by the heat conduction equation of the ground temperature in cylindrical coordinates:

$$\frac{1}{a} \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \quad (1.1)$$

The initial and boundary temperatures are assumed to be constant. The heat extraction function, $q(t)$ for N piecewise steps:

$$q(t) = \sum_{n=1}^N \{(q_n - q_{n-1}) * \text{He}(t - t_n)\} \quad (q_0 = 0) \quad (1.2)$$

Here He is Heavyside's step-function. By superposition, the time-dependent heat extraction step may be regarded as a sum of the basic extraction steps. Superposition of the step responses makes it possible to give a good description of the physical character of the heat extraction process. The simplified temperature functions are detailed below:

(A) Temperature at the borehole wall:

$$T_b = T_{om} - q_1 \times R_q(t) \quad (1.3)$$

where

T_b = Borehole temperature

T_{om} = Undisturbed ground temperature

q_1 = Extraction step

R_q = Thermal resistance due to extraction step

$$R_q = \frac{1}{2\pi\lambda} g(t / ts, r_b / H)$$

where

λ = Thermal conductivity of ground

$g = g(t/ts, r_b/H)$ (*the g-function*)

r_b = Borehole radius

t = Temperature

$$ts = \frac{H^2}{9\alpha} = \text{Steady state temperature}$$

where H = Borehole depth

α = Thermal diffusivity of the ground

The g-function is essentially the temperature response of the borehole field to a unit step function heat input. It is pre-computed for individual configurations using a finite difference program and spatial superposition.

(B) Mean Fluid Temperature:

At each depth H and time t , there is a local steady state process with heat flow between the pipe and the ground around the borehole. Variations of temperature along the pipes depend on pumping rate. When pumping rate is high the flow becomes turbulent so that the variation of temperature can be neglected. The correlation among borehole temperature, the mean fluid temperature and borehole resistance can be formulated as follows:

$$T_b - T_f = q * R_b \quad (1.4)$$

where

T_b = Average temperature at the borehole wall

T_f = Mean fluid temperature

q = Heat extraction step

R_b = Borehole thermal resistance

(C) Temperature variation along the borehole:

$$T_{f,in} = T_f - \frac{qH}{2C_f \rho_f V_f} \quad (1.5)$$

$$T_{f,out} = T_f + \frac{qH}{2C_f \rho_f V_f} \quad (1.6)$$

where

$T_{f,in}$ = Fluid temperature entering ground loop

$T_{f,out}$ = Fluid temperature exiting ground loop

q = Heat extraction

H = Active borehole depth

C_f = Fluid heat capacity

ρ_f = Fluid density

V_f = Pumping rate

Eskilson's model can account for different load profiles due to different building type, ground thermal conductivity, grouting, thermal interference effects of the nearby boreholes, and the effects of on/off equipment cycling on the heat transfer between the pipe and the ground. The main drawback of this model is that it does not have the capability to account for the varying conductivity, soil moisture, frozen or unfrozen soil state. Also, this model only offers fixed configurations; using these fixed configuration results in the surface area of the borehole field changing size every time the borehole depth is adjusted.

1.2.2 Simple Line Source Model

This model (Ingersoll and Plass, 1948) assumes that heat is transferred from an infinitely long permanent line source or sink with a constant strength in an infinite

medium (i.e., soil) at a uniform initial temperature T_0 . The subsequent temperature at any point of the medium is given by the equation

$$T - T_0 = \frac{Q'}{2\pi k} \int_x^\infty \frac{e^{-\beta^2}}{\beta} d\beta = \frac{Q'}{2\pi k} I(X) \quad (1.7)$$

where

$$X = \frac{r}{2\sqrt{\alpha t}}$$

T = Temperature in soil at any select distance from the pipe,

T_0 = Initial temperature of soil

Q' = Heat emission of pipe (negative for absorption)

r = Distance from the center line of pipe

k = Thermal conductivity of the soil

α = Thermal diffusivity of the soil

ρ = Density of the soil

t = time (hour) since start of operations

β = variable of integration

The temperature at any selected distance from the pipe can be calculated using Equation 1.7. Ingersoll and Plass states that this equation is exact only for a true line source, which means that the line source or pipe must be infinitely long, and the heat flow must be radial. It may introduce a negligible error after a few hours operation for the small pipe (2 in. diameter or less). For larger pipes (4 in. to 8 in.) and for period less than a few days

a significant error is involved. In its original formulation, this model does not account for thermal interference between boreholes, and the thermal properties of the grouting material. However, it has been extended to incorporate thermal interference, see Hart and Couvillion (1986) for example. Also, it can not account for the edge effects.

1.2.3 Hart and Couvillion's Model

This model (Hart and Couvillion, 1986) employs Kelvin's line source theory of continuous time-dependent heat transfer between the line source and the ground to derive a time-dependent temperature distribution around the line source.

$$T - T_o = \frac{Q'}{4\pi k_y} \int_0^{\infty} \frac{e^{-\lambda y}}{\lambda} d\lambda \quad (1.8)$$

where

$$y = \frac{r^2}{4\alpha t}$$

$$\lambda = \beta^2$$

The superposition principal is applied to model thermal interference effects (superposition in space). The important aspect of this model is the introduction of the far-field radius, r_{∞} . Couvillion and Hart state that the ground temperature at a distance from the line source greater than r_{∞} is assumed to be the far-field temperature. The value of the this far-field temperature mainly depends on the length of time the line source has

been operating, and the thermal diffusivity of the soil. The far-field radius is used to check for interference. It is computed by:

$$r_{\infty} = 4(\alpha t)^{0.5} \quad (1.9)$$

This model has similar limitations to the simple line source model, except it accounts for thermal interference using the concept of far-field radius and far-field temperature.

1.2.4 Kavanaugh's Model

Kavanaugh's model (1991) is based on the cylindrical source theory to determine the temperature distribution or the heat transfer rate. It is an exact solution for a buried cylindrical pipe of infinite length, and can be applied for either a constant pipe surface temperature or a constant heat transfer rate between the buried pipe and the earth. It assumes that the heat transfer between the borehole and soil with a perfect contact is pure heat conduction. The soil is considered to be an infinite homogeneous solid. The cylindrical solution for a constant heat flux is shown below:

$$T - T_o = \frac{Q'}{kL} G(z, p) \quad (1.10)$$

where

$G(z, p) =$ Cylindrical source integral.

$$z = \frac{\alpha t}{r^2}$$

$$p = \frac{r}{r_o}$$

r_o = Outer pipe radius

L = Pipe length

Kavanaugh also provides an equation to calculate the temperature difference across the closely positioned pipes for a non-uniform heat flux.

$$\Delta T_p = \frac{Q'}{CN_i 2\pi r_o L h_{eq}} \quad (1.11)$$

where

C = The correction factor for non-uniform heat flow

N_i = Number of U-tubes.

h_{eq} = Equivalent heat transfer coefficient per unit area

Kavanaugh's model accounts for the short circuit heat transfer within the borehole due to the temperature difference between the channels of the U-tube. It also has the ability to calculate the fluid temperature entering and exiting the ground heat exchanger.

1.2.5 Review Summary

Ideally, a perfect model for analysis and design ground-source heat pump systems should be able to predict how soil properties, soil moisture content, ground temperature distribution, piping materials and size, heat carrier fluid properties, and the heat pump

model impact the performance and size of the ground heat exchanger. Also, the model should be able to account for the equipment on/off cycling, seasonal earth temperature variation, and heat exchanger surface temperatures below freezing. However, because accounting for all these factors in one model would create a significant mathematical challenge, the above four models have different simplifications. Table 1-1 is the summary of the features of various models reviewed above.

Table 1-1 Features of Various Models

Model	Interactions Or Factors Account For			
	Eskilson's Model	Simple Line Source Model	Couvillion and Hart's Model	Kavanaugh's Model
Analytical Method	Numerical Model using a Line-segment Source	Line-Source	Line-Source	Cylindrical-Source
On/Off Cycling	Yes	No	Yes	Yes
Soil Moisture Freezing	No	No	Yes (approximate)	No
Thermal Interference Effects	Yes	No	Yes	Yes
Thermal effect of Grouting	Yes	No	No	Yes
Edge Effects	Yes	No	No	No

1.3 GLHEPRO Version 1.02

GLHEPRO, (Marshall and Spitler, 1994) the Professional Ground Loop Heat Exchanger design software, version 1.02 was developed at Oklahoma State University. It uses the methodology developed by Eskilson (1987). GLHEPRO can be used to design and study the vertical borehole-type ground loop heat exchangers. It can be used to perform a simulation of the ground loop heat exchanger to determine monthly average fluid temperatures, inlet fluid temperatures, and exit fluid temperatures in the borehole(s), the power consumed by the heat pump, and the heat extraction rate per unit length of borehole. More importantly, it can be used to determine the require borehole loop length that will satisfy a user specified temperature exiting the heat pump. Figure 1-1 is a flow chart of the operation of GLHEPRO. The program operates with a series of menu and input screens; it requires three basic sets of input data:

- Monthly heating and cooling loads on the heat pump - the average monthly loads can be entered manually or read from an output file that was created by a building loads analysis program, such as BLAST.
- Description of the ground loop heat exchanger- this includes the selection of the borehole configuration, borehole radius, borehole thermal resistance, and the ground properties, etc.
- User description of the heat pump - GLHEPRO uses curve-fit equations to describe the performance of the heat pump.

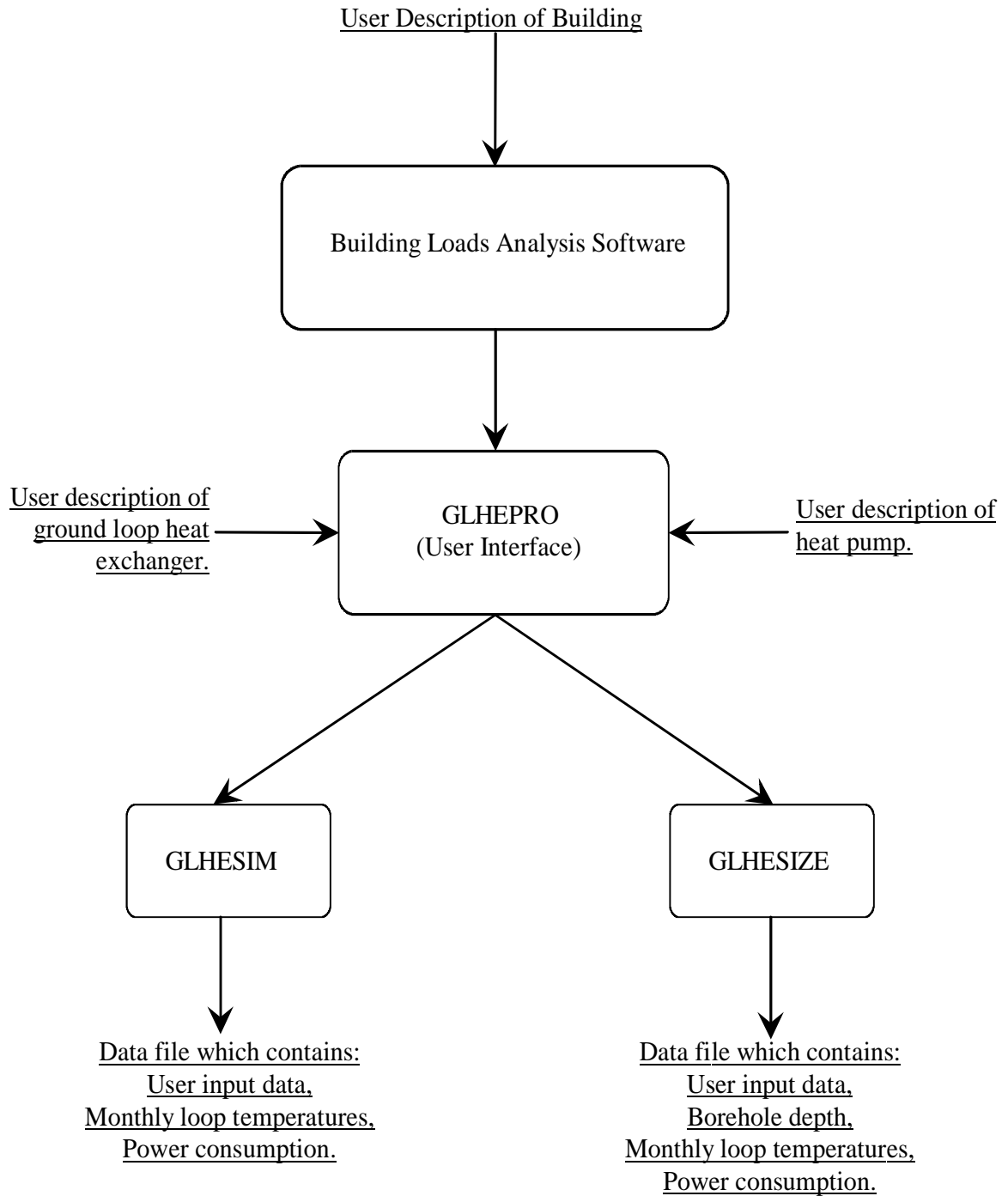


Figure 1-1 Flow chart of the operation of GLHEPRO

GLHEPRO utilizes two analysis programs written in FORTRAN, called GLHESIM and GLHESIZE, and a user interface user program written in C.

The user interface program allows the user to enter heat pump and ground loop heat exchanger data, as well as average monthly heating and cooling loads. It also collects information pertaining to various portions of the design process, such as the borehole configurations, selection of the circulating fluid properties, or selection of heat pump models. Once all the necessary data has been entered, the user interface program creates an input data file that consists of the description of ground loop heat exchanger, heat pump, and building loads, which will be used by either GLHESIM or GLHESIZE.

GLHESIM is used to run a simulation of the performance of the ground loop heat exchanger that was defined by the input data file generated by the interface program with a known borehole loop length. While it is running the simulation, it creates an output file which contains the monthly loop temperatures and the power consumption by the heat pump.

GLHESIZE is used to determine the required active borehole depth to meet a desired fluid temperature exiting the heat pump. Because it uses an iterative process to determine this borehole depth, the active borehole depth entered by the user will be used as an initial guess.

1.4 Daycare Center

A daycare center located in Oklahoma City, Oklahoma will be used as an example throughout this thesis. The center is a single-story building of about 4800 square foot, and it is Southwest facing. Figure 1-2 shows the floor plan.

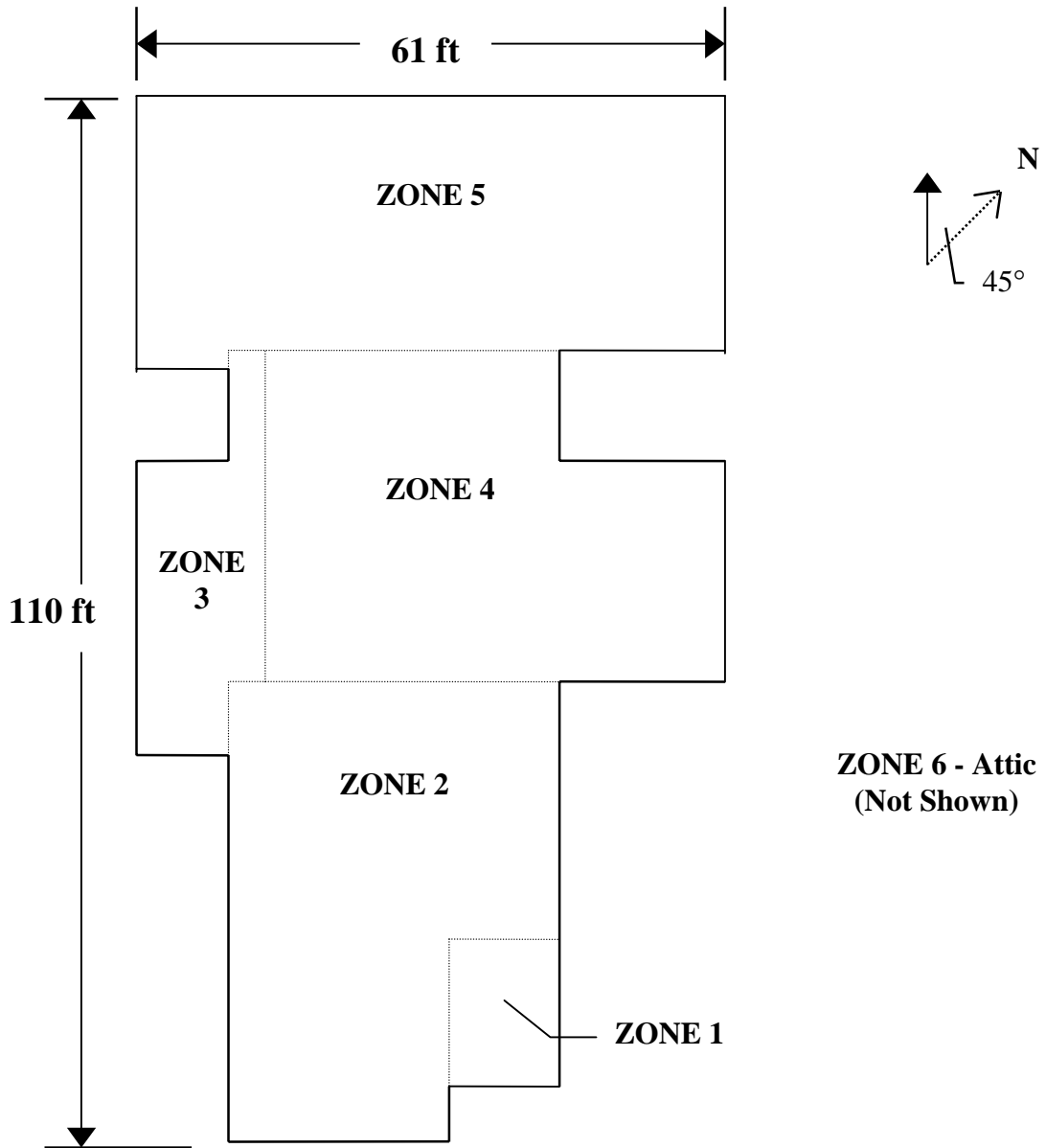


Figure 1-2 Daycare Center

The building and system energy demand is predicted by the Building Loads Analysis and System Thermodynamics (BLAST) program. BLAST requires an input file which has the detail description of the building, building materials, internal loads, control profiles, control schedule etc. Appendix 1 provides further details of the input file.

The building is divided into six thermal zones, and they are summarized in Table 1-2.

Table 1-2 Summary of the thermal zones of the daycare center

	Zone Description	# Occupants
Zone 1	Mechanical room - unconditioned zone (no heating and cooling provided)	0
Zone 2	Smurf room and storage room - include kitchen, bathroom and janitor room	25
Zone 3	Reception room and office - a lot of windows and glass doors	10
Zone 4	Muppet room, office and storage room - interior zone	25
Zone 5	Shirt tails room, explorer room and super friends room - exterior walls face northeast and northwest	30
Zone 6	Attic - space between the false ceiling and the roof	0

The monthly heating and cooling loads were analyzed using BLAST and are summarized in Table 1-3 below: The building utilizes a water loop heat pump system, and the peak cooling load is about 310 KBtu/Hr (26 tons).

Monthly Loads		
Month	Heating(Btu)	Cooling(Btu)

January	29940000.000	725200.000
February	23910000.000	358600.000
March	17920000.000	1769000.000
April	8233000.000	4817000.000
May	1386000.000	13990000.000
June	364500.000	29130000.000
July	25350.000	38870000.000
August	11140.000	42700000.000
September	874300.000	18570000.000
October	5782000.000	11080000.000
November	19540000.000	374800.000
December	25250000.000	495400.000
Peak Information		
	Heating	Cooling
Peak Hourly Loads	166700.000	309400.000
Peak load Month	2.000	8.000

Table 1-3 Summary of the monthly loads and the peak information from BLAST

1.5 Objectives

GLHEPRO version 1.02 was released in Fall of 1994. Since then, a number of desirable features have been identified. The objective of this study is to add those features.

The first objective of this study is to develop an algorithm for automatic selection of the borehole configurations based on the user-defined borehole field surface dimensions, and the maximum and minimum entering fluid temperatures. There are 185 different borehole configuration available in GLHEPRO. It can be tedious and time consuming to choose a reasonable and feasible configuration from the many possible borehole configurations when using the current version of GLHEPRO. The decision mainly depends on the user's experience. A program is intended to be implemented to help the user to select the possible configurations for a given set of physical constraints.

The second objective of this study is to develop an optimization routine utilizing the existing methodology. Initially, the optimization problem was limited to minimizing the life cycle cost with the borehole depth being the independent variable. Input parameters for the optimization would include drilling cost, piping cost, heat pump and circulating pump costs, operating cost, etc. The user-defined temperature constraints will constrain the minimum borehole depth. This is a one-dimensional optimization, and a unimodal search, such as golden section search, may be used to optimize the active borehole depth. In addition, other parameters that may be important such as the fluid flow rate, fluid type, and the piping size are investigated.

The third objective is to allow the program to size the ground loop heat exchanger based on the peak fluid temperatures entering the heat pump. With the addition of peak information, GLHEPRO may size systems with better descriptions of the energy demand of the buildings, and it will result a more reliable and accurate designs, which satisfy even the worst condition. The entering fluid temperature is preferred over the exiting temperature by most of the GLHEPRO users.

The fourth objective is to provide a series of input checks and appropriate advice when poor inputs are chosen. The new version of GLHEPRO is intended to be even more user-friendly than the version 1.02. Input parameters to be checked include: fluid flow rate, maximum and minimum entering fluid temperatures, and peak load information.

The fifth objective is to provide some guidance to the user on borehole resistance. This is investigated with a simple model using conduction shape factors.

CHAPTER II

AUTOMATED SELECTION

There are more than 180 different borehole configurations available in GLHEPRO. The configurations are the combinations of different number of boreholes, different arrangement of the boreholes, and different B/H values (B/H factor is the ratio of the distance between borehole centers, B to the active borehole depth, H). The borehole configurations describe the pattern of the boreholes at the surface of the ground, which varies in number from one borehole to one hundred boreholes, and includes shape such as squares, rectangles, “L’s” and U’s” etc.. The B/H factor varies from 0.05 to 1.0. Also, there are two types of borehole orientations, vertical and graded. Vertical borehole configurations are the configurations that have vertical boreholes. Graded borehole configurations have their boreholes inclined outward away from each other, and they are not perpendicular to the ground surface.

It is not an easy task to choose a reasonable and feasible configuration from the many possible borehole configurations when using GLHEPRO, and the decision mainly depends on the user’s experience and some common sense. For this reason, a program called ‘SELECT’ has been written to help the user select from the possible borehole configurations for a given set of physical constraints.

2.1 Program Description and Implementation

SELECT is the program to help the user to choose some possible borehole configurations according to the field limitations. It was originally written in FORTRAN, and translated to C language later for the convenience of implementation of the program into GLHEPRO. Appendix 2 contains the SELECT program source code.

First, the program asks the user to input the physical constraints: maximum field length, maximum field width, and maximum and minimum borehole depth. The depth range is used to select reasonable configurations according to the total loop length requirement. For instance, it is not practical to have one 2000 feet deep borehole, and it is not practical to have hundred 20 feet deep boreholes as well. The field length and width are the surface dimensional constraints of the borehole field. They describe how big the borehole field may be.

SELECT calculates an average total loop length internally by running GLHESIZE three times with different selected borehole configurations. The three borehole configurations are chosen based on the building load, and are listed in Table 2-1. The choice of borehole configurations has been made heuristically. The average total loop length is a rough estimation of the size of the ground loop heat exchanger with the given heat carrier fluid type, fluid flow rate, heat pump, building loads, borehole diameter, soil type, and the undisturbed ground temperature. Though the average total loop length is not the actual total loop length requirement for a particular configuration, it gives a reasonable first estimation of the ground loop size. However, some configurations may be shown to be feasible which are not feasible. (This will be determined when the user runs

GLHESIZE on the specific configuration.) Conversely there may be some configurations that are feasible, but are not found by SELECT.

Table 2-1 Category of testing configurations

Building Category	Testing Configurations
Peak Load < 20 tons (1 ton = 12,000 Btu/Hr)	G1005 - Nine boreholes in a square G1705 - Seven boreholes in an L configuration G0905 - Six boreholes in a rectangle
20 tons ≤ Peak Load < 60 tons	G1110 - Fifteen boreholes in a rectangle G1210 - Sixteen boreholes in a square G1505 - 6 x 2 boreholes in a rectangle
Peak Load ≥ 60 tons	G4810 - 6 x 6 (=36) boreholes in a square G4910 - 8 x 8 (=64) boreholes in a square G5010 - 10 x 10 (=100) boreholes in a square

After the calculation of the average total loop length, SELECT reads in a data file which contains the physical descriptions of all (146) vertical borehole configurations. It describes the number of boreholes, the B/H value, the spacing requirements in the surface dimensions according to the B/H factor and the pattern of the boreholes for each configuration. An example of the data file is shown below:

G1310 12 4.000 2.000 0.10

Figure 2-1 Example of the SELECT data file

The first item G1310 is the name of the configuration, it is a “Twelve Boreholes in a Rectangle”. The second item 12 states that there are twelve boreholes in this case. The third and fourth items describe the spacing requirements in terms of the number of the distance between the borehole centers for length and width respectively. The last item states the B/H factor, 0.1 here means that the ratio of the distance between the borehole centers to the active borehole depth is equal to 0.1, or $B = 0.1H$.

SELECT seeks the appropriate borehole configurations from the 146 vertical borehole configurations (the graded borehole configurations are not considered here) that are likely to meet the user-defined field constraints. Then, it prints out a list of the sorted possible borehole configurations according to the total number of boreholes. The following equations are employed to compute the borehole depth, the distance between the borehole centers, the field length and width requirements.

$$H = \text{tot_loop_len} / \text{NB} \quad (2.1)$$

$$B = H * (\text{B/H}) \quad (2.2)$$

$$\text{field_length} = \text{space_length} * B \quad (2.3)$$

$$\text{field_width} = \text{space_width} * B \quad (2.4)$$

where

H = Borehole depth

$\text{tot_loop_len} = \text{Total loop length}$

$\text{NB} = \text{Number of boreholes}$

$\text{B} = \text{Distance between the borehole centers}$

$\text{B/H} = \text{Ratio of B to H}$

$\text{field_length} = \text{Field length requirement}$

$\text{field_width} = \text{Field width requirement}$

$\text{space_length} = \text{Number of distance, "B" in length direction}$

$\text{space_width} = \text{Number of distance, "B" in width direction}$

The above equations show that once the average total loop length is obtained, the depth of each borehole may be obtained, and the distance between the borehole centers, B may be computed using the B/H factor. Then, the field length and width requirements may be found immediately after the B is calculated. Finally, SELECT checks whether the particular configuration satisfies the physical constraints:

- Is the borehole depth within the desired depth range?
- Are the field length and width requirements within the surface dimensions?

SELECT chooses the particular configuration if it satisfies these constraints.

SELECT not only provides useful information to the user, but also accelerates the optimization process later on. It reduces the number of possible borehole configurations from 146 to some reasonable number, such as 10, which depend on the constraints provided by the user. It is the first step of the optimization of the life cycle cost of the heat pump system, the details are shown in Chapter 3.

2.2 Example

The daycare center is used as an example to demonstrate how the selection is done by SELECT. The 20% GS4 solution is used as the heat carrier fluid with the flow rate of 65 GPM. The undisturbed ground temperature is assumed to be 55 °F, and the ground assumed to be an average rock soil with the thermal conductivity of 1.4 Btu/(Hr·ft·°F). Other input information of the borehole profile is detailed in Appendix 3, which contains the GLHEDATA.DAT file.

The borehole field is constrained to have surface dimension no greater than 50 ft by 50 ft. The maximum depth allowed is 300 ft, and the minimum depth is 150 ft. Using these inputs, SELECT gives the following results:

SUMMARY OF THE POSSIBLE BOREHOLE CONFIGURATIONS				
Total Loop Length	=	2871.5 ft		
Field Length Allow	=	50.0 ft		
Field Width Allow	=	50.0 ft		
Field Depth Allow	=	150.0 - 300.0 ft		
CONFIGURATION CODE	TOTAL NO. OF BOREHOLES	FIELD LENGTH REQUIRED	FIELD WIDTH REQUIRED	FIELD DEPTH REQUIRED
G1805	10	44.1	44.1	287.2
G1305	12	48.9	24.9	239.3
G1405	12	36.9	36.9	239.3
G1105	15	39.3	20.1	191.4
G1205	16	27.9	27.9	179.5
Total number of possible borehole configurations			=	5
NOTE: G1530 refers to Borehole configuration 15, B/H = 0.30				

Table 2-2 Results from SELECT for the daycare center

First of all, SELECT calculates the average total loop length by using the average value of the three testing cases, which is 2871.5 ft in this case. Then SELECT reads in the data file which contains the physical description of the borehole configuration, and checks whether the configuration satisfies the specified field constraints. SELECT goes through each of the 146 possible configurations, and finds 5 feasible borehole configurations for the daycare center under the field constraints stated above. The following example illustrates the selection process.

G1105 is one of the feasible configurations, it has fifteen boreholes in a rectangle, and the ratio of the distance between borehole centers and the active borehole depth (B/H) is equal to 0.05. Since the average total loop length is 2871.5 ft, and there are 15 boreholes, the active borehole depth is simply equal to $2871.5/15 = 191.4$ ft, which is within the

specified depth range. Once the borehole depth is found, the distance between the borehole centers, B can be determined using the B/H ratio (0.05), $B = 191.4 * 0.05 = 9.57$ ft. Since this configuration is 15 boreholes in a rectangle, it indicates that there are 5 boreholes in the length direction, and 3 boreholes in the width direction. Hence, the required field length is equal to $4 * 9.57 = 38.3$ ft. The same procedure is done for the field width requirement, and it is equal to 19.1 ft. It shows that both the field length and width requirements satisfy the specified field surface constraints (≤ 50 ft). Therefore, G1805 satisfies the field constraints, and it is a feasible configuration for the daycare center. One may notice that the calculated field length and width requirements, 38.3 ft and 19.1 ft respectively are 1 ft less than that in the result printout shown above. It is because SELECT applies this 1 ft as a rough estimate to account for the space requirement for the boreholes. The same selection process is done for the other configurations, and each of the selected possible configuration satisfies the specified field constraints.

One should pay attention that the average total loop length is only the average of the three pre-selected configurations. It is not the actual total loop length requirement for a particular selected configuration. For instance, the total loop length requirement for the Configuration G1105 is 2798.3 ft, which is slightly less than the average value; and for Configuration G1805, the actual total loop requirement is 2988.3 ft, which is about 4% higher than the average value. So, it is possible that SELECT will choose some configurations which may not ultimately fit in the user-constrained area. However, it

quickly finds a small subset which is *likely* to work, and may still significantly reduce the user's effort.

CHAPTER III

OPTIMIZATION WITH BOREHOLE DEPTH AS THE VARIABLE

This chapter presents an examination of optimal design of GLHE's with borehole depth, fluid flow rate, and pipe diameter as independent variables. Initially, the borehole depth was intended as the independent variable to optimize. Further investigation showed that that the optimal borehole depth was generally constrained to be the minimum depth required to meet the minimum or maximum fluid temperature. Then other variables were considered for significant potential for optimization, though no general-purpose optimization routines were developed for the other variables

3.1 Methodology

The objective function is chosen to be the life cycle cost. This includes the first installation cost and the annual operating cost. The mathematical expression of the life cycle cost (LCC) is given as:

$$LCC = FIC + N * AOC \quad (3.1)$$

where

LCC = Life cycle cost

FIC = First installation cost

N = Series present worth factor

AOC = Annual operating cost

3.1.1 *First Installation Cost*

The first installation cost of the heat pump system is estimated to be the total of

- drilling cost
- heat pump cost
- circulating pump cost
- pipe cost

It is difficult to write a function describing drilling cost, as they are highly variable with region of the country, size of the job, geology, etc. A first attempt is made here by treating the drilling cost as the sum of two components, a per foot cost and a per hole cost. The user must specify the per foot cost and the per hole cost. The heat pump cost and circulating pump cost are also assumed to be constant here. The sum of the first cost is formulated as:

$$\begin{aligned} \text{FIC} = & (\text{Drilling Cost /ft}) * (\text{Total Loop Length}) \\ & + (\text{Drilling Cost/borehole}) * (\text{Total Number of Boreholes}) \\ & + (\text{Heat Pump Cost}) + (\text{Circulating Pump Cost}) \\ & + (\text{Piping Cost/ft}) * (\text{Total Piping Length}) \quad (3.2) \end{aligned}$$

$$\text{Total Loop Length} = H * NB \quad (3.3)$$

where

H = Active borehole depth where heat exchange takes place

NB = Total number of boreholes

To account for the U-tubes, and account approximately for the header piping between the boreholes, the total piping length becomes

$$\text{Total Piping Length} = 2 * \{ \text{Total Loop Length} + (\text{BH} * \text{H} * \text{NB}) \}$$

(3.4)

where

BH = ratio of the distance between borehole centers to the
active borehole depth

This is a rough estimate and does not include all header costs. It does take into account the effect of spacing the boreholes further apart though.

3.1.2 Present Worth

To compare the life cycle cost, it is necessary to determine the present worth of the annual operating cost. Assume that the annual operating cost of the heat pump system during its life span is a constant, the series present worth factor translates the value of this series of uniform amount of annual operating cost into the present worth (Stoecker, 1989). The series present worth factor is given by

$$N = [(1+i)^n - 1] / [i(1+i)^n] \quad (3.5)$$

where

N = Series present worth factor

i = y = Yearly interest rate

n = Number of the years

The ground loop heat pump for this study is assumed to be in operation for 20 years. For optimization purposes, it is necessary to calculate the present worth of 20 years of operating cost of the ground loop heat pump and circulating pump.

3.1.3 Annual Operating Cost

The annual operating cost of the ground loop heat pump is the sum of the operating cost for the heat pump and the operating cost for the circulating pump.

$$AOC_TOT = AOC_HP + AOC_CP \quad (3.6)$$

where

AOC_TOT = Total annual operating cost

AOC_HP = Annual operating cost for heat pump

AOC_CP = Annual operating cost for circulating pump

The annual operating cost for the heat pump is obtained by using the power requirements determined by GLHESIM. The annual operating cost for the circulating pump is obtained by considering the power requirements to account for the head losses in the pipe flow.

A. Annual Operating Cost for Heat Pump:

The power requirement to operate the heat pump is determined by GLHESIM, based on the coefficients obtained by curve fitting the data from the heat pump manufacturer. A quadratic curve is used to determine the power required for heating and cooling as follows:

$$\text{Power for cooling (kw)} = Q_C(d + e(\text{EFT}) + f(\text{EFT})^2) \quad (3.7)$$

$$\text{Power for heating (kw)} = Q_H(x + y(\text{EFT}) + z(\text{EFT})^2) \quad (3.8)$$

where

Q_C = Cooling loading per month

Q_H = Heating loading per month

EFT = Entering fluid temperature to heat pump

d, e, f, x, y and z = Coefficients obtained from curve fit

Once the power requirements are found for the heat pump, the annual operating cost is given by the following formula:

$$\text{AOC}_{\text{HP}} = (1/10) * \left\{ \sum_{\text{month} = 1}^{120} [\text{Power}_{\text{HP}} * (\text{Days}/\text{month}) * (24 \text{ hours}/\text{day}) * (\text{Cost}/\text{KWH})] \right\} \quad (3.9)$$

where

AOC_HP = Annual operating cost for heat pump

Power_HP = Average monthly power requirement by heat pump

Days/month = Number of days in a particular month

Cost/KWH = Electricity cost per KWH

The power requirement for the heat pump is the sum of power requirements in both cooling and heating modes. In order to have a good prediction of ground loop heat pump performance, this optimization calculates the power required for the heat pump for 10 years (120 months) by GLHESIM. To apply the series present worth factor, we have to take the average monthly values of the 10 year operating cost.

B. Annual Operating Cost for Circulating Pump:

Before determining the power required by the circulating pump, the head loss of piping system has to be calculated first. The head loss is given by

$$H = f \left(\frac{L}{D} \right) \frac{V^2}{2g} \quad (3.10)$$

The value of the friction factor (f) can be determined using the empirical formula taken from Bose (1985) as follows:

- *For laminar flow*

$$f = \frac{64}{Re} \quad (3.11)$$

- *For turbulent flow*

$$f = \frac{0.3164}{Re^{0.25}} \quad \text{for } Re \text{ up to } 10^5 \quad (3.12)$$

$$f = 0.0032 + \frac{0.221}{Re^{0.237}} \quad \text{for } 10^5 < Re < 3 \times 10^6 \quad (3.13)$$

where

H = Head loss in piping (m)

f = Friction factor

L = Total pipe length in a circuit (m)

D = Pipe inside diameter (m)

V = Fluid velocity (m/s)

g = Gravity (9.8 m/s²)

Re = Reynolds number = $\frac{VD\rho}{\mu}$

V = Fluid velocity (m/s)

D = Pipe inside diameter (m)

ρ = Fluid density (kg/m³)

μ = Fluid viscosity (N s/m²)

After calculating head loss, the required power for circulating pump can be calculated from the following formula:

$$\text{Power_CP (watt)} = \{\rho g Q (H_TOT)\} / \eta \quad (3.14)$$

where

Q = Fluid volume flow rate (m³/s)

H_TOT = Total head loss in system (m)

η = Typical heat pump efficiency (assumes 0.8 here)

Note that head loss due to elbows and other fittings is neglected in the calculation of H_TOT. The loss due to elbows and other fittings is relative insignificant compare the loss due the long straight pipe in GLHE.

The annual operating cost of the circulating pump can be computed once the power requirement is found. The annual operating cost of the circulating pump is given by the formula similar to the one for the heat pump.

$$\text{AOC}_{\text{CP}} = \sum_{\text{month} = 1}^{12} \{ \text{Power}_{\text{CP}} * (\text{Days/month}) * (24 \text{ hours/day}) * (\text{Cost/KWH}) \} \quad (3.15)$$

where

AOC_{CP} = Annual operating cost for circulating pump

Power_{CP} = Power requirement by circulating pump

Days/month = Number of days in a particular month

Cost/KWH = Electricity cost per KWH

3.1.4 Optimization

The life cycle cost of the vertical ground loop heat pump system can be minimized by varying parameters such as borehole depth, fluid flow rate, pipe diameter, and fluid flow circuit etc. For this study, the active borehole depth where heat transfer takes place was initially chosen as the variable to optimize. Since the ground-loop heat pump system requires the minimum borehole depth to keep the fluid temperature exiting the heat pump within a temperature range specified by the user, a constant is placed on borehole depth (minimum borehole depth).

Since only one variable, active borehole depth is optimized, a golden section search is chosen to perform this one-dimensional optimization to minimize the life cycle cost for

the heat pump system. While keeping everything else constant, the minimum value of objective function (life cycle cost) is searched by varying the borehole depth between the minimum depth and maximum depth specified. The objective function in this case is a unimodal function. As explained by Stoecker (1989), a unimodal function is one having only one peak (or valley) in the interval of interest. In this case, it means that there is only one minimum life cycle cost for the system in the specified range of borehole depth.

The concept of a golden section search in one-dimension is explained by Press, et. al. (1992) It guarantees that each new function evaluation will bracket the minimum to an interval of 0.61803 (R_{golden}) times the size of the preceding interval after self-replicating ratios have been achieved. At each stage, it brackets three points, the next point to be evaluated is that which is a fraction 0.38197 , $(1 - R_{\text{golden}})$ into the larger of the two intervals (measuring from the central point to the triplet). A simple algorithm is listed below:

1. Given a unimodal function, f with boundaries, a and c , pick a point, b between a and c randomly to form a bracketing triplet. (Note: if start out with a bracketing triplet whose segments are not in the golden ratios, the procedure of choosing successive points at the golden mean point of the larger segment will quickly converge you to the proper, self-replicating ratios).
2. Place an observation point $0.38197I_o$ in the larger of the two intervals (measuring from the central point of the triplet).
3. Repeat step 2 until a desired interval is reached.

3.1.5 Program Description

The golden section search has been implemented into a FORTRAN program, called OPTIMIZE.FOR (refer to the program listing in Appendix 4) to determine the minimum life cycle cost of the ground-loop heat pump system. First, the program reads in the economic data input by the user as show below:

Multiplier of the First Installation Cost (FIC), a	1.000
Number of years, n	20.000
Annual interest rate (%)	8.000
Drilling cost per borehole (\$)	0.000
Drilling cost per foot (\$)	4.000
Electricity cost per KWH (\$)	0.110
Heat pump cost (\$)	5000.000
Circulating pump cost (\$)	1000.000
Number of boreholes per circuit	4.000
Minimum borehole depth (ft)	114.030
Maximum borehole depth (ft)	150.000
Inside diameter of the pipe (in)	1.554
Piping cost per foot (\$)	0.560

Table 3-1 Economic data for optimization

Other input data comes from GLHEDATA.DAT for the Daycare Center, shown in Appendix 2.

It calculates the series present worth factor (N) by using the annual interest rate and the number of years. Then, it starts the Golden Section Search as described above to bracket the minimum life cycle cost. This search process will continue until the bracketing interval is acceptably small (0.1 ft in this case). Finally, it outputs the minimum life cycle cost, as well as the corresponding borehole depth in a file called OPTIMIZE.OUT (refer to Appendix 5).

OPTIMIZE.FOR includes the following subroutines to determine the annual operating cost for the heat pump, annual operating cost for the circulating pump, and the first installation cost:

1. HP_AOC Determines the annual electricity cost of the Heat Pump based upon the power requirements calculated by GLHESIM.
2. CP_AOC Determines the annual electricity cost of the circulating pump.
3. FICOST Determines the first installation cost of the heat pump system.
4. GLHESIM It is called by the subroutine HP_AOC to determine the power requirements for the heat pump. GLHESIM reads in the data file, GLHEDATA.DAT

3.1.6 Optimization with Multiple Borehole Configurations

Minimization of the life cycle cost of the ground-loop heat pump is done with the co-operation of SELECT, GLHESIZE, and OPTIMIZE. Both SELECT and GLHESIZE are implemented in GLHEPRO.

SELECT basically helps the user to choose the possible borehole configurations and appropriate B/H (ratio of the distance between borehole centers to the active borehole depth) value for a given set of physical constraints: field length, field width, maximum and minimum field depth.. It determines whether a particular configuration is acceptable for the set of the constraints. Then, it will print out a list of the sorted possible borehole configurations according to the total number of boreholes. The average total loop length is provided internally inside GLHEPRO by calling 'GLHESIZE' several times to obtain the average value. The program accelerates the optimization process by reducing the number of possible borehole configurations from 185 to some reasonable number, such as 10, which depends on the constraints provided by the user.

After SELECT chooses a reasonable number of possible borehole configurations, GLHESIZE is then used to check each of these possible configurations to determine whether the active borehole depth of these configurations are actually within the range of the field depth specified by the user. Recall that SELECT only approximately estimates total loop length.

Then, OPTIMIZE is used to minimize the life cycle cost for each of the remaining possible configurations, and compares the minimum cost for each configuration to determine which one results the minimum life cycle cost amount of them.

As mentioned above, a daycare center near Oklahoma City, OK will be used as an example to demonstrate how the optimization with multiple borehole configurations is done.

3.2 Example

SELECT was run for the daycare center described in Section 1.4. The detailed results are shown in Appendix 6. Using the physical constraints: field length = 30 feet; field width = 30 feet; range of field depth = 30 to 150 feet; and the average total loop length = 1510.4 feet., 7 possible borehole configurations are chosen. Table 3-2 summarizes the results.

Table 3-2 Summary of results from SELECT

Configuration Code	Number of Boreholes	Configuration
G1305	12	3 × 4
G1405	12	in a square
G1105	15	3 × 5
G1210	16	4 × 4
G1205	16	4 × 4
G4810	36	6 × 6
G4710	50	5 × 10

Then, GLHESIZE was used to check each of the above 7 possible borehole configurations to determine whether they actually satisfy the range of field depth, which ranges from 30 to 150 feet. Table 3-3 summaries the results:

Table 3-3 Summary of the validating results using GLHESIZE

Configuration Code	Actual Borehole Depth (ft)	Status
G1305	163.69	Fail
G1405	162.53	Fail
G1105	153.85	Fail
G1210	114.03	OK
G1205	149.62	OK
G4810	69.70	OK
G4710	58.14	OK

Table 3-3 shows that the first three configurations do not satisfy the field depth constraint (maximum depth \leq 150 ft) when validated by GLHESIZE and resulting the actual borehole depths. So, the total number of possible configurations is down to 4.

Once the actual possible borehole configurations are found, OPTIMIZE is used to perform the minimization of the life cycle cost for each of the above 4 remaining configurations. Table 3-4 summarizes the results by running the OPTIMIZE, using the 1.5'' nominal size high-density polyethylene, SDR-11 pipes.

Table 3-4 Summary of the results from OPTIMIZE

Configuration Code	# borehole/circuit	Min. LCC (\$)	depth (ft)
G1210	4	33797.21	114.07
G1205	4	34952.23	149.65
G4810	4	33837.88	69.73
G4710	5	34655.79	58.18

From Table 3-4, it indicates that the Configuration G1210 (16 boreholes, 4 by 4, B/H = 0.1) has the lowest minimum life cycle cost with the corresponding depth of 114.07 feet. Also, one may notice that the minimum costs occur at the minimum depth requirement by each configuration. It seems that the piping cost, annual operating cost for the circulating pump, and the drilling cost offsets the benefit of the lower annual operating cost for the heat pump with longer borehole depth. Even with assumptions of very high electricity cost (11 cents/KHW), very low drilling cost (\$1/ft, and drilling cost per hole = 0), the same results are observed.

Figure 3-1 shows how the life cycle cost varies with borehole depth for the Configuration 1210, with 4 boreholes per circuit (refer to Appendix 7).

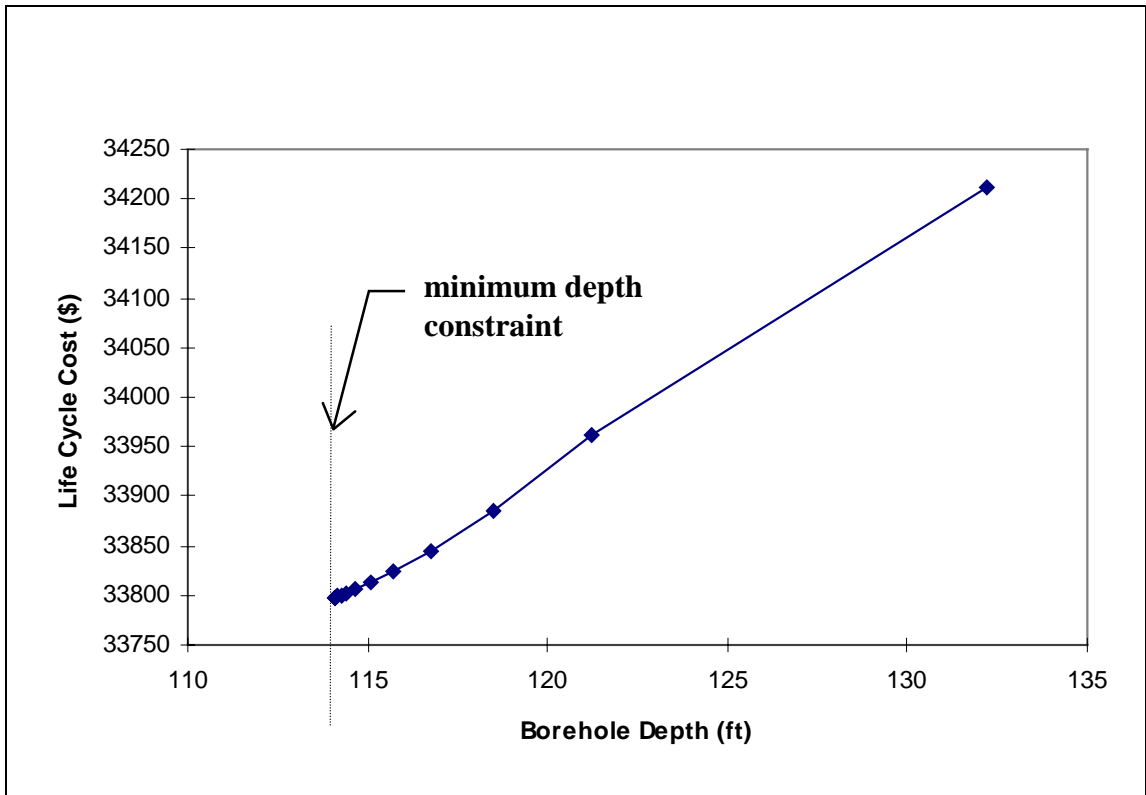


Figure 3-1 Life Cycle Cost Vs. borehole depth for Configuration G1210

3.3 Other Independent Variables

Further investigation showed that that the optimal borehole depth was generally constrained to be the minimum depth required to meet the minimum or maximum fluid temperature. Then other variables were considered for significant potential for optimization, they are: fluid flow rate and pipe diameter.

3.3.1 Pipe Diameter

In order to investigate the effect of piping size on LCC, five different piping sizes were used with configuration G1210 for daycare center, with 6 inch borehole diameter, and 4 boreholes per circuit (i.e. 4 circuits in parallel). The results are shown in Table 3-5.

Table 3-5 Life Cycle Cost of different piping sizes

Nominal Size (in)	\$ / ft	Min. LCC (\$)
3/4	0.20	48896.71
1	0.28	37655.53
1 1/4	0.41	34142.59
1 1/2	0.56	33797.21
2	0.78	33992.37

Table 3-5 shows that the 1 1/2 inch pipe results in the lowest life cycle cost. Increasing the piping size decreases the head loss in the system, and thus lowers the annual operating cost of the circulating pump. But at the same time increasing the piping size, increases the first installation cost due to the higher unit price for the larger pipes. For this case, it turns out that the optimum piping size is 1 1/2 inch.

3.3.2 Fluid Flow Rate

Heat pumps require a sufficient fluid flow rate to keep from overheating. Fluid flow rate has a significant impact on the annual operating cost of the circulating pump.

Lowering the flow rate, lowers the total head loss in the system, and hence lowers the

annual operating cost of the circulating pump. On the other hand, lowering the flow rate, increases the size of the ground loop heat exchanger, and thus increases the first cost. In general, a common rule of thumb is to use 2.5 gallons per minute per tons (12,000 Btu/hour) of the maximum load on the heat pump. Flow rates vary from 0.5 to 3.5 GPM per tons of the peak cooling load on the heat pump (25 tons for the daycare center) were simulated, and the results are shown in the Table 3-6 below:

Table 3-6 Summary of the Life Cycle Cost with different flow rates

GPM/ton max. load	Flow rate, GPM	Min. depth (ft)	Min LCC (\$)
0.5	12.60	117.34	32090.94
1.0	25.20	115.19	32563.54
1.5	37.80	114.56	32881.50
2.0	50.40	114.24	33268.11
2.5	63.00	114.03	33797.21
3.0	75.60	113.90	34514.88
3.5	88.20	113.80	35456.63

From the above table and Figure 3-2, one may notice that the minimum borehole depth requirements for the flow rate from 0.5 to 3.5 GPM per tons of the peak load on the heat pump do not have significant difference, less than 4 foot. It seems that inside the range of the depth constraint, lower the flow rate, lower the annual operating cost of the

circulating pump, and hence lower the life cycle cost of the system. However, the heat pump performance was assumed to be only a function of entering water temperature, not flow rate. The curve fits of heat pump performance were for a specific flow rate, and the same curve fit was used for all flow rates. Further investigation, utilizing a more sophisticated heat pump model, is probably warranted.

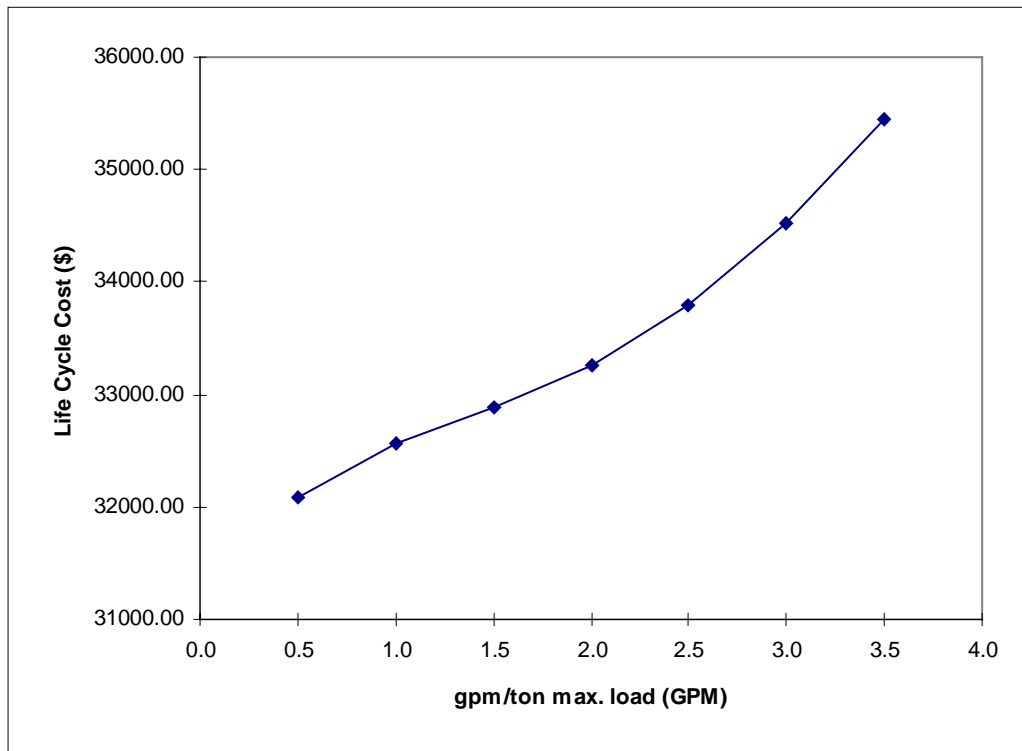


Figure 3-2 Life Cycle Cost Vs. flow rate (max. load = 25 tons)

CHAPTER IV

PEAK LOADS AND ENTERING FLUID TEMPERATURE TO THE HEAT PUMP

4.1 Introduction

GLHEPRO version 1.02 uses the monthly average fluid temperature exiting the heat pump to size the ground loop heat exchanger (GLHE). Conversations with users have indicated that they would prefer to size the GLHE based on the peak fluid temperature entering the heat pump. While there are several ways this could be done, it was decided to not modify GLHESIZE. (GLHESIZE uses average monthly fluid temperature exiting the heat pump as its design criterion.) Instead, the average monthly exiting temperature corresponding to a peak entering fluid temperature was estimated. In order to accommodate this, a number of changes to GLHEPRO were required. They include: conversion of the peak entering fluid temperature to the average entering temperature and conversion of the average entering fluid temperature to the exiting temperature.

The only new information required by the user is the peak load information, which is shown in Table 4-1. The peak information helps to simulate a real heat pump system with better sizing accuracy. It is also used to enhance the program, such as flow rate checking, and finding the initial guess of the active borehole depth.

	Heating	Cooling
Peak load Month	2.000	8.000
Peak Hourly Loads	166700.000	309400.000
Hours at Peak	8.000	8.000

Table 4-1 Sample of peak information in GLHEPRO Version 2.00

4.2 Methodology

The capability of being able to account for the peak loads when sizing the ground loop heat exchanger, with the desirable feature of being able to design the system based on the entering fluid temperature to the heat pump have been implemented in the GLHEPRO version 2.00. Peak load is treated as a pulse superimposed with the average loads using the methodology developed by Eskilson, 1987. The conversions between the peak temperature (T_{peak}) to the average temperature (T_{average}), and from temperature exiting from the heat pump to the temperature entering the heat pump (T_{entering}) are described in Section 4.2.1 to 4.2.4 . Figure 4-1 is a schematic drawing which illustrates the relationship between the temperatures with and without peak loads.

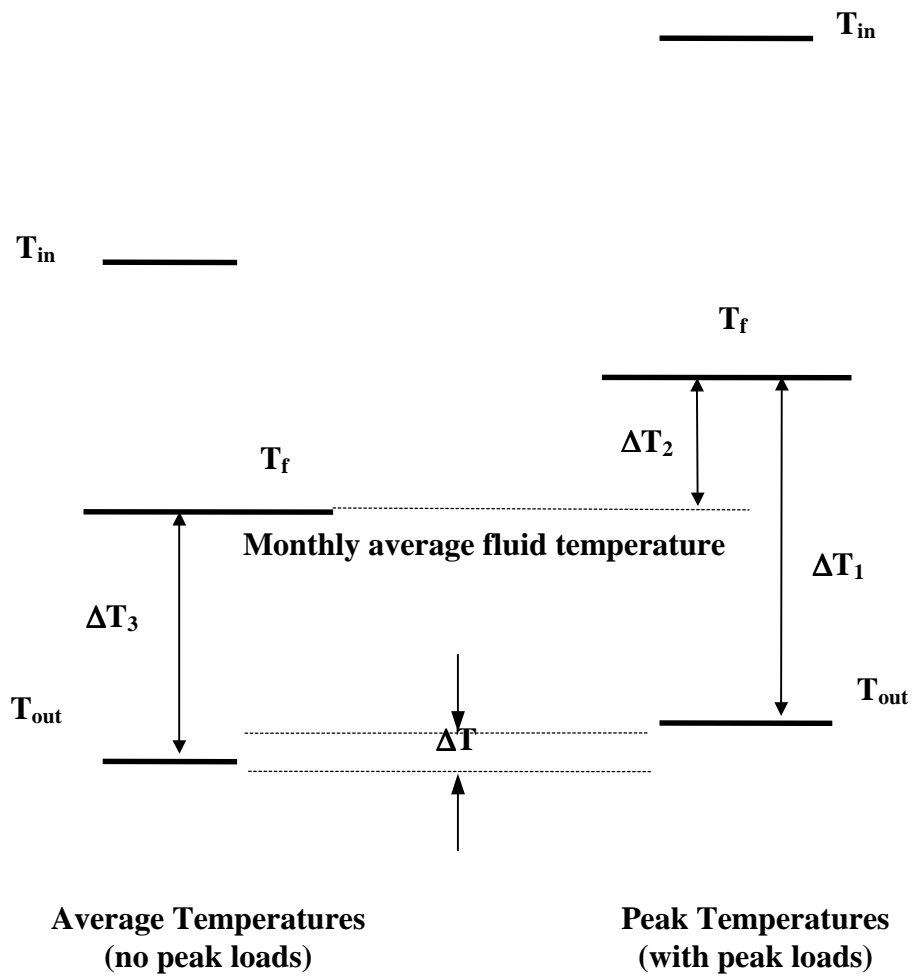


Figure 4-1 Comparison of average and peak temperatures for cooling case
(T_{out} = Fluid temperature entering to the heat pump)

4.2.1 $T_{peak,entering}$ to $T_{average,entering}$

Figure 4-1 shows that in order to convert a peak temperature to an average temperature to account for the peak loads, three ΔT s must be calculated. The following pseudo-code is used to estimate the $T_{average,entering}$, given the $T_{peak,entering}$, peak information (peak cooling and heating loads, number of hours at peak, and the months where peaks occur), with the average monthly heating and cooling loads.

IF peak load is equal to 0 (meaning the user did not enter a value)

$$T_{average,entering} = T_{peak,entering}$$

ELSE

$$T_{average,entering} = T_{peak,entering} - \Delta T \quad (\text{for cooling}) \quad (4.1)$$

$$T_{average,entering} = T_{peak,entering} + \Delta T \quad (\text{for heating}) \quad (4.2)$$

ENDIF

ΔT is the total offset of the peak temperature from the average temperature, which is shown in Figure 4-1. The following summary is the steps used to compute ΔT for peak cooling. Similar steps are used to compute the ΔT for the heating case.

1. Convert the average monthly heating and cooling loads to hourly loads in the month where peak cooling occurs.
2. Calculate the ratio of heat rejected to the ground to the cooling load, and the ratio of heat extracted from the ground to the heating load.
3. Calculate the average hourly heat rejection and heat extraction.

4. Calculate the net heat rejection, i.e.,
average heat rejection - average heat extraction
5. Calculate the peak hourly heat rejection.
6. Calculate the pulse heat rejection, i.e.,
peak heat rejection - net heat rejection
7. Calculate the total offset, ΔT using the following equations:

$$\Delta T = -\Delta T_1 + \Delta T_2 + \Delta T_3 \quad (4.3)$$

$$\Delta T_1 = \frac{1}{2} \left(\frac{\dot{Q}_{\text{peak_rej}}}{\dot{m} c_p} \right) \quad (4.4)$$

$$\Delta T_2 = \frac{Q_{\text{pulse_rej}} / L}{4\pi k} \left\{ \ln \left(\frac{4\alpha t}{r_b^2} \right) - \gamma \right\} \quad (4.5)$$

$$\Delta T_3 = \frac{1}{2} \left(\frac{\dot{Q}_{\text{net_rej}}}{\dot{m} c_p} \right) \quad (4.6)$$

where

$\dot{m} c_p$ = Fluid flow rate * fluid heat capacity

L = Initial guess of the total loop length

= 150 * tons of peak load on the heat pump

k = Thermal conductivity

α = Thermal diffusivity

r_b = Borehole radius

γ = Euler's constant (≈ 0.5772)

If $\Delta T_2 < (\Delta T_3 - \Delta T_1)$, ΔT is set to zero

Equation 4.5 comes from Eskilson's thesis (1987), it is an approximate analytical solution that describes the temperature change at the end of a single heat extraction pulse. The final total loop length L is determined by iterating between the initial guess value and the value reported by the simulation routine based on 10 feet accuracy.

4.2.2 $T_{average, entering}$ to $T_{average, exiting}$ (before simulation)

The average temperature exiting from the heat pump, $T_{average, exiting}$ before the simulation can be computed using Equations 4.7 and 4.8. The conversion from the entering temperature to exiting temperature is necessary because the simulation program, GLHESIZE, requires $T_{average, exiting}$ to size the system as the temperature constraint.

$$T_{average, exiting} = T_{average, entering} + \frac{Q_{net_rej}}{\dot{m} c_p} \quad (\text{for cooling})(4.7)$$

$$T_{average, exiting} = T_{average, entering} - \frac{Q_{net_abs}}{\dot{m} c_p} \quad (\text{for heating})(4.8)$$

where Q_{net_rej} , Q_{net_abs} can be calculated using the steps described in section 4.2.1 above with the $T_{average, entering}$ temperatures.

4.2.3 $T_{average, exiting}$ to $T_{average, entering}$ (after simulation)

After the simulation is complete, the average exiting maximum and minimum fluid temperatures are reported by simulation program, GLHESIZE or GLHESIM. In order to

report the user with the entering fluid temperatures, Equations 4.9 to 4.12 are applied to convert the exiting temperatures to the entering temperatures. One may notice that the conversion here is different from that in section 4.2.2, and it is in a more complicated form. The reason is because the heat pump performance is based on the entering fluid temperature. In section 4.2.2, the entering fluid temperature is readily available, it is straight forward to use this temperature to calculate the heat rejection or extraction. In this section, in order to find the entering temperature, it is necessary to compute the net heat transfer, however it is also a function of the entering fluid temperature. Therefore, a quadratic equation is resulted.

Case A (cooling):

$$T_{\text{average, entering}} = T_{\text{average, exiting}} - \frac{\dot{Q}_{\text{net_rej}}}{m c_p} \quad (4.9)$$

$$\begin{aligned} \dot{Q}_{\text{net_rej}} = & \dot{Q}_{\text{cool_avg}} * \{a + b * T_{\text{average, entering}} + c * (T_{\text{average, entering}})^2\} \\ & - \dot{Q}_{\text{heat_avg}} * \{u + v * T_{\text{average, entering}} + w * (T_{\text{average, entering}})^2\} \end{aligned} \quad (4.10)$$

By substituting Equation 4.10 into Equation 4.9, we have the quadratic equation as a function of the average entering fluid temperature for cooling. Then, the entering temperature, $T_{\text{average, entering}}$ can be computed by solving the resulting quadratic equation. A positive root is selected.

Case B (Heating):

$$T_{\text{average, entering}} = T_{\text{average, exiting}} + \frac{\dot{Q}_{\text{net_abs}}}{\dot{m}c_p} \quad (4.11)$$

$$\begin{aligned} Q_{\text{net_abs}} = & Q_{\text{heat_avg}} * \{u + v * T_{\text{average,entering}} + w * (T_{\text{average,entering}})^2\} \\ & - Q_{\text{cool_avg}} * \{a + b * T_{\text{average,entering}} + c * (T_{\text{average,entering}})^2\} \end{aligned} \quad (4.12)$$

where: a, b, c = Heat pump performance coefficients for cooling mode

u, v, w = Heat pump performance coefficients for heating mode

(**Note:** If the heat pump coefficients a or u equals zero the resulting equation is not in a quadratic form. So instead of solving a quadratic equation the linear equation is solved.)

4.2.4 $T_{\text{average,entering}}$ to $T_{\text{peak,entering}}$

The average entering fluid temperature is converted back to the peak entering temperature before reporting to the user as shown in the below pseudo-code, which is similar to that shown in section 4.2.1.

IF peak load is equal to 0

$$T_{\text{peak,entering}} = T_{\text{average,entering}}$$

ELSE

$$T_{\text{peak,entering}} = T_{\text{average,entering}} + \Delta T \quad (\text{for cooling}) \quad (4.13)$$

$$T_{\text{peak,entering}} = T_{\text{average,entering}} - \Delta T \quad (\text{for heating})(4.14)$$

ENDIF

where ΔT is calculated using the procedures described in section 4.2.1.

4.3 Example

The daycare center is used as an example to demonstrate how the fluid temperature conversions between peak and average, entering and exiting are done in GLHEPRO version 2.00. by running GLHESIZE. The desired maximum fluid temperature entering the heat pump is set to 90°F, and the minimum temperature is set to 35°F. The simulation is run for 10 years. The building loads and other input information of the heat pump system are detailed in Appendix 3, GLHEDATA.DAT.

Figure 4-2 is the summary illustrating how all the conversions are done. First, the specified maximum entering fluid temperature (90°F), and the minimum entering fluid temperature (35°F) are converted to the average entering temperatures. The ΔT s are 14.43 and 4.36 °F for maximum and minimum temperatures respectively, computed using equations 4-3 to 4-6, which are described in Section 4.2.1. Then, the average entering temperatures are converted to the average exiting temperatures using the Equations 4.7 and 4.8. Before running GLHESIZE, the allowed exiting temperature range is 38.56 to 77.77 °F. After the simulation is complete, the returned the exiting temperature range is 47.75 to 77.77 °F, which satisfies the desire range specified. Next, the exiting average temperatures are converted to the average entering temperature using the equation in section 4.2.3. Finally, the average entering temperatures are converted to

the peak entering temperatures before report to the user. The maximum temperature is 87.85°F, which is below the specified upper bound, 90°F. The minimum temperature is 44.28°F, which is above the specified lower bound, 35°F. To meet the specified temperature range, the total loop length of the ground loop system is about 2300 feet.

EFT EFT EXIT EXIT EFT EFT
PEAK AVG. AVG. AVG. AVG. PEAK

Max. Temp.

90 $\xrightarrow{\Delta T = 14.43}$ 75.57 $\xrightarrow{\Delta T = 2.20}$ 77.77 $\xrightarrow{\text{Simulation}}$ 77.77 $\xrightarrow{\Delta T = 0.97}$ 76.80 $\xrightarrow{\Delta T = 11.05}$ 87.85

Min. Temp.

35 $\xrightarrow{\Delta T = 4.36}$ 39.36 $\xrightarrow{\Delta T = 0.80}$ 38.56 $\xrightarrow{\text{Simulation}}$ 47.75 $\xrightarrow{\Delta T = 0.66}$ 48.41 $\xrightarrow{\Delta T = 4.13}$ 44.28

**Figure 4-2 Peak and average temperature conversions chart for the daycare center
(desired peak temperature range: 35-90 °F)**

4.4 Length of Peak Pulse

The length of a peak pulse (hours at peak) is critical to estimate the temperature difference between the fluid temperatures with and without the peak load (ΔT_2). The longer the length of a peak pulse, the larger the ΔT_2 , and hence the smaller the allowed average exiting temperature range. The smaller average exiting temperature range may require a longer total borehole loop-length. For instance, using the inputs shown in Appendix 3, GLHEDATA.DAT for the daycare center, the borehole loop-length decreases about 13% when the “hours at peak” decreases from 8 to 4 hours. Figure 4-3 and Figure 4-4 show the sensitivity of the length of a peak pulse. The total temperature offset (ΔT) in Figure 4-3 is obtained by running GLHESIM. While keeping the total borehole loop length constant, hours at peak change from 0 to 12 hours to show the temperature rise. The total loop length in Figure 4-4 is obtained by running GLHESIZE. While keeping the peak temperature constant, change the hours at peak from 0 to 12 hours to show the increase of the loop length requirement. Both Figure 4-3 and Figure 4-4 show significant change in ΔT and L as the length of the peak pulse increases.

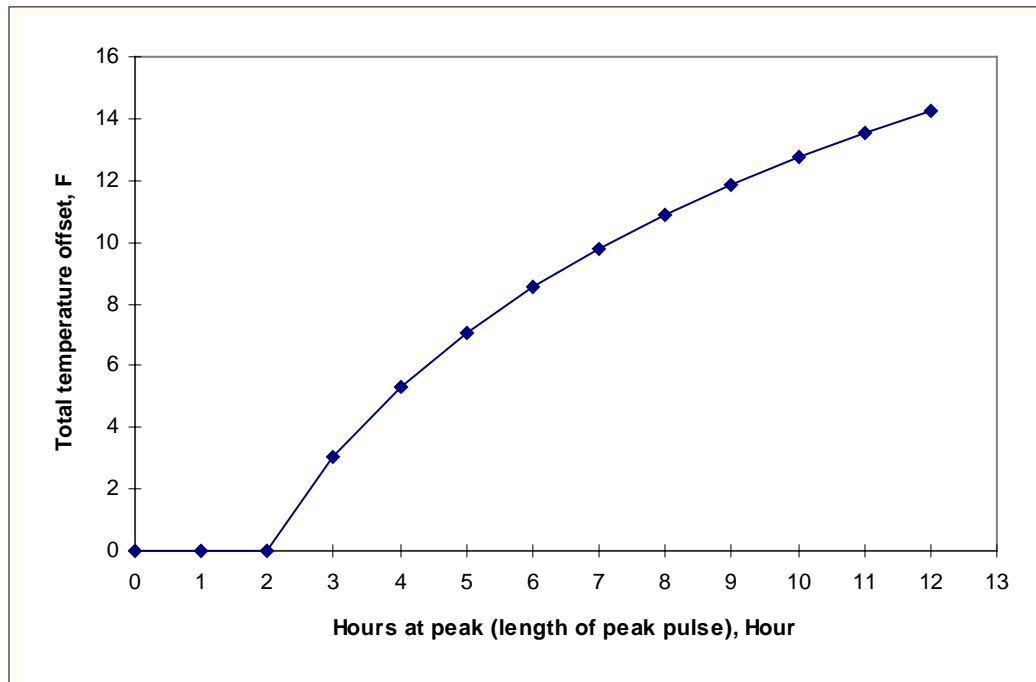


Figure 4-3 Total temperature offset Vs. length of peak pulse

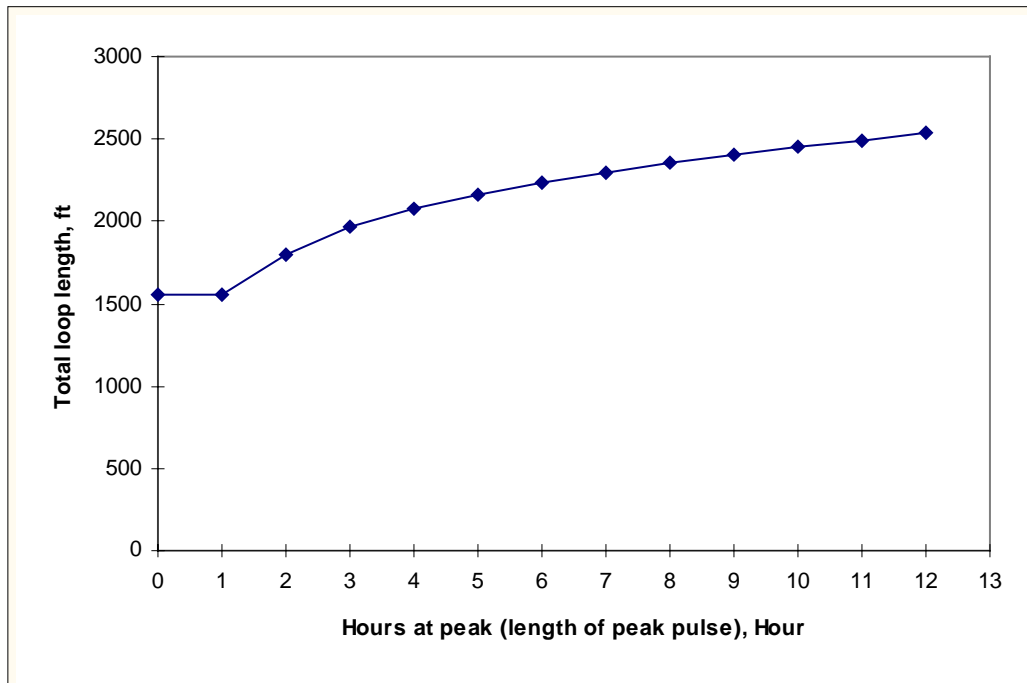


Figure 4-4 Total loop length Vs. length of peak pulse

A typical profile of an annual average monthly loads is shown in Figure 4-5. From the figure, one can identify that August has the largest heat rejection to the ground. One may notice that the monthly load is represented by a constant average value. But for a real-life building, such as the daycare center, the actual loads vary from day to day, and hour to hour. A fictitious set of representative hourly loads for a month are shown in Figure 4-6.

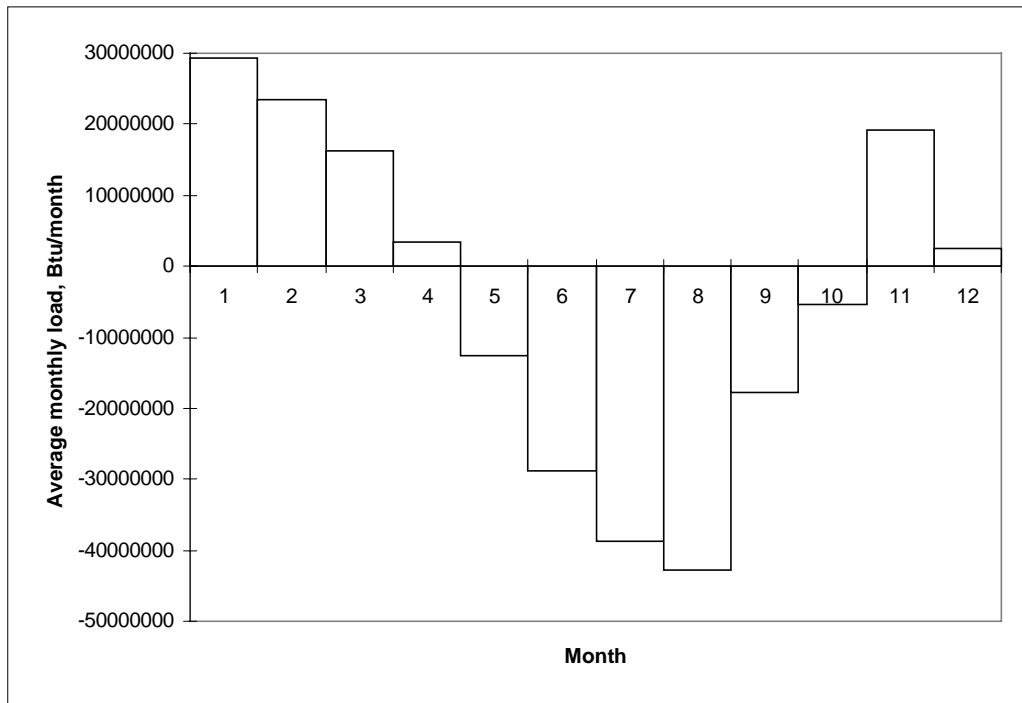


Figure 4-5 Average monthly load for daycare center

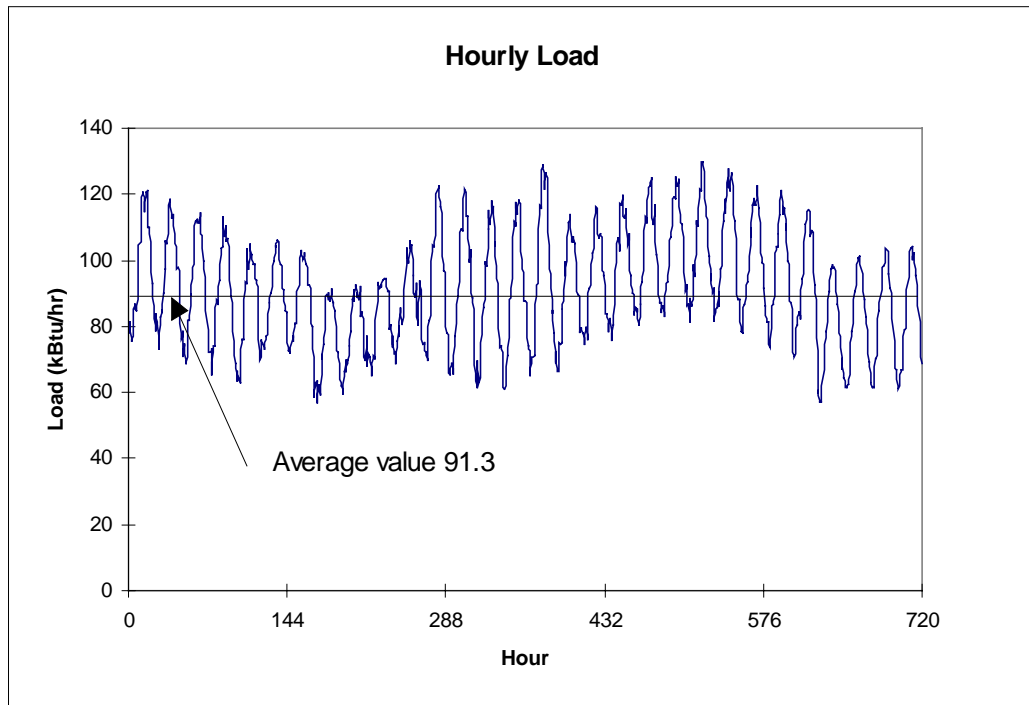


Figure 4-6 Actual hourly load in a month

Using the daycare center as an example, the actual hourly load in the design day is shown in Figure 4-7.

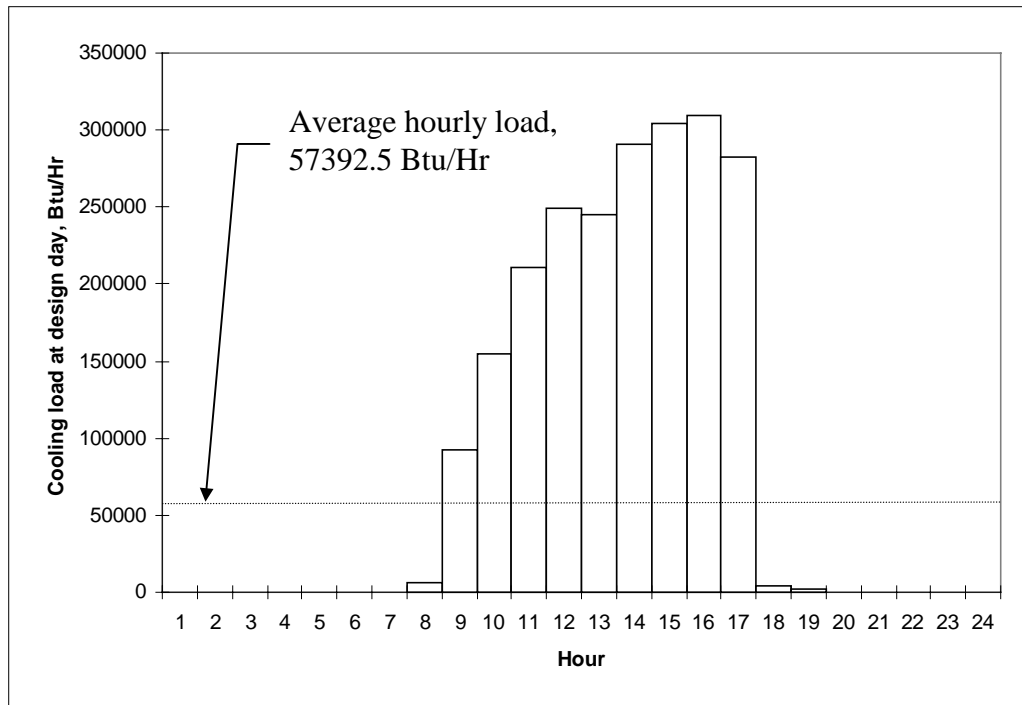


Figure 4-7 Hourly cooling at the design day

In order to account for the peak hourly load, a rectangular pulse is employed, which attempts to represent the peak loads shown in Figure 4-7. The question is what is the length of a rectangular pulse with amplitude equal to the peak hourly load that will give a rise in temperature equivalent to the actual hourly design loads? Ideally, a more detailed simulation would be done, but it is beyond the scope of the current investigation.

Therefore, a brief investigation is made here to estimate the length of the pulse that will give a temperature rise equivalent to the actual hourly loads.

A simple algorithm is used to estimate an appropriate length of the peak pulse for the daycare center in August. Assume that the maximum entering fluid temperature is 90 °F.

Once the hourly load in the design day is estimated, ΔT can be computed using Equation 4.3 as discussed in Section 4.2.1. Furthermore, assume that the temperature of the fluid is at the monthly average at midnight before the peak day. The results are shown in Table 4-2.

Table 4-2 Hourly load at design day and the ΔT s

Hours	Actual Hourly Load (Btu/Hr)	Average Hourly Load (Btu/Hr)	Superimposed ΔT ($^{\circ}F$)
1 to 4	0	57392.5	-1.96
5 to 8	1023.3	57392.5	-3.16
9 to 12	176954.5	57392.5	2.15
13 to 16	280775.0	57392.5	8.97
17 to 20	72246.5	57392.5	5.90
21 to 24	0	57392.5	1.51

The superimposed ΔT is plotted against the hour in Figure 4-8.

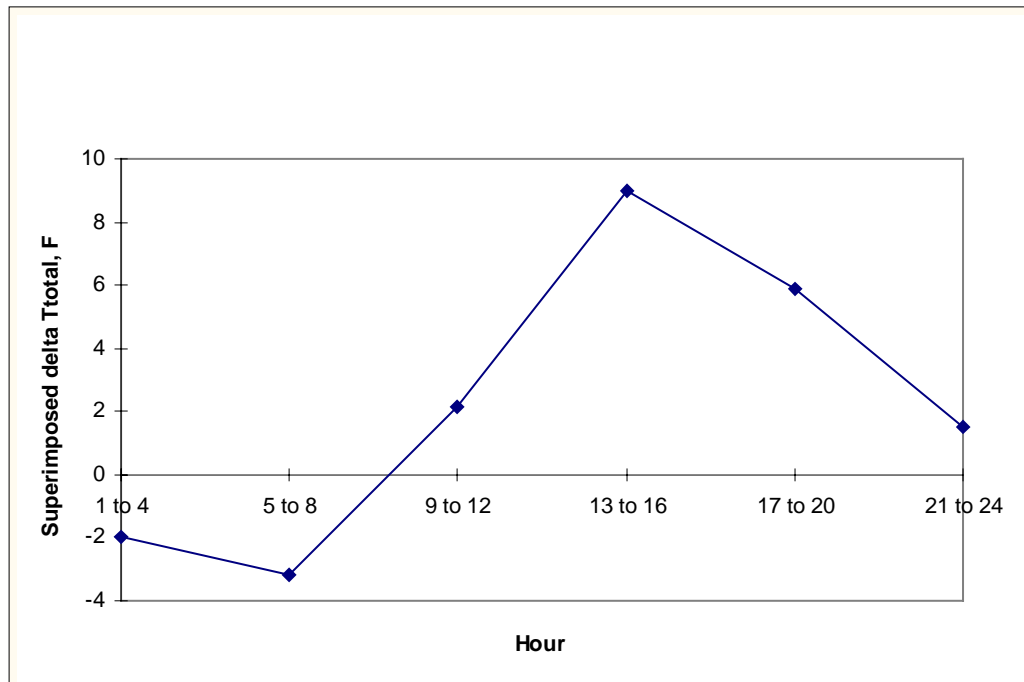


Figure 4-8 Superimposed ΔT Vs. hour

From Figure 4-8 and Table 4-2, one can identify that the maximum temperature rise experienced by the heat pump is 8.97 °F between Hour 13 and 16. This means that the single peak pulse should have length which results in a total temperature offset of 8.97 °F

. By running GLHESIM with the total loop-length equals that used to estimate the ΔT (Note: active borehole depth = total loop-length / number of boreholes), the equivalent length of the peak pulse is found to be about 6.3 hours.

There are different ways to estimate the length of a peak pulse, the method used here may not be the best, but it provides some understanding of the hours at peak for the daycare center. Due to only one real building is studied here, no general guidance or rule

of thumb can be provided. In order to provide more general guidance, more real-life buildings should be investigated. Ideally, a more detailed simulation should be performed, but it will require much more tightly-coupled building energy analysis and ground loop heat exchanger design program that are currently available.

CHAPTER V

INPUT CHECKING AND ADVISING

To make the GLHEPRO program more user friendly, a series of input checks and appropriate advice were desired to aid users of the program. Input parameters to be checked include: fluid flow rate, maximum and minimum temperatures, and peak load information.

5.1 Flow Rate

Fluid flow rate is an essential input to the GLHEPRO, it describes the volume flow rate of the heat carrier fluid inside the ground loop heat pump system. It should not be undersized, but it is not wise to be grossly oversized as well. When undersizing the flow rate, a longer borehole depth is required to prevent the working fluid temperature from dropping or exceeding a user-defined temperature range, which is obviously not cost effective. On the other hand, when the flow rate is grossly oversized, it increases not only the initial equipment cost, but also the operating cost due to the higher pumping power resulting from the higher fluid flow rate. The common rule of thumb is to use 2.5 - 3.0 gallons per minute per ton of the maximum load on the heat pump.

A problem with GLHEPRO 1.02 is that if a user attempts to simulate a large system with the default flow rate of 1 GPM, GLHESIM and GLHESIZE will crash. In version 2.00, if the user forgets to enter the appropriate value, or enters a grossly undersized value, GLHEPRO will give the user a warning message, as well as a suggestion for the fluid flow rate. The suggestion is based on the building loads, and applies the rule of thumb mentioned above, 2.5 GPM per ton of the maximum load on the heat pump. Hence, if the user for any reason does not know a reasonable fluid flow rate to input in the program, and wants the program to suggest a reasonable value, the user just leaves the default value, and the program will give the warning message, which includes a flow rate suggestion based on the building loads. The flow rate input checking and advising procedures is detailed below.

If the peak of the building loads has been specified by the user, the program compares the peak heating and cooling loads. Once the comparison is done, the larger value of the peak heating and cooling loads is used to compute the fluid flow rate using the formula below:

$$\text{flow rate} = 2.5 * (\text{peak load} / 12,000) \quad (5.1)$$

If the peak information is not included, the program will search for the largest value among the twelve pairs of the heating and cooling monthly loads. Then it converts the monthly average load to hourly load, and calculates the flow rate based on this average hourly load by using the formula above. This flow serves the minimum flow rate requirement, if the user inputs a flow rate less than this value, the program gives a

warning message and this suggested value. If the user ignores this warning and suggestion, and insists on using a smaller flow rate, the program will continue after displaying the warning.

The Daycare center serves as an example to illustrate how the flow rate checking is done. The building load information is listed below:

Monthly Loads		
Month	Heating(Btu)	Cooling(Btu)

January	29940000.000	725200.000
February	23910000.000	358600.000
March	17920000.000	1769000.000
April	8233000.000	4817000.000
May	1386000.000	13990000.000
June	364500.000	29130000.000
July	25350.000	38870000.000
August	11140.000	42700000.000
September	874300.000	18570000.000
October	5782000.000	11080000.000
November	19540000.000	374800.000
December	25250000.000	495400.000
Peak Information		
	Heating	Cooling
	-----	-----
Peak Hourly Loads	166700.000	309400.000
Hours at Peak	8.000	8.000
Peak load Month	2.000	8.000

Table 5-1 Summary of the monthly loads and the peak information from BLAST

First, the program sees that the peak information is included, it compares the peak heating and cooling loads. It finds that the peak cooling load is higher than the peak heating load, so the cooling load is used for the flow rate calculation:

$$\text{flow rate} = 2.5 * (\text{peak load} / 12,000)$$

$$\text{flow rate} = 2.5 * (309400 / 12,000)$$

$$\text{flow rate} = \underline{64.4 \text{ GPM}}$$

If the user inputs the flow rate less than 64.4 GPM, the program gives the warning message as shown Figure 5-1:

**Your current building loads suggest that you need
a fluid flow rate of approximately 64.4 gal/min.**

Figure 5-1 Flow rate warning and suggestion

If the peak information is not included, the peak loads are set to zero, and GLHEPRO will seek the largest value among the average monthly heating and cooling loads. In this case, cooling load in August is the largest value, hence the flow rate calculation will be based on this value. Notice that before the flow rate is computed, the cooling load is converted from monthly to hourly:

hourly load = $4270000/31/24 = 57392.5$

flow rate = $2.5 * (57392.5/12,000)$

flow rate = 12.0 GPM

Note that this flow rate is much smaller than the one predicted using the peak loads. This is one reason why the peak information is important.

5.2 Check on Maximum / Minimum Temperatures

GLHEPRO Version 2.00 allows the user to specify the maximum fluid temperature entering the heat pump, and the minimum fluid temperature entering the heat pump.

Whether the maximum temperature or the minimum temperature is critical, depends on the building loads and the defined temperature range. In general, a cooling dominated building rejects more heat to ground than it extracts on an annual basis, so the heat will build up in the ground where the ground heat exchanger is installed and the area nearby. So, the maximum temperature should be a concern from the design stand point.

Similarly, for a heating dominated building, the minimum temperature should be the focal point to consider.

Also, the user-defined maximum and minimum temperatures cannot be too close to the undisturbed ground temperature (T_{ug}). It is obvious that if the user-defined temperatures are very close to T_{ug} , an infinite loop length is required for the heat pump system. In GLHEPRO Version 2.00, the user-defined minimum and maximum temperatures will

need to have the temperature clearance of at least 5 °F after accounting for the peaks (refer to Section 4.2). If either $|T_{\max, \text{avg_exiting}} - T_{\text{ug}}|$ or $|T_{\min, \text{avg_exiting}} - T_{\text{ug}}|$ less than 5 °F, a warning message is given to the user, and it suggests the user to redefine the temperature range to avoid an unrealistic borehole loop length requirement. It states whether the maximum temperature or the minimum temperature needs to be redefined and what is the appropriate range after accounting for the peak loads.

Besides the common sense limit of 5 °F between the maximum / minimum temperature and the undisturbed ground temperature, there are absolute temperature limits as shown in Figure 5-2.

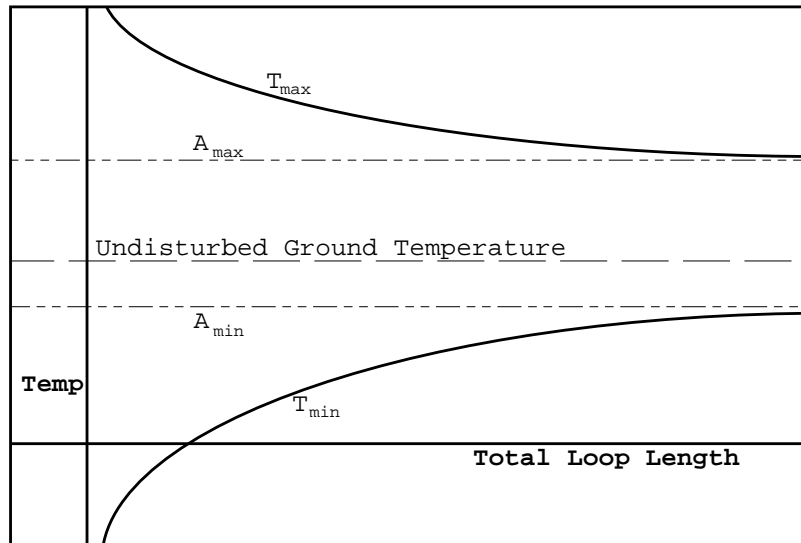


Figure 5-2 Asymptotic boundary of the temperatures

Theoretically, an infinite amount of pipe would raise the minimum temperature to asymptotic minimum temperature, A_{\min} , and decrease the maximum temperature to asymptotic maximum temperature, A_{\max} . But for the computational convenience, these asymptotic boundaries can be obtained by using a relatively 'long' pipe, such as several miles. Both the maximum fluid temperature (T_{\max}), and the minimum temperature (T_{\min}) approach fixed finite values after that total loop length.

GLHEPRO uses a Newton-Raphson convergence algorithm to find the loop length that corresponds to the desired temperature range. Newton-Raphson uses the ratio of the function value (temperature as a function of loop length) to the derivative of the function (rate of change in temperature compared to change in loop length) to determine the next loop length to examine, i.e. $L_{\text{new}} = L_{\text{old}} - T(\text{old}) / T'(\text{old})$. If the change in temperature per foot of loop length is very large, it will only change the loop length a small amount. If the change in temperature is very small, it will change the loop length a great deal. This allows it to converge quickly to the correct temperature. However, if the desired temperature is inside the asymptotic boundaries (between A_{\max} and A_{\min} in Figure 5-2), the convergence scheme will never reach it. GLHEPRO recognizes this condition by noticing that changing the loop length results in no change in temperature (or in other words, when the derivative of the function, $T'(\text{old})$ equals zero). Technically, there should always be at least a small change in temperature, but due to the limitations of computers, any number below a certain value is considered to be zero. At that point, no matter how much the loop length is increased, the temperature will not change. The temperature where this occurs is the asymptotic boundary for either T_{\min} or T_{\max} whichever was being calculated at the time.

If the user specifies a desire maximum temperature below the asymptotic boundary of the maximum temperature, A_{\max} , a similar warning will be given:

The maximum bound must be above 70. Set the maximum temperature at least 70 or higher. A higher maximum temperature will result in shorter total loop length.

Figure 5-3 Sample warning for maximum/minimum temperature checking

5.3 Peak Load Information

Information about the peak loads needs to be realistic and accurate when running the GLHEPRO Version 2.00. If the peak information is misentered, or ignored, the program will give senseless results. Therefore, an algorithm is developed to prevent this problem.

IF Peak Load or Hours at Peak (Cooling or Heating) \leq 0 THEN

Give warning message

Allow user go back to the load input screen to reset peak information

ELSEIF Peak Load \leq Average Load THEN

Give warning message

Set Peak Load = 1.2 * Average Load

Allow user go back to the load input screen to reset

peak information

ENDIF

ELSE

Continue to run simulation program

ENDIF

After allowing the user go back to the load input screen to reset the peak information, if the hours at peak still less than zero, or the peak loads still less than the average loads, GLHEPRO give a warning message again, then continue to run the simulation program and ignore the peak loads. Refer to Table 5-1, if we set the peak heating load to zero, the following warning will be given:

**If you wish to design for peak temperature instead of monthly temperature,
you should set the 'Peak Heating Load ' to some value greater than 0**

Figure 5-4 Sample warning for peak load information checking

CHAPTER VI

BOREHOLE THERMAL RESISTANCE CALCULATION

One of the user input parameters to GLHEPRO is the "Borehole Thermal resistance". As claimed by Eskilson (1987), the borehole thermal resistance is one of the most important parameter of a heat extraction borehole.

The borehole thermal resistance is the resistance between the heat carrier fluid and the borehole wall. The total resistance depends on the borehole radius, the thermal conductivity of the grouting material inside the borehole outside the pipes, the thermal conductivity of the piping, and the spacing between the pipes and the borehole wall etc. The thermal resistance also depends on the thermal resistance over the borehole wall and between the bulk fluid in the pipes and the inner pipe wall with different expressions for laminar and turbulent flow. The cross-section view of a typical borehole is shown in Figure 6-1.

For the purpose of understanding the local thermal processes in the borehole and its immediate vicinity, one must comprehend the relationship between the borehole geometry and thermal properties and its resistance. But unfortunately, there is no simple model available that can be used directly to predict the borehole thermal resistance for a given borehole diameter or radius, its geometry, thermal conductivity of the grouting, and thermal conductivity of the pipes.

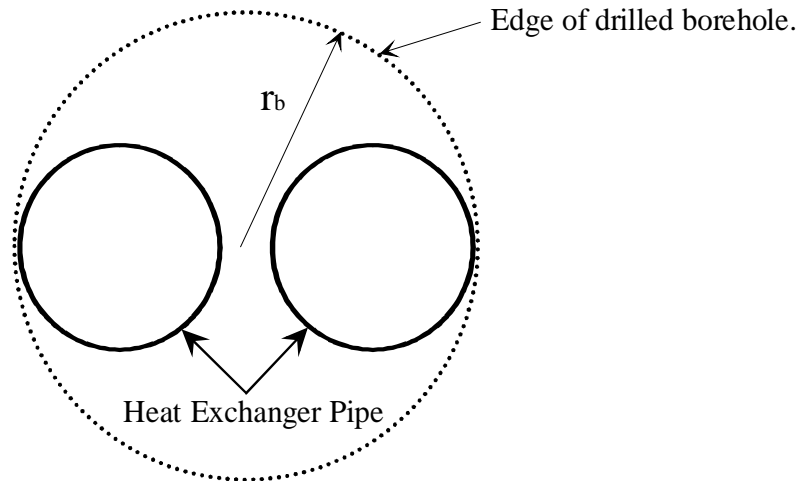


Figure 6-1 Top view of a typical borehole

6.1 Methodology

The aim of this study is to establish a relationship between the thermal resistance of a borehole and its geometry, grouting conductivity, etc. Conduction shape factors will be employed to estimate the borehole resistance. However, at present no experimental data is available which may be used to validate the model. Furthermore, the use of conduction shape factors, which assume isothermal surfaces, causes some significant errors as the heat exchanger pipe gets close to the borehole wall. Therefore, the material in this chapter must be considered tentative. When experimental data is available, the model may be validated and/or calibrated, as necessary.

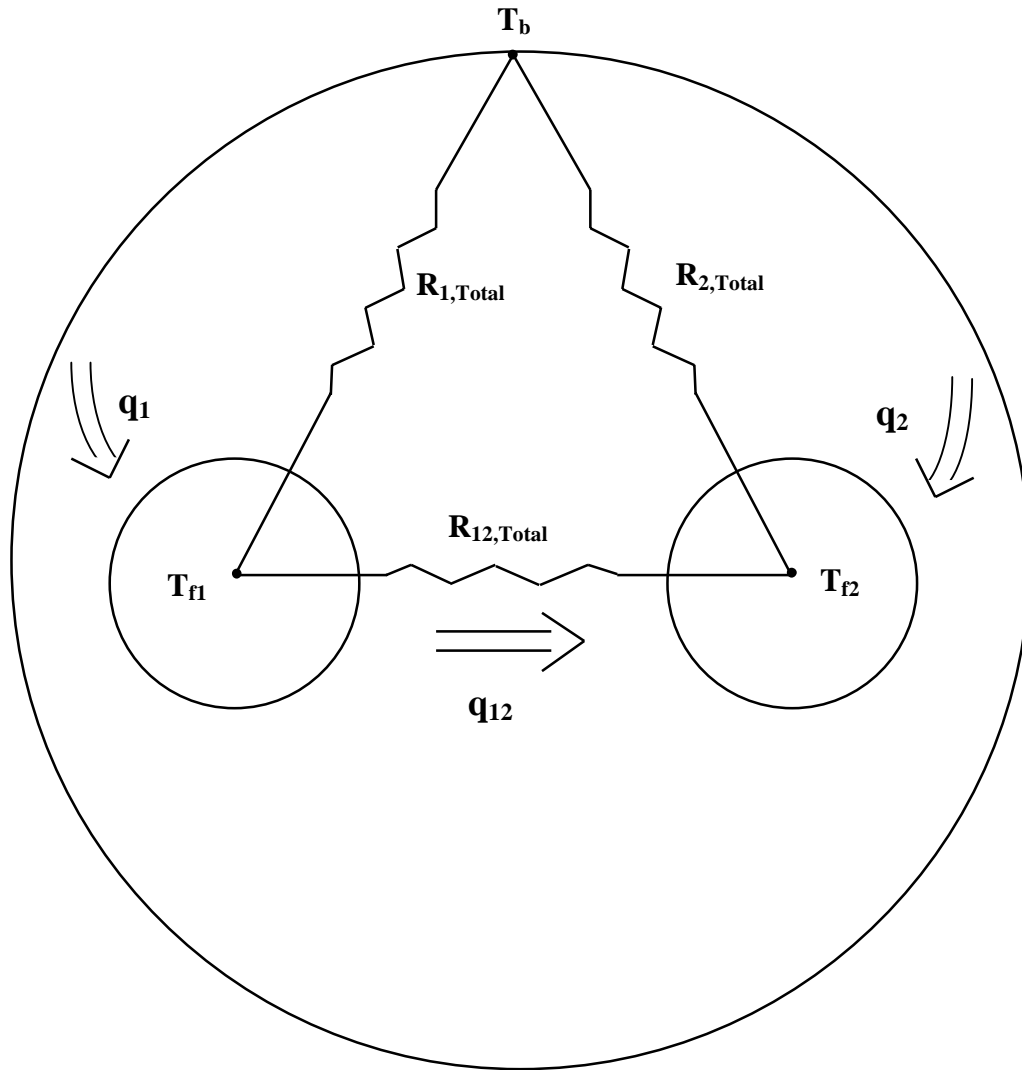


Figure 6-2 Heat flow and thermal resistance diagram for a borehole

The total thermal resistance of the borehole R_{borehole} is defined by Equation 6.1.

$$R_{\text{borehole}} = \Delta T / (q_1 + q_2) \quad (6.1)$$

Where

ΔT =overall temperature difference

$$=T_b - (T_{f1} + T_{f2}) / 2$$

q_1, q_2 =heat transfer from the ground outside the borehole
to the pipes

T_b =ground temperature around the borehole

T_{f1} =temperature of the downward flowing fluid

T_{f2} =temperature of the upward flowing fluid

In accordance to Eskilson (1987), each depth z and time t , the heat transfer between the pipes and the ground around the borehole may be approximates as steady state. The steady-state heat balance equations are

$$q_1 - q_2 = (T_b - T_{f1}) / R_{1,\text{total}} - (T_{f1} - T_{f2}) / R_{12,\text{total}} \quad (6.2)$$

$$q_2 + q_{12} = (T_b - T_{f2}) / R_{2,\text{total}} + (T_{f1} - T_{f2}) / R_{12,\text{total}} \quad (6.3)$$

Where

q_{12} =heat transfer from the downward channel to
the upward channel

$R_{1,\text{total}}$ =total resistance (from the ground around the

borehole to the downward channel)

$R_{2,\text{total}}$ =total resistance (from the ground around the
borehole to the upward channel)

$R_{12,\text{total}}$ = total resistance (from the downward channel to
the upward channel)

From the above equations, the sum of q_1 and q_2 can be determined. The equation is

$$\begin{aligned} q_1 + q_2 &= (q_1 - q_{12}) + (q_2 + q_{12}) \\ &= ((T_b - T_{f1})/R_{1,\text{total}}) - (T_{f1} - T_{f2})/R_{12,\text{total}} \\ &\quad + \\ &\quad ((T_b - T_{f2})/R_{2,\text{total}}) + (T_{f1} - T_{f2})/R_{12,\text{total}} \end{aligned} \quad (6.4)$$

The total resistance : $R_{1,\text{total}}$, $R_{2,\text{total}}$, and $R_{12,\text{total}}$ are defined by Equations 6.5, 6.6 and 6.7:

$$R_{1,\text{total}} = R_1 + R_{\text{other}} \quad (6.5)$$

$$R_{2,\text{total}} = R_2 + R_{\text{other}} \quad (6.6)$$

$$R_{12,\text{total}} = R_{12} + 2.0 * R_{\text{other}} \quad (6.7)$$

Where the R_{other} is the sum of the conduction resistance of the pipe and convection resistance of the inside pipe wall to the bulk fluid, which is described as

$$R_{\text{other}} = R_{\text{cond}} + R_{\text{conv}} \quad (6.8)$$

$$R_{\text{cond}} = \ln(r_o/r_i) / (2\pi kL) \quad (6.9)$$

$$R_{\text{conv}} = 1 / (2\pi r_i L h_{c,i}) \quad (6.10)$$

where

r_o, r_i = Inside and outside radius of a pipe

L = Borehole depth

$h_{c,i}$ = convective heat transfer coefficient

The resistance in Equation 6.5, 6.6 and 6.7 can be determined by using the conduction *shape factors, S*. In order to model the borehole with two pipes in it, three different shape factors need to be used, and the summary is as shown in Table 6-1.

Table 6-1 Summary of the conduction shape factors, S

Physical System	Conduction Shape Factor, S
Eccentric cylinders of length L	$S_1 = S_2 = 2\pi L / (\cosh^{-1}((r_1^2 + r_2^2 - D^2)/(2r_1 r_2)))$
Two isothermal cylinders buried in infinite medium	$S_{12} = 2\pi L / (\cosh^{-1}((D_{12}^2 - r_1^2 - r_2^2)/(2r_1 r_2)))$

$$R_1 = 1 / (k_1 S_1) \quad (6.11)$$

$$R_2 = 1 / (k_2 S_2) \quad (6.12)$$

$$R_{12} = 1 / (k_{12} S_{12}) \quad (6.13)$$

$$D = \text{Radius of borehole} \quad (6.14)$$

Also, S_1 is equal to S_2 , hence, R_1 is exactly equal to R_2 if the thermal conductivity is assumed to be uniform, i.e., $k_1 = k_2 = k_{12} = k_{\text{grout}}$ = thermal conductivity of the grouting.

The convective heat transfer coefficient, $h_{c,i}$ in Equation 6.10 calculated using the Equation 6.15 and 6.16.

$$\text{Nu} = 0.023 * \text{Re}^{0.8} * \text{Pr}^{0.4} \quad (6.15)$$

$$h_{c,i} = \text{Nu} * k_{\text{fluid}} / d_i \quad (6.16)$$

where

$$\text{Pr} = 7.88 \text{ (Prandtl number of water at } 60 \text{ }^\circ\text{F)}$$

$$k_{\text{fluid}} = 0.344 \text{ (Water at } 60 \text{ }^\circ\text{F)}$$

$$d_i = \text{diameter of the pipe}$$

$$\text{Re} = \text{Reynolds number} = V * d_i / \nu$$

where

$$V = \text{Flow rate of the fluid}$$

$$\nu = \text{Kinematic viscosity}$$

The thermal and physical properties of water at 60 °F have been utilized, and the flow is assumed to be fully developed turbulent flow inside a smooth pipe.

Once the shape factors are calculated, the total resistance can be easily obtained. Then, use Equation 6.4 to find the sum of q_1 and q_2 , and substitute the sum into Equation 6.1 to compute the borehole thermal resistance, R_{borehole} . The above methodology is

implemented in a FORTRAN computer program, BORERES.FOR (refer to the Appendix 8). The input variables are summarized as follow:

Table 6-2 Summary of the input variables in the program

Variable Name	Meaning
k_{grout}	Thermal conductivity of the grouting, Btu/hr*ft*°F
k_{pipe}	Thermal conductivity of the pipe, Btu/hr*ft*°F
V	Volume flow rate of the hear carrier fluid, GPM
r_{nominal}	Nominal size of the pipe, inch
r_b	Radius of the borehole, inch
Space	Spacing between the pipe and borehole wall, inch

The program calculates the borehole resistance, R_{borehole} . Table 6-3 gives the most common polyethylene pipe sizes used in ground heat exchanger design.

Table 6-3 Polyethylene pipe sizes

Option Number	Nominal Size (in)	Outside Diameter (in)	Inside Diameter (in)
1	3/4	1.050	0.860
2	1	1.315	1.077
3	1 1/4	1.660	1.358
4	1 1/2	1.900	1.554
5	2	2.375	1.943

6.2 Results and Discussion

Several parameters were studied by using the program BORERES.FOR, their results will be discussed below. The results were obtained by keeping all the input variables into the program constants except the parameter of interest. The results may not be quantitatively useful, but they show the trend, as well as the magnitude of the changes.

From the discussions below, one may find that the *Conduction Shape Factor* method is able to establish relationships between the borehole resistance and grouting thermal conductivity, piping thermal conductivity, fluid flow rate, piping size, borehole radius, and the spacing between the pipe and the borehole wall.

6.2.1 Grouting Conductivity (k_{grout})

It is quite obvious that grouting inside the borehole has direct and significant impact on the overall thermal resistance of the borehole. Figure 6-3, shows that the thermal resistance of the borehole increases sharply as the thermal conductivity of the grouting material decreases, especially in the lower range of k_{grout} . The change of $R_{borehole}$ from $k_{grout} = 1.5$ to $k_{grout} = 0.3$ is more than 150%. The common grouting material is Bentonite clay, it has a typical value of 0.74 Btu/hr*ft*°F. This study shows that it is extremely important to develop a grouting material with higher thermal conductivity to enhance the heat transfer by reducing the borehole resistance. Physical properties also need to pay attention when choosing a grouting material, such as the ease of backfilling, etc.

INPUT VARIABLES:

$k_{grout} = ?$ (dependent variable)

$k_{pipe} = 0.225$

$V = 20$

$r_{nominal} = 1$ inch (option 2)

$r_b = 3$

space = 0.5

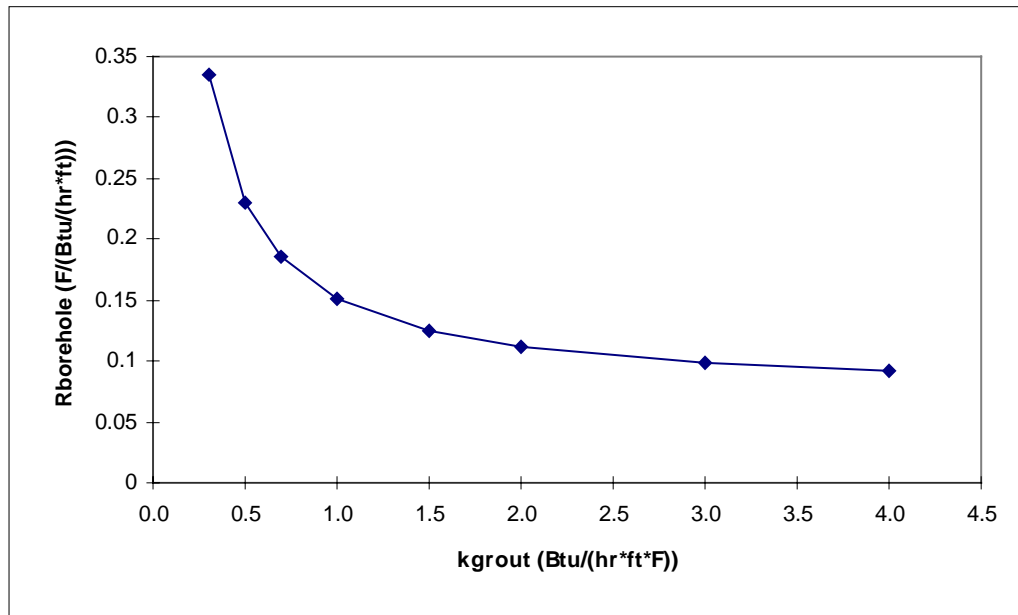


Figure 6-3 Grouting Conductivity (k_{gROUT}) Vs. Borehole thermal resistance ($R_{borehole}$)

6.2.2 Pipe Conductivity (k_{pipe})

The thermal resistance of the pipes inside the borehole (k_{pipe}) affects the heat transfer between the heat carrier fluid inside the pipe and its surrounding. Figure 6-4 shows that the borehole resistance $R_{borehole}$ decreases as k_{pipe} increases. As the conductivity increases, heat is easier to transfer through the pipe wall. In other word, the overall resistance decreases. Therefore, a piping material with higher thermal conductivity is desired for the application in ground-loop heat exchanger. Currently, the common piping material for GLHE is high density polyethylene (HDPE), its typical thermal conductivity value is about 0.202 Btu/hr*ft*°F. Polyethylene offers a good balance of physical properties, allowing optimal pipe thickness, providing a reasonable thermal conductivity.

INPUT VARIABLES:

$k_{\text{pipe}} = ?$ (dependent variable)

$k_{\text{grout}} = 0.74$

$V = 20$

$r_{\text{nominal}} = 1$ inch (option 2)

$r_b = 3$

space = 0.5

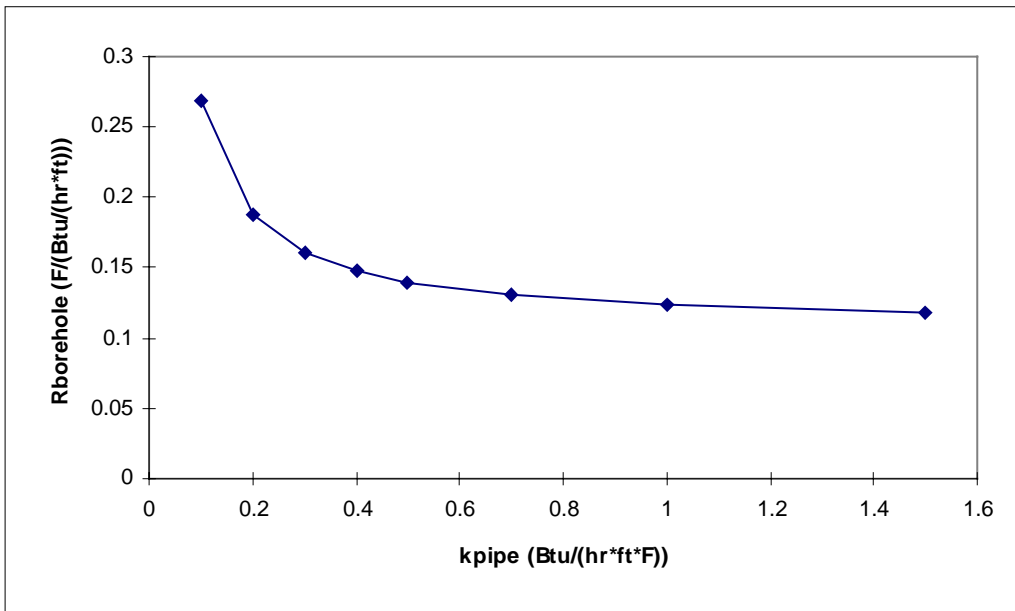


Figure 6-4 Pipe Conductivity (k_{pipe}) Vs. Borehole thermal resistance (R_{borehole})

6.2.3 Fluid Flow Rate (V)

Fluid flow rate affects the heat transfer between the bulk fluid and the inner pipe wall.

Ideally, a fully developed turbulent flow should be used for a heat exchangers to enhance

heat transfer. The higher the fluid flow rate, the better the development of a turbulent flow, and hence the better the heat transfer. Figure 6-5 shows that the overall borehole thermal resistance (R_{borehole}) decreases significantly as the flow rate (V) increases, especially when the flow rates smaller than 5 GPM. When the flow rate greater than 5 GPM, the turbulence inside the pipe is well developed, and hence the change of R_{borehole} is negligible. It supports that the flow rate should be large enough to cause turbulence inside the pipe to help to maintain good heat transfer between the circulating fluid and the inside pipe wall.

INPUT VARIABLES:

$V = ?$ (dependent variable)

$k_{\text{grout}} = 0.74$

$k_{\text{pipe}} = 0.225$

$r_{\text{nominal}} = 1$ inch (option 2)

$r_b = 3$

space = 0.5

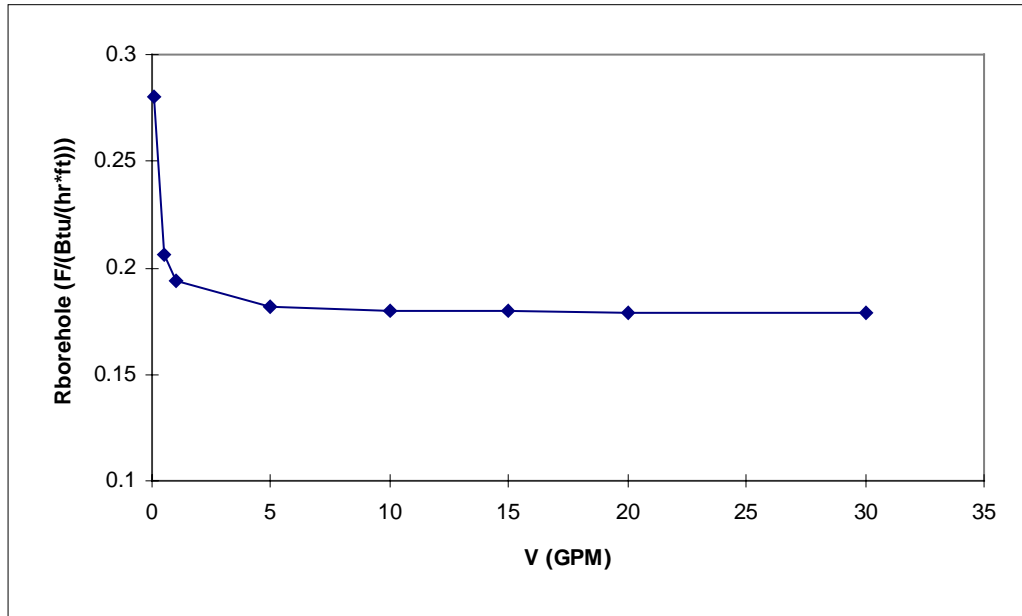


Figure 6-5 Fluid flow rate (V) Vs. Borehole thermal resistance (R_{borehole})

6.2.4 Pipe nominal size (r_{nominal})

Pipe size affects the borehole thermal resistance the same way as the fluid flow rate. Smaller pipes promote more turbulence inside the pipe, and hence better heat transfer, and lower overall borehole thermal resistance. Figure 6-6 shows the borehole thermal resistance for five piping sizes. It shows exactly what is expected, smaller the pipe, smaller the borehole thermal resistance.

INPUT VARIABLES:

$r_{\text{nominal}} = ?$ (dependent variable)

$k_{\text{grout}} = 0.74$

$k_{\text{pipe}} = 0.225$

$$V = 20$$

$$r_b = 3$$

$$\text{space} = 0.5$$

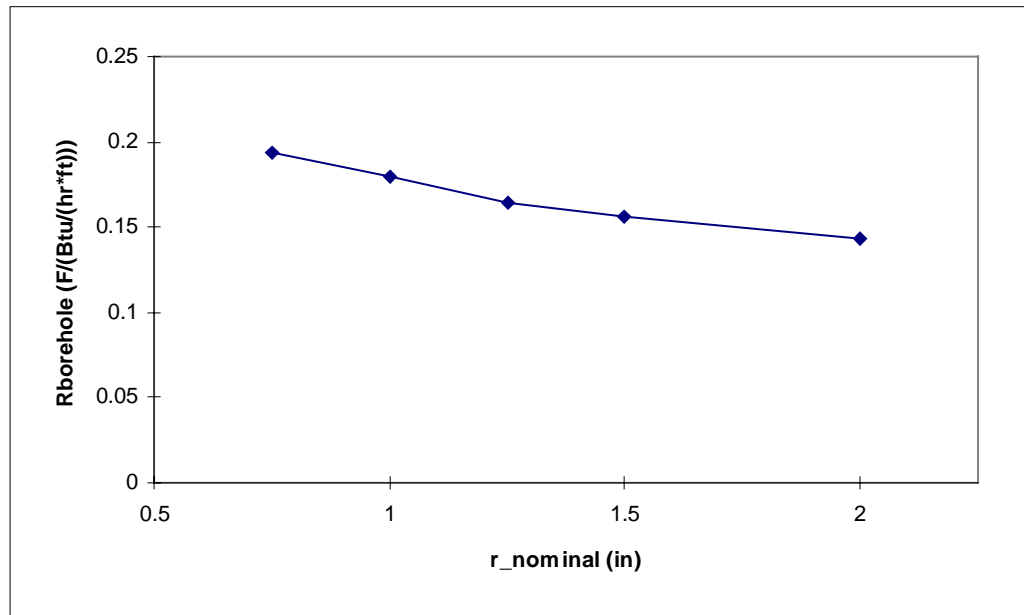


Figure 6.6 Pipe nominal size (r_{nominal}) Vs. Borehole thermal resistance (R_{borehole})

6.2.5 Borehole radius (r_b)

Figure 6-7 shows that the larger the borehole, the larger the borehole thermal resistance. The reason is because a larger borehole requires more grouting inside the borehole, and hence has more thermal resistance. Also, a larger borehole, smaller the conduction factors according equations in Table 6-1.

INPUT VARIABLES:

$r_b = ?$ (dependent variable)

$k_{\text{grout}} = 0.74$

$k_{\text{pipe}} = 0.225$

$V = 20$

$r_{\text{nominal}} = 1$ inch (option 2)

space = 0.5

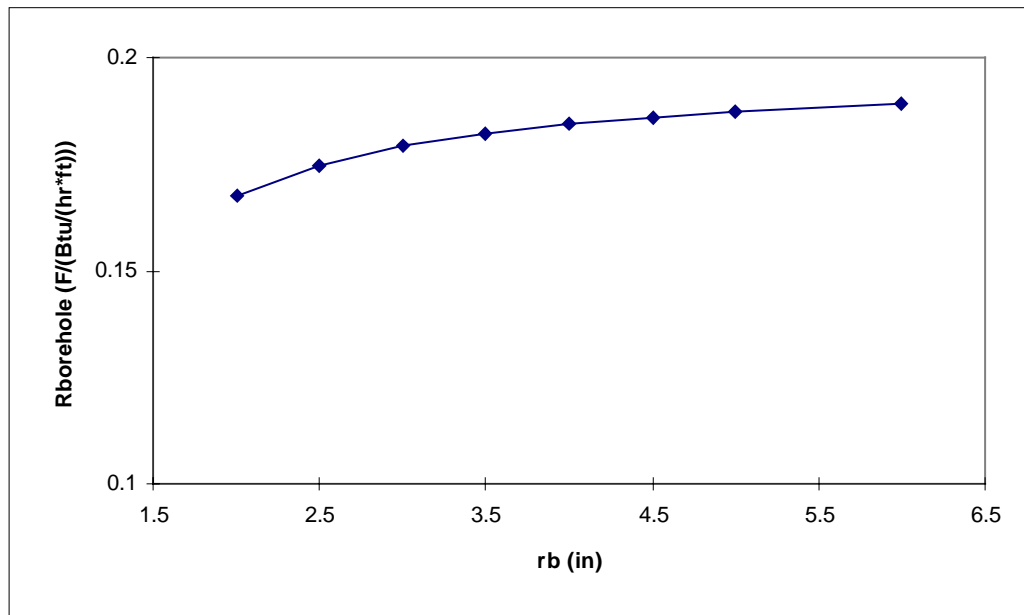


Figure 6-7 Borehole radius (r_b) Vs. Borehole thermal resistance (R_{borehole})

6.2.6 Spacing between pipe and borehole wall (space)

Figure 6-8 show that the overall borehole thermal resistance increase significantly as the spacing between the pipe and the borehole wall increases. As expected, as the spacing

increases, thermal resistance between the pipe and the borehole wall increases, due to more grouting between. Also, as mentioned earlier, this model assumes an isothermal surface for each cylinder, therefore the borehole thermal resistance is highly (and artificially) dependent on the this spacing.

INPUT VARIABLES:

space = ? (dependent variable)

$$k_{\text{grout}} = 0.74$$

$$k_{\text{pipe}} = 0.225$$

$$V = 20$$

$$r_{\text{nominal}} = 1 \text{ inch (option 2)}$$

$$r_b = 3$$

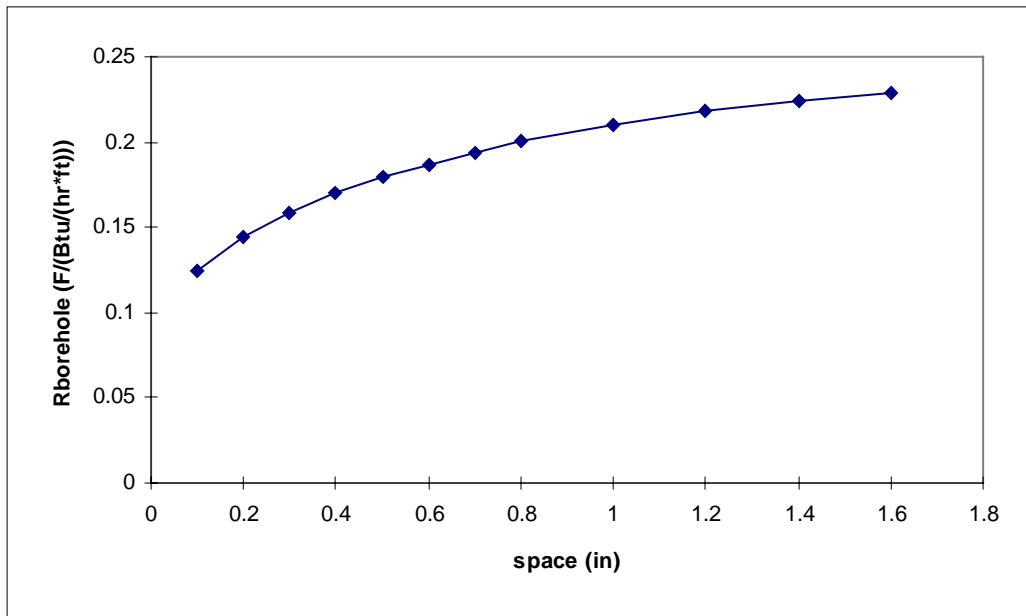


Figure 6-8 Spacing between pipe and borehole wall (space) Vs. Borehole thermal resistance (R_{borehole})

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the conclusions that can be drawn from the previous chapters, and gives recommendations for potential further work and for improvements. The following conclusions can be drawn from this study:

1. Automatic selection of the borehole configuration is implemented in the new GLHEPRO version 2.00 by using the program, called SELECT. SELECT helps the user to choose from the many possible configurations according to the field constraints.
2. A FORTRAN program, OPTIMIZE, has been written to minimize the life cycle cost of the ground-loop heat pump system. Some of the important parameters have been studied:
 - For the cases evaluated, the results show that the minimum life cycle cost is always coincident with the minimum borehole depth. The much higher first cost offsets the benefit from the lower annual operating cost with longer borehole depth.
 - The optimal piping size depends on the fluid flow rate inside the pipe, and piping cost. The optimal piping size for the daycare center is 1.5 inch.
 - The results suggest that the lower the flow rate, the lower the life cycle cost.

3. GLHEPRO Version 2.00 incorporates algorithms that allow the user to enter a peak load and a desired peak entering fluid temperature. These should be useful extensions. One area that requires further research is the length of the peak pulse.
4. Some checking and advising have been implemented in the GLHEPRO version 2.00:
 - Fluid flow rate checking
 - Temperature setting checking
 - Peak load information checking
5. A FORTRAN program, BORERES has been written to predict the borehole thermal resistance for a given borehole radius, its geometry, thermal conductivity of the grouting, and thermal conductivity of the pipes by using the methodology of the Conduction Shape Factor.

Recommendations for further study and development of GLHEPRO include:

1. Convert the current DOS version of GLHEPRO to WINDOW version, which should have better user interface.
2. Implement a multi-variate optimization search in GLHEPRO, so the optimization process will be easier and more useful. Independent variables to be optimized should at least include: borehole depth, fluid flow rate, fluid type, piping size.
3. Develop additional borehole configurations and methods for interpolating between the configurations.

4. Develop a methodology to estimate the number of hours at peak automatically.

Alternatively, the actual hourly load profile could be used in the conjunction with a detailed short-time step model of the ground loop heat exchanger.

5. Validate this *Shape Factor* model by other methods or experimental data.

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APPENDIXES

Appendix 1

BLAST input file for the daycare center

```

0      1
0      2      BEGIN INPUT;
0      3      RUN CONTROL:
0      4          NEW ZONES,
0      5          NEW AIR SYSTEMS,
0      6          PLANT,
0      7          REPORTS(WLHPS REPORT),
0      8          UNITS(IN=ENGLISH, OUT=ENGLISH);
0      9          TEMPORARY WALLS:
0     10              WALL1
0     11                  = (A7 ,
0     12                      B1 ,
0     13                          PL4 ,
0     14                              IN3 ,
0     15                                  PL4);
0     16              WALL2
0     17                  = (PL4 ,
0     18                      B1 ,
0     19                          PL4);
0     20      END;
0     21      TEMPORARY ROOFS:
0     22          ROOF1
0     23              = (RF4 ,
0     24                  C14);
0     25          CEILING1
0     26              = (PL4 ,
0     27                  E4 ,
0     28                      IN3 ,
0     29                          PL4);
0     30      END;
0     31      TEMPORARY FLOORS:
0     32          FLOOR1
0     33              = (CO18 ,
0     34                  BM2 ,
0     35                      C5 ,
0     36                          FF1);
0     37          FLOOR2
0     38              = (PL4 ,
0     39                  E4 ,
0     40                      IN3 ,
0     41                          PL4);
0     42      END;

```

```

0      43      TEMPORARY DOORS:
0      44      DOOR1
0      45          = (ME2 ,
0      46              B1 ,
0      47              ME2);
0      48      END;
0      49      TEMPORARY SCHEDULE (FAN OPERATION):
0      50      MONDAY THRU FRIDAY=(0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,1.00,1.00,
0      51      1.00,1.00,1.00,1.00,1.00,1.00,1.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00),
0      52      SATURDAY=(0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,
0      53      0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00),
0      54      SUNDAY=(0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,
0      55      0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00),
0      56      HOLIDAY=(0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,
0      57      0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00),
0      58      SPECIAL1=(0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,
0      59      0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00),
0      60      SPECIAL2=(0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,
0      61      0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00),
0      62      SPECIAL3=(0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,
0      63      0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00),
0      64      SPECIAL4=(0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,
0      65      0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00);
0      66      END;
0      67      TEMPORARY CONTROLS (DC):
0      68      PROFILES:
0      69          BEG=(1.0000 AT 68.00, 0.0000 AT 69.00, 0.0000 AT 72.00,
0      70              -1.0000 AT 73.00);
0      71          SETBACK=(1.0 AT 60.0, 0.0 AT 61.0, 0.0 AT 80, -1.0 AT 81);
0      72      SCHEDULES:
0      73          MONDAY THRU FRIDAY=(07 TO 17-BEG, 17 TO 07-SETBACK),
0      74          SATURDAY=(0 TO 24-SETBACK),
0      75          SUNDAY=(0 TO 24-SETBACK),
0      76          HOLIDAY=(0 TO 24-SETBACK),
0      77          SPECIAL1=(0 TO 24-BEG),
0      78          SPECIAL2=(0 TO 24-BEG),
0      79          SPECIAL3=(0 TO 24-BEG),
0      80          SPECIAL4=(0 TO 24-BEG);
0      81      END;
0      82      PROJECT="DAYCARE CENTER";
0      83      LOCATION=TULSA ;
0      84      **      DESIGN DAYS=TULSA SUMMER ,

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```

0      85  **                TULSA WINTER ;
0      86      WEATHER TAPE FROM 01JAN THRU 31DEC;
0      87      GROUND TEMPERATURES=(55, 55, 55, 55, 55, 55, 55, 55, 55, 55, 55, 55);
0      88      CATEGORY CODE=74014;
0      89      BEGIN BUILDING DESCRIPTION;
0      90      BUILDING="DAYCARE CENTER ";
0      91      NORTH AXIS=315.00;
0      92      SOLAR DISTRIBUTION=-1;
0      93  ** ZONE 1 INCLUDES ONLY THE MECHANICAL ROOM NEXT TO THE KITCHEN.
0      94      ZONE 1 "MECHANICAL ROOM ":
0      95      ORIGIN:(28.17, 5.92, 0.00);
0      96      NORTH AXIS=0.00;
0      97      EXTERIOR WALLS :
0      98      STARTING AT(0.00, 0.00, 0.00)
0      99      FACING(180.00)
0     100      TILTED(90.00)
0     101      WALL1 (11.42 BY 8.00),
0     102      STARTING AT(11.42, 0.00, 0.00)
0     103      FACING(90.00)
0     104      TILTED(90.00)
0     105      WALL1 (17.88 BY 8.00)
0     106      WITH DOORS OF TYPE
0     107      DOOR1 (5.00 BY 7.00)
0     108      AT (1.00, 0.00);
0     109      PARTITIONS :
0     110      STARTING AT(11.42, 17.88, 0.00)
0     111      FACING(0.00)
0     112      TILTED(90.00)
0     113      WALL1 (11.42 BY 8.00),
0     114      STARTING AT(0.00, 17.88, 0.00)
0     115      FACING(270.00)
0     116      TILTED(90.00)
0     117      WALL1 (17.88 BY 8.00);
0     118      SLAB ON GRADE FLOORS :
0     119      STARTING AT(0.00, 17.88, 0.00)
0     120      FACING(180.00)
0     121      TILTED(180.00)
0     122      FLOOR1 (11.42 BY 17.88);
0     123      INTERZONE CEILINGS :
0     124      STARTING AT(0.00, 0.00, 8.00)
0     125      FACING(180.00)
0     126      TILTED(0.00)

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0 127 CEILING1 (11.42 BY 17.88)
0 128 ADJACENT TO ZONE (6);
0 129 OTHER =13.65,OFFICE OCCUPANCY ,
0 130 85.00 PERCENT RADIANT, 15.00 PERCENT LATENT, 0.00 PERCENT LOST,
0 131 FROM 01JAN THRU 31DEC;
0 132 INFILTRATION=30.00,CONSTANT ,
0 133 WITH COEFFICIENTS (0.606000, 0.020200, 0.000598, 0.000000),
0 134 FROM 01JAN THRU 31DEC;
0 135 END ZONE;
0 136 ** ZONE 2 INCLUDES THE SMURF ROOM AND THE KITCHEN, BATHROOM,
0 137 ** JANITOR AND STORAGE ROOM CLOSE TO THE SMURF ROOM.
0 138 ZONE 2 "SMURF ROOM ":
0 139 ORIGIN:(9.75, 0.00, 0.00);
0 140 NORTH AXIS=0.00;
0 141 EXTERIOR WALLS :
0 142 STARTING AT(0.00, 0.00, 0.00)
0 143 FACING(180.00)
0 144 TILTED(90.00)
0 145 WALL1 (18.42 BY 8.00),
0 146 STARTING AT(18.42, 0.00, 0.00)
0 147 FACING(90.00)
0 148 TILTED(90.00)
0 149 WALL1 (5.92 BY 8.00)
0 150 WITH WINDOWS OF TYPE
0 151 SINGLE PANE HW WINDOW (1.00 BY 4.00)
0 152 REVEAL(0.00)
0 153 AT (0.75, 3.00)
0 154 WITH DOORS OF TYPE
0 155 DOOR1 (3.00 BY 7.00)
0 156 AT (2.20, 0.00),
0 157 STARTING AT(29.83, 23.79, 0.00)
0 158 FACING(90.00)
0 159 TILTED(90.00)
0 160 WALL1 (20.21 BY 8.00),
0 161 STARTING AT(0.00, 33.42, 0.00)
0 162 FACING(270.00)
0 163 TILTED(90.00)
0 164 WALL1 (33.42 BY 8.00)
0 165 WITH WINDOWS OF TYPE
0 166 SINGLE PANE HW WINDOW (4.67 BY 4.00)
0 167 REVEAL(0.00)
0 168 AT (17.00, 3.00);

```

```

0 169 PARTITIONS :
0 170 STARTING AT(29.83, 44.00, 0.00)
0 171 FACING(0.00)
0 172 TILTED(90.00)
0 173 WALL2 (29.83 BY 8.00)
0 174 WITH DOORS OF TYPE
0 175 SWD (3.00 BY 7.00)
0 176 AT (26.03, 0.00),
0 177 STARTING AT(0.00, 44.00, 0.00)
0 178 FACING(270.00)
0 179 TILTED(90.00)
0 180 WALL1 (10.58 BY 8.00);
0 181 WALL TO UNCOOLED SPACES:
0 182 STARTING AT(18.42, 5.92, 0.00)
0 183 FACING(90.00)
0 184 TILTED(90.00)
0 185 WALL1 (17.88 BY 8.00),
0 186 STARTING AT(18.42, 23.79, 0.00)
0 187 FACING(180.00)
0 188 TILTED(90.00)
0 189 WALL1 (11.42 BY 8.00);
0 190 SLAB ON GRADE FLOORS :
0 191 STARTING AT(0.00, 39.18, 0.00)
0 192 FACING(180.00)
0 193 TILTED(180.00)
0 194 FLOOR1 (26.57 BY 39.18);
0 195 INTERZONE CEILINGS :
0 196 STARTING AT(0.00, 0.00, 8.00)
0 197 FACING(180.00)
0 198 TILTED(0.00)
0 199 CEILING1 (25.57 BY 39.18)
0 200 ADJACENT TO ZONE (6);
0 201 INTERNAL MASS: WALL2
0 202 ( 85.00 BY 8.00);
0 203 PEOPLE=25,FAN OPERATION ,
0 204 AT ACTIVITY LEVEL 0.45, 70.00 PERCENT RADIANT,
0 205 FROM 01JAN THRU 31DEC;
0 206 LIGHTS=1.70,OFFICE LIGHTING ,
0 207 0.00 PERCENT RETURN AIR, 20.00 PERCENT RADIANT,
0 208 40.00 PERCENT VISIBLE, 40.00 PERCENT REPLACEABLE,
0 209 FROM 01JAN THRU 31DEC;
0 210 OTHER =8.50,OFFICE OCCUPANCY ,

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0 211          40.00 PERCENT RADIANT, 20.00 PERCENT LATENT, 00.00 PERCENT LOST,
0 212          FROM 01JAN THRU 31DEC;
0 213 **      VENTILATION=0.00,INTERMITTENT ,
0 214 **      65.00 MIN TEMP, 40.00 DEL TEMP,
0 215 **      FROM 01JAN THRU 31DEC;
0 216          CONTROLS=DC ,
0 217          54 HEATING, 60 COOLING,
0 218          45.00 PERCENT MRT,
0 219          FROM 01JAN THRU 31DEC;
0 220          INFILTRATION=140.00,CONSTANT ,
0 221          WITH COEFFICIENTS (0.606000, 0.020200, 0.000598, 0.000000),
0 222          FROM 01JAN THRU 31DEC;
0 223          END ZONE;
0 224 ** ZONE 3 INCLUDES THE RECEPTION THE SMALL OFFICE NEXT TO IT AND
0 225 ** THE HALL WAY IN BETWEEN THE RECEPTION AND THE MUPPET ROOM.
0 226          ZONE 3 "RECEPTION " :
0 227          ORIGIN:(0.00, 33.42, 0.00);
0 228          NORTH AXIS=0.00;
0 229          EXTERIOR WALLS :
0 230          STARTING AT(0.00, 0.00, 0.00)
0 231          FACING(180.00)
0 232          TILTED(90.00)
0 233          WALL2 (9.75 BY 8.00),
0 234          STARTING AT(9.75, 42.67, 0.00)
0 235          FACING(270.00)
0 236          TILTED(90.00)
0 237          WALL1 (10.92 BY 8.00),
0 238          STARTING AT(9.75, 31.75, 0.00)
0 239          FACING(0.00)
0 240          TILTED(90.00)
0 241          WALL1 (9.75 BY 8.00),
0 242          STARTING AT(0.00, 31.75, 0.00)
0 243          FACING(270.00)
0 244          TILTED(90.00)
0 245          WALL1 (10.58 BY 8.00),
0 246          STARTING AT(0.00, 21.17, 0.00)
0 247          FACING(270.00)
0 248          TILTED(90.00)
0 249          WALL2 (21.17 BY 8.00)
0 250          WITH WINDOWS OF TYPE
0 251          SINGLE PANE HW WINDOW (21.00 BY 0.70)
0 252          REVEAL(0.00)

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0 253 AT (0.00, 7.20)
0 254 WITH DOORS OF TYPE
0 255 GLD (3.00 BY 7.00)
0 256 AT (1.00, 0.00);
0 257 PARTITIONS :
0 258 STARTING AT(9.75, 0.00, 0.00)
0 259 FACING(90.00)
0 260 TILTED(90.00)
0 261 WALL1 (10.58 BY 8.00),
0 262 STARTING AT(9.75, 10.58, 0.00)
0 263 FACING(180.00)
0 264 TILTED(90.00)
0 265 WALL2 (5.92 BY 8.00)
0 266 WITH DOORS OF TYPE
0 267 SWD (3.00 BY 7.00)
0 268 AT (0.80, 0.00),
0 269 STARTING AT(15.67, 10.58, 0.00)
0 270 FACING(90.00)
0 271 TILTED(90.00)
0 272 WALL2 (34.83 BY 8.00)
0 273 WITH DOORS OF TYPE
0 274 SWD (3.00 BY 7.00)
0 275 AT (0.50, 0.00)
0 276 WITH DOORS OF TYPE
0 277 SWD (3.00 BY 7.00)
0 278 AT (17.00, 0.00)
0 279 WITH DOORS OF TYPE
0 280 SWD (3.00 BY 7.00)
0 281 AT (21.25, 0.00),
0 282 STARTING AT(9.75, 45.42, 0.00)
0 283 FACING(270.00)
0 284 TILTED(90.00)
0 285 WALL1 (2.75 BY 8.00);
0 286 SLAB ON GRADE FLOORS :
0 287 STARTING AT(0.00, 38.71, 0.00)
0 288 FACING(180.00)
0 289 TILTED(180.00)
0 290 FLOOR1 (13.32 BY 38.71);
0 291 INTERZONE CEILINGS :
0 292 STARTING AT(0.00, 0.00, 8.00)
0 293 FACING(180.00)
0 294 TILTED(0.00)

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0 295          CEILING1 (13.32 BY 38.71)
0 296          ADJACENT TO ZONE (6);
0 297          INTERNAL MASS: WALL2
0 298          ( 23.00 BY 8.00);
0 299          PEOPLE=10,FAN OPERATION ,
0 300          AT ACTIVITY LEVEL 0.45, 70.00 PERCENT RADIANT,
0 301          FROM 01JAN THRU 31DEC;
0 302          LIGHTS=0.85,OFFICE LIGHTING ,
0 303          0.00 PERCENT RETURN AIR, 20.00 PERCENT RADIANT,
0 304          40.00 PERCENT VISIBLE, 40.00 PERCENT REPLACEABLE,
0 305          FROM 01JAN THRU 31DEC;
0 306          OTHER =5.10,OFFICE OCCUPANCY ,
0 307          40.00 PERCENT RADIANT, 10.00 PERCENT LATENT, 00.00 PERCENT LOST,
0 308          FROM 01JAN THRU 31DEC;
0 309          **          VENTILATION=0.00,INTERMITTENT ,
0 310          **          65.00 MIN TEMP, 50.00 DEL TEMP,
0 311          **          FROM 01JAN THRU 31DEC;
0 312          CONTROLS=DC ,
0 313          35 HEATING,38 COOLING,
0 314          45.00 PERCENT MRT,
0 315          FROM 01JAN THRU 31DEC;
0 316          INFILTRATION=75.00,CONSTANT ,
0 317          WITH COEFFICIENTS (0.606000, 0.020200, 0.000598, 0.000000),
0 318          FROM 01JAN THRU 31DEC;
0 319          END ZONE;
0 320          ** ZONE 4 INCLUDES THE MUPPET ROOM, THE BIG OFFICE AND STORAGE ROOM.
0 321          ZONE 4 "MUPPET ROOM ":
0 322          ORIGIN:(15.67, 44.00, 0.00);
0 323          NORTH AXIS=0.00;
0 324          EXTERIOR WALLS :
0 325          STARTING AT(23.92, 0.00, 0.00)
0 326          FACING(180.00)
0 327          TILTED(90.00)
0 328          WALL1 (20.67 BY 8.00)
0 329          WITH DOORS OF TYPE
0 330          DOOR1 (3.00 BY 7.00)
0 331          AT (2.38, 0.00)
0 332          WITH WINDOWS OF TYPE
0 333          SINGLE PANE HW WINDOW (1.00 BY 4.00)
0 334          REVEAL(0.00)
0 335          AT (5.75, 3.00),
0 336          STARTING AT(44.58, 0.00, 0.00)

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0 337 FACING(90.00)
0 338 TILTED(90.00)
0 339 WALL1 (21.17 BY 8.00),
0 340 STARTING AT(44.58, 21.17, 0.00)
0 341 FACING(0.00)
0 342 TILTED(90.00)
0 343 WALL1 (20.67 BY 8.00)
0 344 WITH DOORS OF TYPE
0 345 DOOR1 (3.00 BY 7.00)
0 346 AT (5.00, 0.00),
0 347 STARTING AT(23.92, 21.17, 0.00)
0 348 FACING(90.00)
0 349 TILTED(90.00)
0 350 WALL1 (13.92 BY 8.00)
0 351 WITH DOORS OF TYPE
0 352 DOOR1 (3.00 BY 7.00)
0 353 AT (0.90, 0.00);
0 354 PARTITIONS :
0 355 STARTING AT(0.00, 0.00, 0.00)
0 356 FACING(180.00)
0 357 TILTED(90.00)
0 358 WALL2 (23.92 BY 8.00),
0 359 STARTING AT(23.92, 35.08, 0.00)
0 360 FACING(0.00)
0 361 TILTED(90.00)
0 362 WALL1 (23.92 BY 8.00),
0 363 STARTING AT(0.00, 35.08, 0.00)
0 364 FACING(270.00)
0 365 TILTED(90.00)
0 366 WALL2 (35.08 BY 8.00)
0 367 WITH DOORS OF TYPE
0 368 SWD (3.00 BY 7.00)
0 369 AT (10.50, 0.00)
0 370 WITH DOORS OF TYPE
0 371 SWD (3.00 BY 7.00)
0 372 AT (14.50, 0.00)
0 373 WITH DOORS OF TYPE
0 374 SWD (3.00 BY 7.00)
0 375 AT (31.00, 0.00);
0 376 SLAB ON GRADE FLOORS :
0 377 STARTING AT(0.00, 31.69, 0.00)
0 378 FACING(180.00)

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0 379          TILTED(180.00)
0 380          FLOOR1 (40.28 BY 31.69);
0 381          INTERZONE CEILINGS :
0 382          STARTING AT(0.00, 0.00, 8.00)
0 383          FACING(180.00)
0 384          TILTED(0.00)
0 385          CEILING1 (40.28 BY 31.69)
0 386          ADJACENT TO ZONE (6);
0 387          INTERNAL MASS: WALL2
0 388          ( 50.00 BY 8.00);
0 389          INTERNAL MASS: WALL1
0 390          ( 34.00 BY 8.00);
0 391          PEOPLE=25,FAN OPERATION ,
0 392          AT ACTIVITY LEVEL 0.45, 70.00 PERCENT RADIANT,
0 393          FROM 01JAN THRU 31DEC;
0 394          LIGHTS=1.87,OFFICE LIGHTING ,
0 395          0.00 PERCENT RETURN AIR, 20.00 PERCENT RADIANT,
0 396          40.00 PERCENT VISIBLE, 40.00 PERCENT REPLACEABLE,
0 397          FROM 01JAN THRU 31DEC;
0 398          OTHER =8.50,OFFICE OCCUPANCY ,
0 399          40.00 PERCENT RADIANT, 5.00 PERCENT LATENT, 0.00 PERCENT LOST,
0 400          FROM 01JAN THRU 31DEC;
0 401          **          VENTILATION=0.00,INTERMITTENT ,
0 402          **          32.00 MIN TEMP, 00.00 DEL TEMP,
0 403          **          FROM 01JAN THRU 31DEC;
0 404          CONTROLS=DC ,
0 405          57 HEATING, 57 COOLING,
0 406          45.00 PERCENT MRT,
0 407          FROM 01JAN THRU 31DEC;
0 408          INFILTRATION=124.00,CONSTANT ,
0 409          WITH COEFFICIENTS (0.606000, 0.020200, 0.000598, 0.000000),
0 410          FROM 01JAN THRU 31DEC;
0 411          END ZONE;
0 412          ** ZONE 5 INCLUDES THE SUPER FRIENDS ROOM, THE SHIRT TALES ROOM,
0 413          ** THE EXPLORER ROOM, THE HALL WAY CONNECTING ALL THREE OF THESE
0 414          ** ROOMS AND THE BATHROOM NEXT TO THE SUPER FRIENDS ROOM.
0 415          ZONE 5 "SHORT TALES ROOM ":
0 416          ORIGIN:(0.00, 76.08, 0.00);
0 417          NORTH AXIS=0.00;
0 418          EXTERIOR WALLS :
0 419          STARTING AT(0.00, 0.00, 0.00)
0 420          FACING(180.00)

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0 421 TILTED(90.00)
0 422 WALL1 (9.75 BY 8.00),
0 423 STARTING AT(39.58, 2.75, 0.00)
0 424 FACING(180.00)
0 425 TILTED(90.00)
0 426 WALL1 (20.67 BY 8.00)
0 427 WITH DOORS OF TYPE
0 428 MID (3.50 BY 7.00)
0 429 AT (0.75, 0.00),
0 430 STARTING AT(60.25, 2.75, 0.00)
0 431 FACING(90.00)
0 432 TILTED(90.00)
0 433 WALL1 (29.92 BY 8.00)
0 434 WITH WINDOWS OF TYPE
0 435 SINGLE PANE HW WINDOW (2.33 BY 4.00)
0 436 REVEAL(0.00)
0 437 AT (6.00, 3.00),
0 438 STARTING AT(60.25, 32.67, 0.00)
0 439 FACING(0.00)
0 440 TILTED(90.00)
0 441 WALL1 (60.25 BY 8.00)
0 442 WITH WINDOWS OF TYPE
0 443 SINGLE PANE HW WINDOW (7.00 BY 4.00)
0 444 REVEAL(0.00)
0 445 AT (30.00, 3.00)
0 446 WITH DOORS OF TYPE
0 447 MID (3.00 BY 7.00)
0 448 AT (1.00, 0.00)
0 449 WITH DOORS OF TYPE
0 450 MID (3.00 BY 7.00)
0 451 AT (20.60, 0.00)
0 452 WITH DOORS OF TYPE
0 453 MID (3.00 BY 7.00)
0 454 AT (45.75, 0.00),
0 455 STARTING AT(0.00, 32.67, 0.00)
0 456 FACING(270.00)
0 457 TILTED(90.00)
0 458 WALL1 (32.67 BY 8.00)
0 459 WITH WINDOWS OF TYPE
0 460 SINGLE PANE HW WINDOW (2.33 BY 4.00)
0 461 REVEAL(0.00)
0 462 AT (24.07, 3.00);

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0 463 PARTITIONS :
0 464     STARTING AT(9.75, 0.00, 0.00)
0 465     FACING(90.00)
0 466     TILTED(90.00)
0 467     WALL1 (2.75 BY 8.00),
0 468     STARTING AT(15.67, 2.75, 0.00)
0 469     FACING(180.00)
0 470     TILTED(90.00)
0 471     WALL1 (23.92 BY 8.00);
0 472 SLAB ON GRADE FLOORS :
0 473     STARTING AT(0.00, 30.00, 0.00)
0 474     FACING(180.00)
0 475     TILTED(180.00)
0 476     FLOOR1 (60.98 BY 30.00);
0 477 INTERZONE CEILINGS :
0 478     STARTING AT(0.00, 0.00, 8.00)
0 479     FACING(180.00)
0 480     TILTED(0.00)
0 481     CEILING1 (60.98 BY 30.00)
0 482     ADJACENT TO ZONE (6);
0 483 INTERNAL MASS: WALL2
0 484     ( 325.00 BY 8.00);
0 485 PEOPLE=30,FAN OPERATION ,
0 486     AT ACTIVITY LEVEL 0.45, 70.00 PERCENT RADIANT,
0 487     FROM 01JAN THRU 31DEC;
0 488 LIGHTS=2.04,OFFICE LIGHTING ,
0 489     0.00 PERCENT RETURN AIR, 20.00 PERCENT RADIANT,
0 490     40.00 PERCENT VISIBLE, 40.00 PERCENT REPLACEABLE,
0 491     FROM 01JAN THRU 31DEC;
0 492 OTHER =5.10,OFFICE OCCUPANCY ,
0 493     40.00 PERCENT RADIANT, 5.00 PERCENT LATENT, 0.00 PERCENT LOST,
0 494     FROM 01JAN THRU 31DEC;
0 495 ** VENTILATION=0.00,INTERMITTENT ,
0 496 **     15.00 MIN TEMP, 00.00 DEL TEMP,
0 497 **     FROM 01JAN THRU 31DEC;
0 498 CONTROLS=DC ,
0 499     91 HEATING, 72 COOLING,
0 500     45.00 PERCENT MRT,
0 501     FROM 01JAN THRU 31DEC;
0 502     INFILTRATION=248.00,CONSTANT ,
0 503     WITH COEFFICIENTS (0.606000, 0.020200, 0.000598, 0.000000),
0 504     FROM 01JAN THRU 31DEC;

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0 505 END ZONE;
0 506 ** THIS LAST ZONE IS THE SPACE BETWEEN THE FALSE CEILING AND THE ROOF.
0 507 ZONE 6 "ATTIC ":
0 508 ORIGIN:(0.00, 0.00, 0.00);
0 509 NORTH AXIS=0.00;
0 510 EXTERIOR WALLS :
0 511 STARTING AT(9.75, 0.00, 8.00)
0 512 FACING(180.00)
0 513 TILTED(90.00)
0 514 WALL1 (18.42 BY 5.00),
0 515 STARTING AT(28.17, 0.00, 8.00)
0 516 FACING(90.00)
0 517 TILTED(90.00)
0 518 WALL1 (5.92 BY 5.00),
0 519 STARTING AT(28.17, 5.92, 8.00)
0 520 FACING(180.00)
0 521 TILTED(90.00)
0 522 WALL1 (11.42 BY 5.00),
0 523 STARTING AT(39.58, 5.92, 8.00)
0 524 FACING(90.00)
0 525 TILTED(90.00)
0 526 WALL1 (38.08 BY 5.00),
0 527 STARTING AT(39.58, 44.00, 8.00)
0 528 FACING(180.00)
0 529 TILTED(90.00)
0 530 WALL1 (20.67 BY 5.00),
0 531 STARTING AT(60.25, 44.00, 8.00)
0 532 FACING(90.00)
0 533 TILTED(90.00)
0 534 WALL1 (21.17 BY 5.00),
0 535 STARTING AT(60.25, 65.17, 8.00)
0 536 FACING(0.00)
0 537 TILTED(90.00)
0 538 WALL1 (20.67 BY 5.00),
0 539 STARTING AT(39.58, 65.17, 8.00)
0 540 FACING(90.00)
0 541 TILTED(90.00)
0 542 WALL1 (13.92 BY 5.00),
0 543 STARTING AT(39.58, 79.08, 8.00)
0 544 FACING(180.00)
0 545 TILTED(90.00)
0 546 WALL1 (20.67 BY 5.00),

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0      547      STARTING AT(60.25, 79.08, 8.00)
0      548      FACING(90.00)
0      549      TILTED(90.00)
0      550      WALL1 (29.92 BY 5.00),
0      551      STARTING AT(60.25, 109.00, 8.00)
0      552      FACING(0.00)
0      553      TILTED(90.00)
0      554      WALL1 (60.25 BY 5.00),
0      555      STARTING AT(0.00, 109.00, 8.00)
0      556      FACING(270.00)
0      557      TILTED(90.00)
0      558      WALL1 (32.67 BY 5.00),
0      559      STARTING AT(0.00, 76.33, 8.00)
0      560      FACING(180.00)
0      561      TILTED(90.00)
0      562      WALL1 (9.75 BY 5.00),
0      563      STARTING AT(9.75, 76.33, 8.00)
0      564      FACING(270.00)
0      565      TILTED(90.00)
0      566      WALL1 (11.17 BY 5.00),
0      567      STARTING AT(9.75, 65.17, 8.00)
0      568      FACING(0.00)
0      569      TILTED(90.00)
0      570      WALL1 (9.75 BY 5.00),
0      571      STARTING AT(0.00, 65.17, 8.00)
0      572      FACING(270.00)
0      573      TILTED(90.00)
0      574      WALL1 (10.58 BY 5.00),
0      575      STARTING AT(0.00, 54.58, 8.00)
0      576      FACING(270.00)
0      577      TILTED(90.00)
0      578      WALL2 (21.17 BY 5.00),
0      579      STARTING AT(0.00, 33.42, 8.00)
0      580      FACING(180.00)
0      581      TILTED(90.00)
0      582      WALL1 (9.75 BY 5.00),
0      583      STARTING AT(9.75, 33.42, 8.00)
0      584      FACING(270.00)
0      585      TILTED(90.00)
0      586      WALL1 (33.42 BY 5.00);
0      587      INTERZONE FLOORS :
0      588      STARTING AT(28.17, 23.79, 8.00)

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0 589 FACING(180.00)
0 590 TILTED(180.00)
0 591 FLOOR2 (11.42 BY 17.88)
0 592 ADJACENT TO ZONE (1),
0 593 STARTING AT(9.75, 39.18, 8.00)
0 594 FACING(180.00)
0 595 TILTED(180.00)
0 596 FLOOR2 (25.57 BY 39.18)
0 597 ADJACENT TO ZONE (2),
0 598 STARTING AT(0.00, 72.13, 8.00)
0 599 FACING(180.00)
0 600 TILTED(180.00)
0 601 FLOOR2 (13.32 BY 38.71)
0 602 ADJACENT TO ZONE (3),
0 603 STARTING AT(15.67, 75.69, 8.00)
0 604 FACING(180.00)
0 605 TILTED(180.00)
0 606 FLOOR2 (40.28 BY 31.69)
0 607 ADJACENT TO ZONE (4),
0 608 STARTING AT(0.00, 106.08, 8.00)
0 609 FACING(180.00)
0 610 TILTED(180.00)
0 611 FLOOR2 (60.98 BY 30.00)
0 612 ADJACENT TO ZONE (5);
0 613 ROOFS :
0 614 STARTING AT(5.00, 7.00, 13.00)
0 615 FACING(180.00)
0 616 TILTED(0.00)
0 617 ROOF1 (50.00 BY 97.00);
0 618 INFILTRATION=400.00,CONSTANT ,
0 619 WITH COEFFICIENTS (0.606000, 0.020200, 0.000598, 0.000000),
0 620 FROM 01JAN THRU 31DEC;
0 621 END ZONE;
0 622 END BUILDING DESCRIPTION;
0 623 BEGIN FAN SYSTEM DESCRIPTION;
0 624 WATER LOOP HEAT PUMP SYSTEM 1
0 625 "WATER LOOP SYSTEM " SERVING ZONES
0 626 2, 3, 4, 5;
0 627 FOR ZONE 2:
0 628 SUPPLY AIR VOLUME=375;
0 629 EXHAUST AIR VOLUME=0.0;
0 630 BASEBOARD HEAT CAPACITY=0.0;

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0 631 BASEBOARD HEAT ENERGY SUPPLY=HOT WATER;
0 632 HEAT PUMP FLOW RATE=6000;
0 633 HEAT PUMP CAPACITY=60;
0 634 HEAT PUMP EER=9.0;
0 635 HEAT PUMP COP=3.6;
0 636 ZONE MULTIPLIER=1;
0 637 END ZONE;
0 638 FOR ZONE 3:
0 639 SUPPLY AIR VOLUME=150;
0 640 EXHAUST AIR VOLUME=0.0;
0 641 BASEBOARD HEAT CAPACITY=0.0;
0 642 BASEBOARD HEAT ENERGY SUPPLY=HOT WATER;
0 643 HEAT PUMP FLOW RATE=3800;
0 644 HEAT PUMP CAPACITY=38;
0 645 HEAT PUMP EER=12.0;
0 646 HEAT PUMP COP=4.4;
0 647 ZONE MULTIPLIER=1;
0 648 END ZONE;
0 649 FOR ZONE 4:
0 650 SUPPLY AIR VOLUME=375;
0 651 EXHAUST AIR VOLUME=0.0;
0 652 BASEBOARD HEAT CAPACITY=0.0;
0 653 BASEBOARD HEAT ENERGY SUPPLY=HOT WATER;
0 654 HEAT PUMP FLOW RATE=5700;
0 655 HEAT PUMP CAPACITY=57;
0 656 HEAT PUMP EER=9.0;
0 657 HEAT PUMP COP=3.6;
0 658 ZONE MULTIPLIER=1;
0 659 END ZONE;
0 660 FOR ZONE 5:
0 661 SUPPLY AIR VOLUME=450;
0 662 EXHAUST AIR VOLUME=0.0;
0 663 BASEBOARD HEAT CAPACITY=0.0;
0 664 BASEBOARD HEAT ENERGY SUPPLY=HOT WATER;
0 665 HEAT PUMP FLOW RATE=9100;
0 666 HEAT PUMP CAPACITY=91;
0 667 HEAT PUMP EER=12.0;
0 668 HEAT PUMP COP=4.2;
0 669 ZONE MULTIPLIER=1;
0 670 END ZONE;
0 671 OTHER SYSTEM PARAMETERS:
0 672 SUPPLY FAN PRESSURE=2.48914;

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0 673 SUPPLY FAN EFFICIENCY=0.7;
0 674 RETURN FAN PRESSURE=0.0;
0 675 RETURN FAN EFFICIENCY=0.7;
0 676 EXHAUST FAN PRESSURE=1.00396;
0 677 EXHAUST FAN EFFICIENCY=0.7;
0 678 COLD DECK CONTROL=FIXED SET POINT;
0 679 COLD DECK TEMPERATURE=60.0;
0 680 COLD DECK THROTTLING RANGE=1.8;
0 681 COLD DECK CONTROL SCHEDULE=(80.0 AT 90.0, 90.0 AT 70.0);
0 682 HEATING COIL ENERGY SUPPLY=HOT WATER;
0 683 HEATING COIL CAPACITY=3412000;
0 684 HOT DECK CONTROL=FIXED SET POINT;
0 685 HOT DECK TEMPERATURE=80.0;
0 686 HOT DECK THROTTLING RANGE=1.8;
0 687 HOT DECK CONTROL SCHEDULE=(50.0 AT 0.0, 40.0 AT 70.0);
0 688 MIXED AIR CONTROL=FIXED PERCENT;
0 689 DESIRED MIXED AIR TEMPERATURE=74;
0 690 OUTSIDE AIR VOLUME=0.0;
0 691 GAS BURNER EFFICIENCY=0.8;
0 692 SYSTEM ELECTRICAL DEMAND=0.0;
0 693 LOOP MASS RATIO=0.5;
0 694 SYSTEM PRESSURE HEAD=401.474213311;
0 695 LOOP PUMP EFFICIENCY=0.85;
0 696 TANK TEMPERATURE=73.65;
0 697 FIXED LOOP TEMPERATURE=69.5;
0 698 MAXIMUM LOOP TEMPERATURE=86;
0 699 MINIMUM LOOP TEMPERATURE=69.8;
0 700 STORAGE VOLUME=0.0;
0 701 SUPPLEMENTAL HEAT TYPE=HOT WATER;
0 702 SUPPLEMENTAL COOL TYPE=COMPRESSION;
0 703 NOMINAL FLOW RATE=100;
0 704 NOMINAL PRESSURE DROP=0.004014742;
0 705 LOOP MASS=1230;
0 706 LOOP CONTROL=FIXED TEMPERATURE;
0 707 COOLING TOWER CAPACITY=3414425.0;
0 708 TOWER ELECTRIC COEFFICIENT=0.241;
0 709 TOWER PUMP COEFFICIENT=0.013;
0 710 PUMP TYPE=VARIABLE FLOW;
0 711 END OTHER SYSTEM PARAMETERS;
0 712 ** IF ANY ONE OF THE FOLLOWING BLOCK IS CHANGED, CHANGE THE REST ACCORDINGLY **
0 713 COOLING COIL DESIGN PARAMETERS:
0 714 COIL TYPE=CHILLED WATER;

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0 715 AIR VOLUME FLOW RATE=0.0000;
0 716 BAROMETRIC PRESSURE=405.489;
0 717 AIR FACE VELOCITY=492.126;
0 718 ENTERING AIR DRY BULB TEMPERATURE=84.92;
0 719 ENTERING AIR WET BULB TEMPERATURE=64.04;
0 720 LEAVING AIR DRY BULB TEMPERATURE=55.04;
0 721 LEAVING AIR WET BULB TEMPERATURE=52.7;
0 722 ENTERING WATER TEMPERATURE=44.96;
0 723 LEAVING WATER TEMPERATURE=55.04;
0 724 WATER VOLUME FLOW RATE=0.0000000;
0 725 WATER VELOCITY=275.59;
0 726 END COOLING COIL DESIGN PARAMETERS;
0 727 HEAT RECOVERY PARAMETERS:
0 728 HTREC1(0.85,0.0,0.0);
0 729 HTREC2(0.0,0.0,0.0);
0 730 HTREC3(0.0,0.0,0.0);
0 731 HTREC4(0.0,0.0,0.0);
0 732 HTREC5(0.0,0.0,0.0);
0 733 HTREC6(0.0,0.0,0.0);
0 734 HTPWR(0.0,0.0,0.0);
0 735 HEAT RECOVERY CAPACITY=3412000;
0 736 END HEAT RECOVERY PARAMETERS;
0 737 WATER SOURCE HEAT PUMP PARAMETERS:
0 738 HHCP(-3.6975,4.3774,0.0745);
0 739 HCCP(3.1175,-2.07,0.07459);
0 740 HCOP(-1.1105,1.93,0.107);
0 741 HEER(7.5,-6.3,0.216337);
0 742 PRSURE(0.0,0.0,0.0);
0 743 WLPT(0.0,1.0,0.0);
0 744 END WATER SOURCE HEAT PUMP PARAMETERS;
0 745 EQUIPMENT SCHEDULES:
0 746 SYSTEM OPERATION= FAN OPERATION, FROM 01JAN THRU 31DEC;
0 747 EXHAUST FAN OPERATION=FAN OPERATION, FROM 01JAN THRU 31DEC;
0 748 HEATING COIL OPERATION=OFF, FROM 01JAN THRU 31DEC;
0 749 COOLING COIL OPERATION=OFF, FROM 01JAN THRU 31DEC;
0 750 TSTAT BASEBOARD HEAT OPERATION=OFF, FROM 01JAN THRU 31DEC;
0 751 HEAT RECOVERY OPERATION=OFF, FROM 01JAN THRU 31DEC;
0 752 MAXIMUM VENTILATION SCHEDULE=FAN OPERATION, FROM 01JAN THRU 31DEC;
0 753 MINIMUM VENTILATION SCHEDULE=FAN OPERATION, FROM 01JAN THRU 31DEC;
0 754 SYSTEM ELECTRICAL DEMAND SCHEDULE=ON, FROM 01JAN THRU 31DEC;
0 755 WLHPS STORAGE TANK OPERATION=OFF, FROM 01JAN THRU 31DEC;
0 756 WLHPS VENTILATION SYSTEM OPERATION=FAN OPERATION, FROM 01JAN THRU 31DEC;

```

```

0 757 WLHPS LOOP CONTROL SCHEDULE=OFF, FROM 01JAN THRU 31DEC;
0 758 END EQUIPMENT SCHEDULES;
0 759 END SYSTEM;
0 760 END FAN SYSTEM DESCRIPTION;
0 761 END INPUT;
0 REPORTING WILL BE DONE IN UNITS ENGLISH
0 SIMULATIONS WILL BE ALLOWED FOR TYPES% ZONES SYSTEMS PLANTS

1 BUILDING SIMULATIONS WILL BE ATTEMPTED

SIMULATIONS WILL BE ATTEMPTED FOR 6 ZONES

SIMULATIONS WILL BE ATTEMPTED FOR 1 SYSTEMS

SIMULATIONS WILL BE ATTEMPTED FOR 0 PLANTS
0 NEW BLDLFL AND AHLDFL FILES WILL BE CREATED
FROM USER INPUT, AS NECESSARY
0 LOCATION TAKEN FROM ATTACHED WTHRFL
TITLE= OKLAHOMA CITY, OK TRY LAT= 35.400 LONG= 97.370 TIME ZONE= 6.0
0 * * * * *
BLDFL FOR
DAYCARE CENTER

LOCATION OKLAHOMA CITY, OK TRY LAT= 35.400 LONG= 97.370 TIME ZONE= 6.0
DATE OF FILE CREATE/UPDATE 5 SEP 95 NUMBER OF ENVIRONMENTS 1
NUMBER OF ZONES 6 WITH ZONE NUMBERS
1 2 3 4 5 6
0 * * * * *
AHLDFL FOR
DAYCARE CENTER

LOCATION OKLAHOMA CITY, OK TRY LAT= 35.400 LONG= 97.370 TIME ZONE= 6.0
DATE OF FILE CREATE/UPDATE 5 SEP 95 NUMBER OF ENVIRONMENTS 1
NUMBER OF SYSTEMS 1 WITH SYSTEM NUMBERS
1

***** SIMULATION PERIOD 1 JAN 1951 THRU 31 DEC 1951
0 ENVIRONMENT NUMBER 1 FOR BLDLFL TITLE IS OKLAHOMA CITY, OK TRY

```

WEATHER STATION 13967 START DATE OF 1 JAN 1951 NO. OF DAYS 365
WITH GROUND TEMPERATURES JAN =55.00 FEB =55.00 MAR =55.00 APR =55.00 MAY =55.00 JUN =55.00
JUL =55.00 AUG =55.00 SEP =55.00 OCT =55.00 NOV =55.00 DEC =55.00
WITH MAKE UP WATER TEMPERATURES JAN =55.00 FEB =55.00 MAR =55.00 APR =55.00 MAY =55.00 JUN =55.00
JUL =55.00 AUG =55.00 SEP =55.00 OCT =55.00 NOV =55.00 DEC =55.00

0 ENVIRONMENT NUMBER 1 FOR AHLDFL TITLE IS OKLAHOMA CITY, OK TRY

WEATHER STATION 13967 START DATE OF 1 JAN 1951 NO. OF DAYS 365
WITH GROUND TEMPERATURES JAN =55.00 FEB =55.00 MAR =55.00 APR =55.00 MAY =55.00 JUN =55.00
JUL =55.00 AUG =55.00 SEP =55.00 OCT =55.00 NOV =55.00 DEC =55.00
WITH MAKE UP WATER TEMPERATURES JAN =55.00 FEB =55.00 MAR =55.00 APR =55.00 MAY =55.00 JUN =55.00
JUL =55.00 AUG =55.00 SEP =55.00 OCT =55.00 NOV =55.00 DEC =55.00

1 US ARMY CORPS OF ENGINEERS -- BLAST VERSION 3.0 (ANSI FORTRAN 77) LEVEL 215 5 SEP 95 22:37:54 PAGE
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ZONE GROUP LOADS FOR OKLAHOMA CITY, OK TRY

SIMULATION PERIOD 1 JAN 1951 THRU 31 DEC 1951

Appendix 2

Program listing of *SELECT*

```

#include <stdio.h>
#include <string.h>
#include <stdlib.h>
#include <conio.h>

// NDATA is 146, but the FORTRAN program used indices from 1-146.
// If arrays are defined as having 146 entries in C, the indices range
// from 0-145.
// Therefore, at the expense of one extra entry for each array, we save
// ourselves
// some thinking by just allocating 147 entries, with indices from 0-
// 146...
#define NDATA 146
//void david_read(char code[NDATA+1][6], int *nboreho, float *lmulti,
float *wmulti, float *bh);
//void david_sort(int count, char code[NDATA+1][6], int *nboreho, float
*l, float *w, float *h);
void david_read(char **code, int *nboreho, float *lmulti, float
*wmulti, float *bh);
void david_sort(int count, char **code, int *nboreho, float *l, float
*w, float *h);

// PROGRAM SELECT
void select (float tl, float Lallow, float Wallow,
            float Dallow, float D_min, char use_select)
//main()
{
// IMPLICIT REAL(A-Z)
// INTEGER I, COUNT, NDATA, NBOREHO
// PARAMETER (NDATA = 146)
// DIMENSION NBOREHO(NDATA), LMULTI(NDATA), WMULTI(NDATA),
BH(NDATA),
// + B(NDATA), L(NDATA), W(NDATA), H(NDATA)
// CHARACTER CODE(NDATA)*5, USE_SELECT*1
int i, count, *nboreho;
float *lmulti, *wmulti, *bh, *b,
      *l, *w, *h,
      /*tl, Lallow, Wallow, Dallow, D_min,*/ Ltemp;
char /*code[NDATA+1][6],*/ /*use_select,*/ buf[132];
char **code;
FILE *unit1;

nboreho = (int *)malloc((NDATA+1)*sizeof(int));
lmulti = (float *)malloc((NDATA+1)*sizeof(float));
wmulti = (float *)malloc((NDATA+1)*sizeof(float));
bh = (float *)malloc((NDATA+1)*sizeof(float));
b = (float *)malloc((NDATA+1)*sizeof(float));
l = (float *)malloc((NDATA+1)*sizeof(float));
w = (float *)malloc((NDATA+1)*sizeof(float));
h = (float *)malloc((NDATA+1)*sizeof(float));
code = (char **)malloc((NDATA+1)*sizeof(char *));
for (i=0; i<=NDATA; i++)
    code[i] = (char *)malloc(6 * sizeof(char));
// OPEN (UNIT = 1, FILE = 'SELECT.OUT', STATUS = 'UNKNOWN')

```



```

unit1 = fopen("select.out","w");
if (unit1 != NULL)
{

//      IF (USE_SELECT .eq. 'N') THEN
// STOP ' '
//      ENDIF
//          Cannot nicely do above statement.  Replace
with
//          if..endif surrounding rest of subroutine and
using the
//          opposite condition.
    if (use_select == 'Y')
    {
//      PRINT *, 'Enter the physical (field) constraints : '
//      cprintf("Enter the physical (field) constraints : \r\n");
//      PRINT *, 'Length : '
//      cprintf("          Length : ");
//      READ *, Lallow
//      buf[0] = 132;
//      Lallow = atof(cgets(buf));
//      PRINT *, 'Width : '
//      cprintf("\r\n          Width : ");
//      READ *, Wallow
//      Wallow = atof(cgets(buf));
//      PRINT *, 'Maximum Depth : '
//      cprintf("\r\nMaximum Depth : ");
//      READ *, Dallow
//      Dallow = atof(cgets(buf));
//      PRINT *, 'Minimum Depth : '
//      cprintf("\r\nMinimum Depth : ");
//      READ *, D_min
//      D_min = atof(cgets(buf));
//      cprintf("\r\n\n");

//      CALL READ(CODE,NBOREHO,LMULTI,WMULTI,BH)
      david_read(code,nboreho,lmulti,wmulti,bh);

//      WRITE (1,5)
      fprintf(unit1,"          SUMMARY OF THE POSSIBLE BOREHOLE
CONFIGURATIONS\n\n");
//      PRINT 5
      cprintf(
"          SUMMARY OF THE POSSIBLE BOREHOLE
CONFIGURATIONS\r\n\n");
//5      FORMAT (15X,'SUMMARY OF THE POSSIBLE BOREHOLE CONFIGURATIONS')

//      WRITE (1,10) TL
      fprintf(unit1," Total Loop Length   = %10.1f ft\n",tl);
//      PRINT 10, TL
      cprintf(
" Total Loop Length   = %10.1f ft\r\n",tl);
//10     FORMAT (//,2X, 'Total Loop Length   =          ', F10.1, 2X,'ft')

      if (Lallow < Wallow)
      {
// Ltemp = Lallow
      Ltemp = Lallow;

```

```

// Lallow = Wallow
    Lallow = Wallow;
// Wallow = Ltemp
    Wallow = Ltemp;
}
if (Dallow < D_min)
{
    Ltemp = Dallow;
    Dallow = D_min;
    D_min = Ltemp;
}

//      WRITE (1,20) Lallow
fprintf(unit1," Field Length Allow  = %10.1f ft\n",Lallow);
//      PRINT 20, Lallow
cprintf(      " Field Length Allow  = %10.1f ft\r\n",Lallow);
//20      FORMAT (2X, 'Field LENGTH Allow  =      ', F6.1,2X, 'ft')

//      WRITE (1,25) Wallow
fprintf(unit1," Field Width Allow   = %10.1f ft\n",Wallow);
//      PRINT 25, Wallow
cprintf(      " Field Width Allow   = %10.1f ft\r\n",Wallow);
//25      FORMAT (2X, 'Field WIDTH Allow   =      ', F6.1,2X, 'ft')

//      WRITE (1,30) Dallow
fprintf(unit1," Field Depth Allow   = %10.1f - %1.1f
ft\n\n",D_min,Dallow);
//      PRINT 30, Dallow
cprintf(      " Field Depth Allow   = %10.1f - %1.1f
ft\r\n\n",D_min,Dallow);
//30      FORMAT (2X, 'Field DEPTH Allow   =      ', F6.1,2X, 'ft',//)

//      WRITE (1,35)
fprintf(unit1," CONFIGURATION      TOTAL NO. OF      FIELD LENGTH
FIELD WIDTH      FIELD DEPTH\n");
//      PRINT 35
cprintf(      " CONFIGURATION      TOTAL NO. OF      FIELD LENGTH
FIELD WIDTH      FIELD DEPTH\r\n");
//35      FORMAT (2X,'CONFIGURATION', 4X,'TOTAL NO. OF', 4X,'FIELD
LENGTH',
//      +      4X,'FIELD WIDTH', 4X,'FIELD DEPTH')

//      WRITE (1,40)
fprintf(unit1,"      CODE      BOREHOLES      REQUIRED
REQUIRED      REQUIRED\n");
//      PRINT 40      cprintf(      "      CODE      BOREHOLES
REQUIRED      REQUIRED      REQUIRED\r\n");
cprintf(      "      CODE      BOREHOLES      REQUIRED
REQUIRED      REQUIRED\r\n");
//40      FORMAT (6X,'CODE', 10X,'BOREHOLES', 8X,'REQUIRE', 9X,'REQUIRE',
//      +      8X,'REQUIRE')

//      WRITE (1,45)

fprintf(unit1,"=====\n");

```

```

//      PRINT 45
//      cprintf(
//      "=====
=====\\r");
//45      FORMAT
(1X,'=====',
//      +      '=====',/)

//      COUNT = 0
//      count = 0;
//      DO 100 I = 1,NDATA
//      for (i=1; i<=NDATA; i++)
//      {
// H(I) = TL / NBOREHO(I)
//      if (nboreho[i] != 0) h[i] = tl/nboreho[i];
// B(I) = H(I) * BH(I)
//      b[i] = h[i] * bh[i];
// L(I) = B(I) * LMULTI(I) + 1.0
//      l[i] = b[i] * lmulti[i] + 1.0;
// W(I) = B(I) * WMULTI(I) + 1.0
//      w[i] = b[i] * wmulti[i] + 1.0;
// IF ((H(I) .LE. Dallow) .AND. (H(I) .GE. D_min) .AND.
//      +      (L(I) .LE. Lallow) .AND. (W(I) .LE. Wallow)) THEN
//      if ( (h[i] <= Dallow) && (h[i] >= D_min) &&
//          (l[i] <= Lallow) && (w[i] <= Wallow) )
//      {
//      COUNT = COUNT + 1
//      count++;
//      CODE(COUNT) = CODE(I)
//      strcpy(code[count], code[i]);
//      NBOREHO(COUNT) = NBOREHO(I)
//      nboreho[count] = nboreho[i];
//      L(COUNT) = L(I)
//      l[count] = l[i];
//      W(COUNT) = W(I)
//      w[count] = w[i];
//      H(COUNT) = H(I)
//      h[count] = h[i];
//      ENDIF
//      }
//100      CONTINUE
//      }

//      CALL SORT(COUNT, CODE, NBOREHO, L, W, H)
//      david_sort(count, code, nboreho, l, w, h);

//      DO 200 I = 1, COUNT
//      for (i=1; i<=count; i++)
//      {
//      WRITE (1,50) CODE(I), NBOREHO(I), L(I), W(I), H(I)
//      fprintf(unit1, "      %5s      %3d      %6.1f
%6.1f      %6.1f\\n",

```

```

                                code[i],      nboreho[i],  l[i],
w[i],      h[i]);
// PRINT 50, CODE(I), NBOREHO(I), L(I), W(I), H(I)
      cprintf(      "      %5s      %3d      %6.1f
%6.1f      %6.1f\r\n",
                                code[i],      nboreho[i],  l[i],
w[i],      h[i]);
//50   FORMAT (6X,A5, 12X,I3, 11X,F6.1, 10X,F6.1, 10X,F6.1)
//200  CONTINUE
      }

//      WRITE (1,55)

fprintf(unit1,"=====  

=====\n");
//      PRINT 55
      cprintf(
"=====  

=====\r");
//55   FORMAT
(1X,'=====  

//      +      '=====',/)

//      IF (COUNT .EQ. 0) THEN
      if (count == 0)
      {
// WRITE (1,60)
      fprintf(unit1,"There is no possible borehole configuration for  

the set of field constraints.\n");
// PRINT 60
      cprintf(      "There is no possible borehole configuration for  

the set of field constraints.\r\n");
//60   FORMAT (2X,'There is no possible borehole configuration for  

the',  

//      +      ' set of field constraints', /)
      }
//      ELSE
      else
      {
// WRITE (1,65) COUNT
      fprintf(unit1," Total number of possible borehole  

configurations      =      %3d\n\n",count);
// PRINT 65, COUNT
      cprintf(      " Total number of possible borehole  

configurations      =      %3d\r\n\n",count);
//65   FORMAT (2X,'Total number of possible borehole configurations',  

//      +      '      =      ', I3, /)
//      ENDIF
      }

//      END
      fprintf(unit1,"NOTE: G1530 refers to Borehole configuration 15,  

B/H = 0.30\n");
      cprintf(      "NOTE: G1530 refers to Borehole configuration 15,  

B/H = 0.30\r\n");

      } // End of if (use_select == 'y')

```

```

        fprintf(unit1, "\f");
        fclose(unit1);
    } // End of if that checked for open files.
} // End of subroutine

//      SUBROUTINE READ(CODE,NBOREHO,LMULTI,WMULTI,BH)
//void david_read(char code[NDATA+1][6], int *nboreho, float *lmulti,
float *wmulti, float *bh)
void david_read(char **code, int *nboreho, float *lmulti, float
*wmulti, float *bh)
{
//      IMPLICIT REAL(A-Z)
//      INTEGER I, NDATA, NBOREHO
    int i;
    FILE *unit10;
//      PARAMETER (NDATA = 146)
//      DIMENSION NBOREHO(NDATA), LMULTI(NDATA), WMULTI(NDATA),
BH(NDATA)
//      CHARACTER CODE(NDATA)*5
    char buf[132];

//      OPEN (UNIT = 10, FILE = 'SELECT.DAT', STATUS = 'OLD')
    unit10 = fopen("select.dat","r");

    if (unit10 != NULL)
    {
        for (i=1; i<=NDATA; i++)
        {
//      DO 100 I = 1, NDATA
// READ (10,10) CODE(I), NBOREHO(I), LMULTI(I), WMULTI(I), BH(I)
//10    FORMAT (A5, 5X,I3, 5X,F6.3, 5X,F5.3, 5X,F4.2)
            fgets(buf,130,unit10);
            strcpy(code[i],strtok(buf, " "));
            nboreho[i] = atoi(strtok(NULL, " "));
            lmulti[i] = atof(strtok(NULL, " "));
            wmulti[i] = atof(strtok(NULL, " "));
            bh[i] = atof(strtok(NULL, " "));
//100    CONTINUE
        }
        fclose(unit10);
    }
//      RETURN
//      END
}

```

```

//      SUBROUTINE SORT(COUNT, CODE, NBOREHO, L, W, H)
//void david_sort(int count, char code[NDATA+1][6], int *nboreho, float
*1, float *w, float *h)
void david_sort(int count, char **code, int *nboreho, float *1, float
*w, float *h)
{
//C
//C
//      IMPLICIT REAL(A-Z)
float holdl, holdw, holdh;
//      INTEGER I, J, PTR, COUNT, FIRST, LAST, NBOREHO, HOLDN
int i, j, ptr, first, last, holdn;
//      DIMENSION NBOREHO(COUNT), H(COUNT), L(COUNT), W(COUNT)
//      CHARACTER CODE(COUNT)*5, HOLDC*5
char holdc[5];

//      LAST = COUNT
last = count;
//      DO 100 I = 1, COUNT-1
for (i=1; i<= count-1; i++)
{
// PTR = I
ptr = i;
// FIRST = I + 1
first = i + 1;
// DO 200 J = FIRST, LAST
for (j=first; j<=last; j++)
{
// IF (NBOREHO(J) .LT. NBOREHO(PTR)) PTR = J
if (nboreho[j] < nboreho[ptr]) ptr = j;
//200 CONTINUE
}
// HOLDN = NBOREHO(I)
holdn = nboreho[i];
// HOLDC = CODE(I)
strcpy(holdc, code[i]);
// HOLDL = L(I)
holdl = l[i];
// HOLDW = W(I)
holdw = w[i];
// HOLDH = H(I)
holdh = h[i];

// NBOREHO(I) = NBOREHO(PTR)
nboreho[i] = nboreho[ptr];
// CODE(I) = CODE(PTR)
strcpy(code[i], code[ptr]);

```

```
// L(I) = L(PTR)
   l[i] = l[ptr];
// W(I) = W(PTR)
   w[i] = w[ptr];
// H(I) = H(PTR)
   h[i] = h[ptr];

// NBOREHO(PTR) = HOLDN
   nboreho[ptr] = holdn;
// CODE(PTR) = HOLDC
   strcpy(code[ptr],holdc);
// L(PTR) = HOLDL
   l[ptr] = holdl;
// W(PTR) = HOLDW
   w[ptr] = holdw;
// H(PTR) = HOLDH
   h[ptr] = holdh;
//100   CONTINUE
   }
//     RETURN
//     END
   }
```

Appendix 3

Printout of *GLHEDATA.DAT*

for the Daycare Center

Borehole Profile and Monthly Loadings Table

Active Borehole Depth 150.000
 Borehole Radius 3.000
 Thermal conductivity of the ground. 1.400
 Volumetric heat capacity of the ground. 35.000
 Volumetric heat capacity of the fluid 62.403
 Undisturbed ground temperature. 55.00
 Borehole thermal resistance 0.173
 Mass flow rate of the fluid 65.000
 Density of the fluid. 65.549
 G-function filename
 c:\glhepro\GFUNC\gl1310.gfc
 Units of input data (1 = IP, 2 = SI). 1
 Units of output data (1 = IP, 2 = SI) 1

Monthly Loadings
 =====

Month	Heating	Cooling
January	29940000.000	725200.000
Febraury	23910000.000	358600.000
March	17920000.000	1769000.000
April	8233000.000	4817000.000
May	1386000.000	13990000.000
June	364500.000	29130000.000
July	25350.000	38870000.000
August	11140.000	42700000.000
September	874300.000	18570000.000
October	5782000.000	11080000.000
November	19540000.000	374800.000
December	25250000.000	495400.000

The first month you want data for 1.00
 The last month you want data for. 120.00
 Desired exiting fluid temperature 76.07
 The desired temp is (1=min, 2=max). 2

Heat pump curve fit equations and coefficients:

Cooling: Heat of Rejection = QC[a+b(EFT)+c(EFT^2)]
 Power = QC[d+e(EFT)+f(EFT^2)]

a = 1.136980
 b = -0.000831
 c = 0.000031
 d = 0.039846
 e = -0.000235
 f = 0.000009

Heating: Heat of Absorption = QH[a+b(EFT)+c(EFT^2)]
 Power = QH[d+e(EFT)+f(EFT^2)]

a = 0.965324
b = -0.009141
c = 0.000092
d = 0.009275
e = 0.002710
f = -0.000027

Output data will be sent to: daycare.out

B/H = 10

Fluid type currently entered:GS4/Water, 20%

Heatpump Manufacturer: Florida Heat Pump, SL Series
Heatpump Model: SL260

Ignore this line-----:

Peak Hourly Loads--Heating:	166700.000	Cooling:	309400.000
Hours at Peak-----Heating:	8.000	Cooling:	8.000
Peak load Month----Heating:	2.000	Cooling:	8.000

Appendix 4

Program listing of *OPTIMIZE.FOR*

```
C***C INCLUDE 'fgraph.fi'
```

```
PROGRAM OPTIMIZE
```

```
C*****  
*  
C*  
C* PROGRAM: OPTIMIZE  
C*  
C* LANGUAGE: FORTRAN  
C*  
C* PURPOSE: To determine the minimum life cycle cost of  
C* a ground loop heat pump (first cost and  
C* operating cost) using Golden Section Search.  
C*  
C*****  
*  
C*  
C* MAJOR ASSUMPTIONS: None  
C*  
C* DEVELOPER: David Yeung  
C* Jefferey D. Spitler, Ph.D., P.E.  
C* Oklahoma State University  
C*  
C* DATE: August 28, 1995  
C*  
C* INCLUDE FILES: None  
C*  
C* SUBROUTINES CALLED: HP_AOC  
C* CP_AOC  
C* FICOST  
C*  
C* FUNCTIONS CALLED: None  
C*  
C* REVISION HISTORY: None  
C*  
C* REFERENCE: Numerical Recipes in FORTRAN, 2nd edition  
C* William H. Press, et al.,  
C* Cambridge University Press, 1992.  
C*  
C*****  
*
```

```
IMPLICIT REAL(A-Z)  
INTEGER ITER, ITERMAX
```

```
R = 0.61803399  
ITERMAX = 200
```

```
OPEN (UNIT=1, FILE='ECON.DAT', STATUS='UNKNOWN')  
READ (1,50) a  
READ (1,50) n  
READ (1,50) int_ann  
READ (1,50) COST_BH  
READ (1,50) COST_FT  
READ (1,50) COST_KWH  
READ (1,50) COST_HP
```

```

READ (1,50) COST_CP
READ (1,50) NB_CIR
READ (1,50) D_MIN
READ (1,50) D_MAX
READ (1,50) ID_PI
READ (1,50) COST_PI
CLOSE (1)

OPEN (UNIT=2, FILE='OPTIMIZE.OUT', STATUS='UNKNOWN')

C***C
OPEN (UNIT=3, FILE='DETAIL.OUT', STATUS='UNKNOWN')
C***C

WRITE (2,100)
WRITE (2,110) a
WRITE (2,120) n
WRITE (2,121) int_ann
WRITE (2,130) COST_BH
WRITE (2,140) COST_FT
WRITE (2,150) COST_KWH
WRITE (2,160) COST_HP
WRITE (2,170) COST_CP
WRITE (2,171) NB_CIR
WRITE (2,180) D_MIN
WRITE (2,190) D_MAX
WRITE (2,191) ID_PI
WRITE (2,192) COST_PI
WRITE (2,200)
WRITE (2,210)

AX = D_MIN
CX = D_MAX
C***Pick a starting point between D_MIN and D_MAX randomly
BX = AX + 0.2*(CX-AX)

X0 = AX
X3 = CX
IF (ABS(CX-BX) .GT. ABS(BX-AX)) THEN
  X1 = BX
  X2 = BX + (1.-R)*(CX-BX)
ELSE
  X2 = BX
  X1 = BX - (1.-R)*(BX-AX)
ENDIF

C***Compute the series present worth factor, SPWF.
C***(NOTE: The interest is compounded annually, not monthly)
int_ann = int_ann/100.
SPWF = ((1.+int_ann)**n-1.)/(int_ann*(1.+int_ann)**n)

C***C
write (3,9) SPWF
9 format(/, 2x, 'series of present worth factor, SPWF = ', f7.3,
//)
C***C

```

```

C***Convert in to m
      ID_PI = ID_PI*0.0254

C***CALCULATE LCC1
      H = X1
      CALL HP_AOC(H, COST_KWH, GPM, NB, BH, RHO, AOC_HP)
      CALL CP_AOC(H, GPM, ID_PI, NB, BH, RHO, NB_CIR, COST_KWH, AOC_CP)
      CALL FICOST(H, NB, BH, COST_FT, COST_BH, COST_HP, COST_CP,
+          COST_PI, FIC)

      AOC_TOT = AOC_HP + AOC_CP
      LCC1 = a*FIC + SPWF*AOC_TOT

C***C
      write (3,11) aoc_hp
      write (3,12) aoc_cp
      write (3,13) fic
      write (3,14) aoc_tot
      write (3,15) lcc1

11      format(2x, 'h = x1', 5x, 'aoc_hp = ', f10.2)
12      format(2x, 'h = x1', 5x, 'aoc_cp = ', f10.2)
13      format(2x, 'h = x1', 5x, 'fic = ', f10.2)
14      format(2x, 'h = x1', 5x, 'aoc_tot = ', f10.2)
15      format(2x, 'h = x1', 5x, 'lcc1 = ', f10.2, //)
C***C

C***CALCULATE LCC2
      H = X2
      CALL HP_AOC(H, COST_KWH, GPM, NB, BH, RHO, AOC_HP)
      CALL CP_AOC(H, GPM, ID_PI, NB, BH, RHO, NB_CIR, COST_KWH, AOC_CP)
      CALL FICOST(H, NB, BH, COST_FT, COST_BH, COST_HP, COST_CP,
+          COST_PI, FIC)

      AOC_TOT = AOC_HP + AOC_CP
      LCC2 = a*FIC + SPWF*AOC_TOT

C***C
      write (3,21) aoc_hp
      write (3,22) aoc_cp
      write (3,23) fic
      write (3,24) aoc_tot
      write (3,25) lcc2

21      format(2x, 'h = x2', 5x, 'aoc_hp = ', f10.2)
22      format(2x, 'h = x2', 5x, 'aoc_cp = ', f10.2)
23      format(2x, 'h = x2', 5x, 'fic = ', f10.2)
24      format(2x, 'h = x2', 5x, 'aoc_tot = ', f10.2)
25      format(2x, 'h = x2', 5x, 'lcc2 = ', f10.2, //)
C***C
C*
      WRITE (2,220) X1, LCC1, X2, LCC2
C*

      ITER = 1

```

```

1000 IF (ABS(X3-X0) .GT. 0.1) THEN
C 1000 IF (ABS(LCC2-LCC1) .GT. 0.1) THEN
      IF (LCC2 .LT. LCC1) THEN
          X0 = X1
          X1 = X2
          X2 = R*X1 + (1.-R)*X3
          LCC1 = LCC2

C***CALCULATE LCC2 WITH THE NEW X2
      H = X2
      CALL HP_AOC(H, COST_KWH, GPM, NB, BH, RHO, AOC_HP)
      CALL CP_AOC(H, GPM, ID_PI, NB, BH, RHO, NB_CIR, COST_KWH,
+           AOC_CP)
      CALL FICOST(H, NB, BH, COST_FT, COST_BH, COST_HP, COST_CP,
+           COST_PI, FIC)

      AOC_TOT = AOC_HP + AOC_CP
      LCC2 = a*FIC + SPWF*AOC_TOT

C***C
      write (3,31) aoc_hp
      write (3,32) aoc_cp
      write (3,33) fic
      write (3,34) aoc_tot
      write (3,35) lcc2

31  format(2x, 'h = new x2', 5x, 'aoc_hp = ', f10.2)
32  format(2x, 'h = new x2', 5x, 'aoc_cp = ', f10.2)
33  format(2x, 'h = new x2', 5x, 'fic = ', f10.2)
34  format(2x, 'h = new x2', 5x, 'aoc_tot = ', f10.2)
35  format(2x, 'h = new x2', 5x, 'lcc2 = ', f10.2, //)
C***C
C*
      WRITE (2,220) X1, LCC1, X2, LCC2
C*
      ELSE
          X3 = X2
          X2 = X1
          X1 = R*X2 + (1.-R)*X0
          LCC2 = LCC1

C***CALCULATE LCC1 WITH THE NEW X1
      H = X1
      CALL HP_AOC(H, COST_KWH, GPM, NB, BH, RHO, AOC_HP)
      CALL CP_AOC(H, GPM, ID_PI, NB, BH, RHO, NB_CIR, COST_KWH,
+           AOC_CP)
      CALL FICOST(H, NB, BH, COST_FT, COST_BH, COST_HP, COST_CP,
+           COST_PI, FIC)

      AOC_TOT = AOC_HP + AOC_CP
      LCC1 = a*FIC + SPWF*AOC_TOT

C***C
      write (3,41) aoc_hp
      write (3,42) aoc_cp
      write (3,43) fic
      write (3,44) aoc_tot

```

```

write (3,45) lcc1

41  format(2x, 'h = new x1', 5x, 'aoc_hp  = ', f10.2)
42  format(2x, 'h = new x1', 5x, 'aoc_cp  = ', f10.2)
43  format(2x, 'h = new x1', 5x, 'fic    = ', f10.2)
44  format(2x, 'h = new x1', 5x, 'aoc_tot = ', f10.2)
45  format(2x, 'h = new x1', 5x, 'lcc1   = ', f10.2, //)
C***C
C*
      WRITE (2,220) X1, LCC1, X2, LCC2
C*
      ENDIF
      ITER = ITER + 1
      IF (ITER .LT. ITERMAX) THEN
          GOTO 1000
      ELSE
          GOTO 2000
      ENDIF
ENDIF

C*
2000 WRITE (2,230)
C*
      IF (LCC1 .LT. LCC2) THEN
          LCC_MIN = LCC1
          X_MIN = X1
      ELSE
          LCC_MIN = LCC2
          X_MIN = X2
      ENDIF

C*
      WRITE (2,240) LCC_MIN
      WRITE (2,250) X_MIN

C*
      CLOSE (2)

50  FORMAT (60X, F10.3)
100 FORMAT (30X, 'OPTIMIZE.OUT')
110 FORMAT (//,5X, 'Multiplier of FIC, a      = ', F10.2)
120 FORMAT ( 5X, 'Number of years, n         = ', F10.2)
121 FORMAT ( 5X, 'Annual interest rate       = ', F10.2, 2X,'(%)')
130 FORMAT ( 5x, 'Drilling cost per borehole = ', F10.2, 2X,'($)')
140 FORMAT ( 5x, 'Drilling cost per foot     = ', F10.2, 2X,'($)')
150 FORMAT ( 5x, 'Electricity cost per KWH    = ', F10.2, 2X,'($)')
160 FORMAT ( 5x, 'Heat pump cost              = ', F10.2, 2X,'($)')
170 FORMAT ( 5x, 'Circulating pump cost       = ', F10.2, 2X,'($)')
171 FORMAT ( 5X, 'No. boreholes per circuit   = ', F10.2)
180 FORMAT ( 5x, 'Minimum field depth         = ', F10.2,
2X,'(ft)')
190  FORMAT ( 5x, 'Maximum field depth         = ', F10.2,
2X,'(ft)')
191  FORMAT ( 5X, 'Inside diameter of the pipe = ', F10.3,
2X,'(in)')
192  FORMAT ( 5X, 'Piping cost per foot       = ', F10.3, 2x,'($)')
200  FORMAT (//,10X, 'X1', 10X, 'LCC1', 18X, 'X2', 10X, 'LCC2')

```



```

210  FORMAT ( 5X,
'=====',
+      '=====')
220  FORMAT ( 4X, F10.2, 4X, F10.2, 10X, F10.2, 4X, F10.2)
230  FORMAT ( 5X,
'=====',
+      '=====, /)
240  FORMAT ( 5X, 'The MINIMUM LIFE CYCLE COST = ',F10.2, 2X,'($)')
250  FORMAT ( 5X, 'BOREHOLE DEPTH = ',F10.2,
2X,'(ft)')

      END

```

```

      SUBROUTINE HP_AOC(H, COST_KWH, GPM, NB, BH, RHO, AOC_HP)

```

```

C*****
*
C*
C*  PROGRAM:    HP_AOC
C*
C*  LANGUAGE:   FORTRAN
C*
C*  PURPOSE:    To determine the annual electricity cost of the
C*              heat pump based upon the power requirements
C*              calculated by GLHE_SIM.
C*
C*****
*
C*
C*  MAJOR ASSUMPTIONS:  None
C*
C*  DEVELOPER:         David Yeung
C*                   Jefferey D. Spitler, Ph.D., P.E.
C*                   Oklahoma State University
C*
C*  DATE:              August 29, 1995
C*
C*  INCLUDE FILES:     None
C*
C*  SUBROUTINES CALLED:  GLHE_SIM
C*
C*  FUNCTIONS CALLED:   None
C*
C*  REVISION HISTORY:   None
C*
C*****
*
C*
C*  INPUT VARIABLES:
C*  H                  -   Borehole length over which heat extraction
C*                      takes place                               (ft)
C*  COST_KWH           -   Rate of electricity in KWH             ($)
C*
C*  OUTPUT VARIABLES:

```

```

C*  GPM          -   Volume flow rate of the fluid
(gpm)
C*  NB          -   The number of boreholes in the current
C*  BH          -   Ratio of the distance between borehole
C*              centers to the active borehole depth
C*  RHO         -   Density of the fluid
(lbm/ft^3)
C*  AOC_HP      -   Annual electricity cost of heat pump      ($)
C*
C*****
*
```

```

IMPLICIT REAL(A-Z)
INTEGER I, J, MONTHS
PARAMETER (MONTHS=300)
DIMENSION ELECTRIC(0:MONTHS), DAYS(12)

CALL GLHESIM(H, GPM, NB, BH, RHO, ELECTRIC)
```

```

days(1)=31.
days(2)=28.
days(3)=31.
days(4)=30.
days(5)=31.
days(6)=30.
days(7)=31.
days(8)=31.
days(9)=30.
days(10)=31.
days(11)=30.
days(12)=31.
```

```

AOC_HP = 0.0
J = 0
DO 100 I = 1,120
    J = J + 1
    AOC_HP = AOC_HP + ELECTRIC(I)*days(J)*24.*COST_KWH
    IF (J .EQ. 12) J = 0
```

```

100 CONTINUE
AOC_HP = AOC_HP/10.
```

```

RETURN
END
```

```

SUBROUTINE CP_AOC(H, GPM, ID_PI, NB, BH, RHO, NB_CIR, COST_KWH,
+
AOC_CP)
```

```

C*****
*
C*
C*  PROGRAM:    CP_AOC
C*
C*  LANGUAGE:   FORTRAN
```

```

C*
C*  PURPOSE:   To determine the annual electricity cost of
C*             the circulating pump.
C*
C*****
*
C*
C*  MAJOR ASSUMPTIONS:  None
C*
C*  DEVELOPER:         David Yeung
C*                   Jefferey D. Spitler, Ph.D., P.E.
C*                   Oklahoma State University
C*
C*  DATE:              August 29, 1995
C*
C*  INCLUDE FILES:     None
C*
C*  SUBROUTINES CALLED: None
C*
C*  FUNCTIONS CALLED:   None
C*
C*  REVISION HISTORY:  None
C*
C*  REFERENCE:         Design/Data Manual for Closed-Loop Ground
C*                   Heat Pump System, J.E. Bose, et. al.,
C*                   ASHRAE, Oklahoma State University, 1985.
C*
C*****
*
C*
C*  INPUT VARIABLES:
C*  H                  -   Borehole length over which heat extraction
C*                       takes place                               (ft)
C*  GPM                -   Volume flow rate of the fluid
C*                       (gpm)
C*  ID_PI              -   Inside diameter of the pipe             (in)
C*  NB                  -   The number of boreholes
C*  BH                  -   Ratio of the distance between borehole
C*                       centers to the active borehole depth
C*  RHO                 -   Density of the fluid
C*                       (lbm/ft^3)
C*  NB_CIR              -   No. boreholes per circuit
C*  COST_KWH            -   Rate of electricity in KWH             ($)
C*
C*  OUTPUT VARIABLES:
C*  AOC_CP              -   The electricity cost of heat pump.     ($)
C*
C*****
*

      IMPLICIT REAL(A-Z)
      DIMENSION DAYS(12)

      g = 9.807
      PI = 3.1415927
C***Assume the fluid viscosity = 0.001 N s/m^2 (water at about 20 C)
      MU = 0.001

```

```

        print *, bh
        print *, id_pi
        TOT_LEN = NB*H
C***Account for the pipes between the bolehole centers
        TOT_LEN = TOT_LEN + BH*H*(NB+1.)
C***Total length = 2*TOT_LEN because of the U tube
        TOT_LEN = 2.*TOT_LEN
C***Compute number of circuits in parallel
        NC = AINT(NB/NB_CIR)
        print *, nc
C***Total length per circuit = TOT_LEN / ( number of circuits)
        CIR_LEN = FLOAT(TOT_LEN / NC)
C***Convert ft to m
        CIR_LEN = CIR_LEN*0.3048
        print *, CIR_LEN
C***Convert lbm/ft^3 to kg/m^3
C        RHO = RHO*16.01847
        print *, rho
C***Convert gpm to m^3/s
        Voldot = GPM*0.0000631
        print *, GPM
        print *, Voldot
C***Volume flow rate in a circuit = Voldot / (number of circuit)
        Voldot = FLOAT(Voldot / NC)
        Vel = Voldot/((PI*ID_PI*ID_PI)/4.)
        print *, vel
        Re = RHO*Vel*ID_PI/MU
        print *, re
        IF (Re .LT. 2000.) THEN
            f = 64./Re
        ELSEIF ((Re .GE. 2000.) .AND. (Re .LT. 1.E5)) THEN
            f = 0.3164/(Re**0.25)
        ELSEIF ((Re .GE. 1.E5) .AND. (Re .LT. 3.E6)) THEN
            f = 0.0032+0.221/(Re**0.237)
        ELSE
            PRINT *, 'UNABLE TO COMPUTE THE FRICTION FACTOR'
            PRINT *, 'Rough estimation is used'
            f = 0.0032+0.221/(Re**0.237)
        ENDIF
        print *, f
        Head = f*(CIR_LEN/ID_PI)*Vel*Vel/(2.*g)
        print *, head
C***Account for the other head losses, include the loss through the
pump
        Head = Head/0.8
        print *, head
        POWER = RHO*g*Voldot*Head
        print *, power
C***Convert Watt to kW
        POWER = POWER/1000.
        print *, power

        days(1)=31.
        days(2)=28.
        days(3)=31.
        days(4)=30.

```

```

    days(5)=31.
    days(6)=30.
    days(7)=31.
    days(8)=31.
    days(9)=30.
    days(10)=31.
    days(11)=30.
    days(12)=31.

    AOC_CP = 0.0
    DO 100 I = 1,12
100   AOC_CP = AOC_CP + POWER*days(I)*24.*COST_KWH
      CONTINUE

    print *, aoc_cp
    print *
    print *
    print *
    RETURN
    END

    SUBROUTINE FICOST(H, NB, BH, COST_FT, COST_BH, COST_HP, COST_CP,
+                   COST_PI, FIC)

C*****
*
C*
C* PROGRAM:    FICOST
C*
C* LANGUAGE:   FORTRAN
C*
C* PURPOSE:    To determine the first installation cost of the
C*              heat pump system.
C*
C*****
*
C*
C* MAJOR ASSUMPTIONS:  None
C*
C* DEVELOPER:         David Yeung
C*                   Jefferey D. Spitler, Ph.D., P.E.
C*                   Oklahoma State University
C*
C* DATE:              August 30, 1995
C*
C* INCLUDE FILES:     None
C*
C* SUBROUTINES CALLED:  None
C*
C* FUNCTIONS CALLED:   None
C*
C* REVISION HISTORY:   None
C*
C*****
*

```

```

C*
C* INPUT VARIABLES:
C* H           - Borehole length over which heat extraction
C*              takes place                               (ft)
C* NB          - The number of boreholes
C* BH          - Ratio of the distance between borehole
C*              centers to the active borehole depth
C* COST_FT     - Drilling cost per foot                   ($)
C* COST_BH     - Drilling cost per borehole              ($)
C* COST_HP     - Unit cost of the heat pump               ($)
C* COST_CP     - Unit cost of the circulating pump       ($)
C* COST_PI     - Piping cost per foot                   ($)
C*
C* OUTPUT VARIABLES:
C* FIC         - First installation cost of heat pump system
C*              ($)
C*
C*****
*
```

```

IMPLICIT REAL(A-Z)
```

```

TOT_LEN = NB*H
```

```

C***Account for the pipes between the borehole centers
```

```

TOT_LEN = TOT_LEN + BH*H*(NB+1.)
```

```

C***Total length = 2*TOT_LEN because of the U tube
```

```

TOT_LEN = 2.*TOT_LEN
```

```

FIC = (COST_FT*(NB*H)) + (COST_BH*NB) + COST_HP + COST_CP
+      + (COST_PI*TOT_LEN)
```

```

RETURN
```

```

END
```

```

C***C INCLUDE 'fgraph.fi'
```

```

SUBROUTINE GLHESIM(H_TEST, GPM, NB, BH, RHO, ELECTRIC)
```

```

C***C INCLUDE 'fgraph.fi'
```

```

C***C PROGRAM GLHESIM
```

```

C*****
```

```

C*
```

```

C* PROGRAM:      GLHESIM
```

```

C*
```

```

C* LANGUAGE:     FORTRAN
```

```

C*
```

```

C* PURPOSE:      To simulate the average fluid temperature,
C*               the inlet fluid temperature, and the outlet
C*               fluid temperature for a given heating load
C*               and borehole profile for a user defined period
C*               of time.
```

```

C*
```

```

C*****
```

Appendix 5

Printout of *OPTIMIZE.OUT*

OPTIMIZE.OUT

Multiplier of FIC, a = 1.00
 Number of years, n = 20.00
 Annual interest rate = 8.00 (%)
 Drilling cost per borehole = .00 (\$)
 Drilling cost per foot = 1.00 (\$)
 Electricity cost per KWH = .11 (\$)
 Heat pump cost = 5000.00 (\$)
 Circulating pump cost = 1000.00 (\$)
 No. boreholes per circuit = 4.00
 Minimum field depth = 114.03 (ft)
 Maximum field depth = 150.00 (ft)
 Inside diameter of the pipe = 1.554 (in)
 Piping cost per foot = .560 (\$)

X1	LCC1	X2	LCC2
121.22	33961.23	132.22	34211.91
118.48	33885.81	121.22	33961.23
116.78	33843.90	118.48	33885.81
115.73	33823.43	116.78	33843.90
115.08	33812.14	115.73	33823.43
114.68	33805.90	115.08	33812.14
114.43	33802.43	114.68	33805.90
114.28	33800.29	114.43	33802.43
114.18	33798.91	114.28	33800.29
114.12	33798.07	114.18	33798.91
114.09	33797.54	114.12	33798.07
114.07	33797.21	114.09	33797.54

The MINIMUM LIFE CYCLE COST = 33797.21 (\$)
 BOREHOLE DEPTH = 114.07 (ft)

Appendix 6

Printout of *SELECT.OUT*

SUMMARY OF THE POSSIBLE BOREHOLE CONFIGURATIONS

Total Loop Length = 1510.4 ft
 Field Length Allow = 30.0 ft
 Field Width Allow = 30.0 ft
 Field Depth Allow = 30.0 - 150.0 ft

CONFIGURATION CODE	TOTAL NO. OF BOREHOLES	FIELD LENGTH REQUIRED	FIELD WIDTH REQUIRED	FIELD DEPTH REQUIRED
G1305	12	26.2	13.6	125.9
G1405	12	19.9	19.9	125.9
G1105	15	21.1	11.1	100.7
G1210	16	29.3	29.3	94.4
G1205	16	15.2	15.2	94.4
G4810	36	22.0	22.0	42.0
G4710	50	28.2	13.1	30.2
Total number of possible borehole configurations			=	7

NOTE: G1530 refers to Borehole configuration 15, B/H = 0.30

Appendix 7

Printout of *DETAIL.OUT*

series of present worth factor, spwf= 9.818

h = 121.22 m

h = x1	aoc_hp	=	2290.86
h = x1	aoc_cp	=	114.74
h = x1	fic	=	10342.73
h = x1	aoc_tot	=	2405.60
h = x1	lcc1	=	33961.23

h = 132.22 m

h = x2	aoc_hp	=	2265.88
h = x2	aoc_cp	=	125.14
h = x2	fic	=	10736.49
h = x2	aoc_tot	=	2391.02
h = x2	lcc2	=	34211.91

h = 118.48 m

h = new x1	aoc_hp	=	2295.80
h = new x1	aoc_cp	=	112.14
h = new x1	fic	=	10244.29
h = new x1	aoc_tot	=	2407.94
h = new x1	lcc1	=	33885.81

h = 116.78 m

h = new x1	aoc_hp	=	2299.34
h = new x1	aoc_cp	=	110.53
h = new x1	fic	=	10183.45
h = new x1	aoc_tot	=	2409.87
h = new x1	lcc1	=	33843.90

h = 115.73 m

h = new x1 aoc_hp = 2302.08
h = new x1 aoc_cp = 109.54
h = new x1 fic = 10145.85
h = new x1 aoc_tot = 2411.61
h = new x1 lcc1 = 33823.43

h = 115.08 m

h = new x1 aoc_hp = 2303.91
h = new x1 aoc_cp = 108.92
h = new x1 fic = 10122.61
h = new x1 aoc_tot = 2412.83
h = new x1 lcc1 = 33812.14

h = 114.68 m

h = new x1 aoc_hp = 2305.11
h = new x1 aoc_cp = 108.54
h = new x1 fic = 10108.25
h = new x1 aoc_tot = 2413.66
h = new x1 lcc1 = 33805.90

h = 114.43 m

h = new x1 aoc_hp = 2305.90
h = new x1 aoc_cp = 108.31
h = new x1 fic = 10099.37
h = new x1 aoc_tot = 2414.21
h = new x1 lcc1 = 33802.43

h = 114.28 m

h = new x1 aoc_hp = 2306.38
h = new x1 aoc_cp = 108.17
h = new x1 fic = 10093.89
h = new x1 aoc_tot = 2414.55
h = new x1 lcc1 = 33800.29

h = 114.18 m

h = new x1	aoc_hp	=	2306.68
h = new x1	aoc_cp	=	108.08
h = new x1	fic	=	10090.50
h = new x1	aoc_tot	=	2414.75
h = new x1	lcc1	=	33798.91

h = 114.12 m

h = new x1	aoc_hp	=	2306.86
h = new x1	aoc_cp	=	108.02
h = new x1	fic	=	10088.40
h = new x1	aoc_tot	=	2414.88
h = new x1	lcc1	=	33798.07

h = 114.09 m

h = new x1	aoc_hp	=	2306.97
h = new x1	aoc_cp	=	107.99
h = new x1	fic	=	10087.11
h = new x1	aoc_tot	=	2414.96
h = new x1	lcc1	=	33797.54

h = 114.07 m

h = new x1	aoc_hp	=	2307.04
h = new x1	aoc_cp	=	107.97
h = new x1	fic	=	10086.31
h = new x1	aoc_tot	=	2415.01
h = new x1	lcc1	=	33797.21

Appendix 8

Program listing of *BOERES*

```

PROGRAM BORERES
C*****
C
C   PROGRAM :      BORERES
C
C   LANGUAGE :     FORTRAN
C
C   PURPOSE :      This program uses the Conduction Shape Factor method
C                   to calculate the overall borehole thermal resistance
C                   for the giving geometry and the thermal properties.
C
C*****
C   MAJOR ASSUMPTIONS :   None
C
C   DEVELOPER :         David Yeung
C                       Jefferey D. Spitler, Ph.D., P.E.
C                       Oklahoma State University
C
C   DATE :              May 12th, 1995
C
C   INCLUDE FILES :     None
C
C   SUBROUTINES CALLED : None
C
C   FUNCTIONS CALLED :  None
C
C   REVISION HISTORY :  None
C
C   REFERENCE :        - Thermal Analysis of Heat Extraction
C                       Boreholes. Per Eskilson, Dept. of
C                       Mathematical Physics, University of
C                       Lund, Sweden, June 1987.
C                       - Heat Transfer, Fifth Edition.
C                       Holman, J.P., McGraw Hill Book Company,
C                       1981.
C
C*****
C   INPUT VARIABLES :
C
C   kgrount :          Thermal conductivity of the grouting
C                       (Btu/hr*ft*F)
C   kpipe :            Thermal conductivity of the PIPES
C                       (Btu/hr*ft*F)
C   V :                Volume flow rate of the fluid (GPM)
C   OPTION NUMBER :    Nominal size of the pipes, (1 - 5)
C   rb :               Radius of the borehole (inch)
C   space :            Spacing between the pipes and the borehole
C                       wall (inch)
C
C*****
C   OUTPUT VARIABLES :
C
C   Btr :              borehole thermal resistance (F/(Btu/(hr*ft)))
C
C*****
C
C   IMPLICIT REAL (A-Z)
C
C   PI = 3.14159

```



```

C
C   Asks the user to provide the input variables
C
  PRINT *, 'Enter the thermal conductivity of the grouting, ',
+      'kgrount  (Btu/hr*ft*F)'
  PRINT *, 'NOTE :   Typical value for Bentonite clay is ',
+      '0.740'
  READ 10, kgrount
10  FORMAT (F10.0)
    IF (kgrount .EQ. 0.0) THEN
      kgrount = 0.740
      PRINT 20, kgrount
20  FORMAT (F8.4)
    ENDIF
    PRINT *, 'Enter the thermal conductivity of the PIPES, kpipe',
+      ' (Btu/hr*ft*F)'
    PRINT *, 'NOTE :   Typical value for Polyethylene pipes ',
+      '(high density) is 0.225'
    READ 10, kpipe
    IF (kpipe .EQ. 0.0) THEN
      kpipe = 0.225
      PRINT 20, kpipe
    ENDIF
    PRINT *, 'Enter the volume flow rate of the fluid, V  (GPM)'
    READ *, VOL
1000 PRINT *, 'Select the OPTION NUMBER for the nominal size of ',
+      'the pipes :'
    PRINT *, '   Option Number      Nominal Size (inch)   '
    PRINT *, '   1                    3/4                '
    PRINT *, '   2                    1                  '
    PRINT *, '   3                    1 1/4              '
    PRINT *, '   4                    1 1/2              '
    PRINT *, '   5                    2                  '
    READ *, OPTION
    IF (OPTION .EQ. 1) THEN
      doin = 1.05
      tin = 0.095
    ELSEIF (OPTION .EQ. 2) THEN
      doin = 1.315
      tin = 0.12
    ELSEIF (OPTION .EQ. 3) THEN
      doin = 1.66
      tin = 0.151
    ELSEIF (OPTION .EQ. 4) THEN
      doin = 1.9
      tin = 0.173
    ELSEIF (OPTION .EQ. 5) THEN
      doin = 2.375
      tin = 0.216
    ELSE
      PRINT *, 'This option is not available, check the',
+      'OPTION NUMBER !!!'
      GOTO 1000
    ENDIF
    PRINT *, 'Enter the RADIUS of the borehole, rb  (inch)'
    READ *, rbin
    PRINT *, 'Enter the spacing between the pipes and the borehole ',
+      'wall, space  (inch)'
    READ *, spacein
C
    IF (rbin .LT. (doin+spacein)) THEN
      PRINT *, 'WARNING !!! Impossible Configuration'
      PRINT *, '          OUTER PIPE RADIUS is too BIG !!!'

```

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PRINT *, '                                OR                                '
PRINT *, '                                BOREHOLE RADIUS is too SMALL !!!'
PRINT *, '                                OR                                '
PRINT *, '                                SPACING between the pipes and the',
+      ' borehole wall is too BIG !!!'
GOTO 1000
ENDIF
C
C
C      CFACTOR = 12.0
C
C      ro = doin / (2.0*CFACTOR)
C      ri = ((doin/2.0)-tin) / CFACTOR
C      di = 2.0 * ri
C      rb = rbin / CFACTOR
C
C      rpipe1 = ro
C      rpipe2 = ro
C
C      space = spacein / CFACTOR
C      D1 = rb - (rpipe1+space)
C      D2 = rb - (rpipe2+space)
C      D12 = 2.0*rb - (rpipe1+space) - (rpipe2+space)
C
C      Calculates the conduction shape factors
C
C      U1TEMP = (rpipe1**2+rb**2-D1**2)/(2.0*rpipe1*rb)
C      U2TEMP = (rpipe2**2+rb**2-D2**2)/(2.0*rpipe2*rb)
C      U12TEMP = (D12**2-rpipe1**2-rpipe2**2)/(2.0*rpipe1*rpipe2)
C
C      IF (U1TEMP .GE. 1.0 .AND. U2TEMP .GE. 1.0 .AND.
+      U12TEMP .GE. 1.0) THEN
S1 = 2.0*PI / (LOG(U1TEMP+SQRT(U1TEMP**2-1.0)))
S2 = 2.0*PI / (LOG(U2TEMP+SQRT(U2TEMP**2-1.0)))
S12 = 2.0*PI / (LOG(U12TEMP+SQRT(U12TEMP**2-1.0)))
ELSE
PRINT *, 'The conduction shape factor, S is undetermined'
PRINT *, 'Check the option of pipes, radius of the borehole,'
PRINT *, 'and the spacing between the pipes and the borehole ',
+      'wall'
GOTO 1000
ENDIF
C
C      PR = 7.88
C      kfluid = 0.344
C      Mdot = (VOL*0.1337/60.0) * 62.3426
C      V = Mdot / (PI*ri**2)
C      RE = V * di / 7.5264E-4
C      PRINT *, RE
C      f = (0.790 * LOG(RE) - 1.64)**(-2)
C      NU = (f/8.0)*(RE-1000)*PR / (1+12.7*SQRT(f/8.0)*(PR**(2/3)-1))
C      NU = 0.023 * (RE**0.8) * (PR**0.4)
C      hci = NU * kfluid / di
C      PRINT *, hci
C
C      RCOND = LOG(ro/ri) / (2.0*PI*kpipe)
C      RCONV = 1.0 / (2.0*PI*ri*hci)
C
C      R1 = 1.0 / (kgrout*S1)
C      R2 = 1.0 / (kgrout*S2)
C      R12 = 1.0 / (kgrout*S12)
C
C      ROTHER = RCOND + RCONV

```

```

R1TOTAL = R1 + ROTHER
R2TOTAL = R2 + ROTHER
R12TOTA = R12 + 2.0*ROther
C
C   Assign arbitrary values to the temperatures (they will cancel
C   each other out)
C
   Tb = 55.0
   Tf1 = 80.0
   Tf2 = 60.0
C
   SUMq1q2 = ((Tb-Tf1)/R1TOTAL - (Tf1-Tf2)/R12TOTA) +
+ ((Tb-Tf2)/R2TOTAL + (Tf1-Tf2)/R12TOTA)
   DT = Tb - (Tf1+Tf2)/2.0
C
   BTR = DT / SUMq1q2
C
C
PRINT *, '*****'
PRINT 100, BTR
100  FORMAT (/,2X,F10.5, 3X,'(F/(Btu/(hr*ft)))',/)
C
C
STOP
END

```

VITA

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