# GLHEPRO –
# A DESIGN TOOL FOR COMMERCIAL BUILDING GROUND LOOP HEAT EXCHANGERS

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## KEY WORDS

Ground source heat pump systems, ground loop heat exchangers, design tools.

## ABSTRACT

GLHEPro is a design tool for commercial building ground loop heat exchangers. The design methodology is based on a simulation that predicts the temperature response of the ground loop heat exchanger to monthly heating and cooling loads and monthly peak heating and cooling demands over a number of years. The design procedure involves automatically adjusting the ground loop heat exchanger size in order to meet user-specified minimum or maximum heat pump entering fluid temperatures.

The prediction of temperature response has three parts: a simple heat pump model allows for building heating and cooling loads to be translated to heat extraction and heat rejection rates; the long term temperature response of a ground loop heat exchanger to heat rejection and extraction is based on a detailed conduction heat transfer simulation developed by Eskilson(1); and short-term temperature response of the ground loop heat exchanger is estimated with a simple analytical approximation for the response of the ground loop heat exchanger to a single peak heat extraction or rejection pulse.

This paper presents the technical basis of the program and use of the program is illustrated by performing a ground loop heat exchanger for a 27,000 $ft^2$ office building located in Ottawa, Ontario.

## INTRODUCTION

A number of design tools for ground loop heat exchangers have been developed in the last decade. Design methodologies available for residential ground loop heat exchangers have been reviewed by Cane and Forgas (2). Yavuzturk (3) provides a more up-to-date review of all available methodologies. Another design procedure commonly used in the U.S. is described by Kavanaugh (4). GLHEPRO(5) is aimed primarily at design of vertical ground loop heat exchangers used with commercial/institutional buildings.

GLHEPRO was developed in order to make the "Swedish" methodology developed by Eskilson (1) tractable for U.S. users. Perhaps one of the most important features of the first version was support for inch-pound (IP) units! Additional features for the first version included a simple heat pump model that allowed the user to enter loads on the heat pump rather than loads on the ground. The version described in this paper is Version 3. It is a native Windows 95/98/NT application incorporating a user-friendly graphical user interface written in Microsoft Visual Basic, and a simulation engine written in Fortran.

## BACKGROUND

As the method developed by Eskilson (1) is the basis for much of GLHEPRO, it will be described first. Eskilson's approach to the problem of determining the temperature distribution around a borehole is based on a hybrid model combining analytical and numerical solution techniques. A two-dimensional numerical calculation is made using transient finite-difference equations on a radial-axial coordinate system for a single borehole in homogeneous ground with constant initial and boundary conditions. The thermal capacitance of the individual borehole elements such as the pipe wall and the grout are neglected. The temperature fields from a single borehole are superimposed in space to obtain the response from the whole borehole field.

The temperature response of the borehole field is converted to a set of non-dimensional temperature response factors, called g-functions. The g-function allows the calculation of the temperature change at the borehole wall in response to a step heat input for a time step. Once the response of the borehole field to a single step heat pulse is represented with a g-function, the response to any arbitrary heat rejection/extraction function can be determined by devolving the heat rejection/extraction into a series of step functions, and superimposing the response to each step function.

This process is graphically demonstrated in Figure 1 for four months of heat rejection.

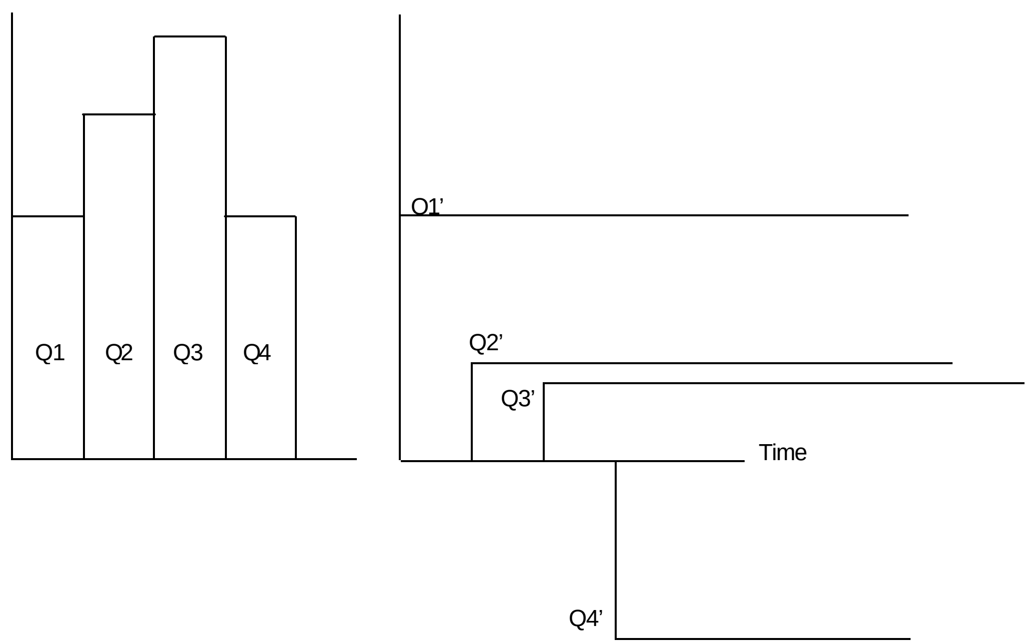



Figure 1: Superposition of Piece-Wise Linear Step Heat Inputs in Time.

The basic heat pulse from zero to Q1 is applied for the entire duration of the four months and is effective as Q1'=Q1. The subsequent pulses are superimposed as Q2'=Q2-Q1 effective for 3 months, Q3'=Q3-Q2 effective for 2 months and finally Q4'=Q4-Q3 effective for 1 month. Thus, the borehole wall temperature at any time can be determined by adding the responses of the four step functions. Mathematically, the superposition gives the borehole wall temperature at the end of the $n^{th}$ time period as:

$$T_{borehole} = T_{ground} + \sum_{i=1}^{n} \frac{(Q_i - Q_{i-1})}{2\pi k} g\left(\frac{t_n - t_{i-1}}{t_s}, \frac{r_b}{H}\right) \tag{1}$$

Where:

$t$ = time (s)
$t_s$= time scale = $H^2/9\alpha$
H= borehole depth (m)
k =ground thermal conductivity (W/m-°C)
$T_{borehole}$ = average borehole temperature in (°C )
$T_{ground}$ = undisturbed ground temperature in (°C )
Q = step heat rejection pulse (W/m)
$r_b$ = borehole radius (m)
i = index to denote the end of a time step. (the end of the 1st hour or 2nd month etc.)

Figure 2 shows the temperature response factor curves (g-functions) plotted versus non-dimensional time for various multiple borehole configurations and a single borehole. The g-functions in Figure 2 correspond to borehole configurations with a fixed ratio of 0.1 between the borehole spacing and the borehole depth. The thermal interaction between the boreholes is stronger as the number of boreholes in the field is increased and as the time of operation increases.

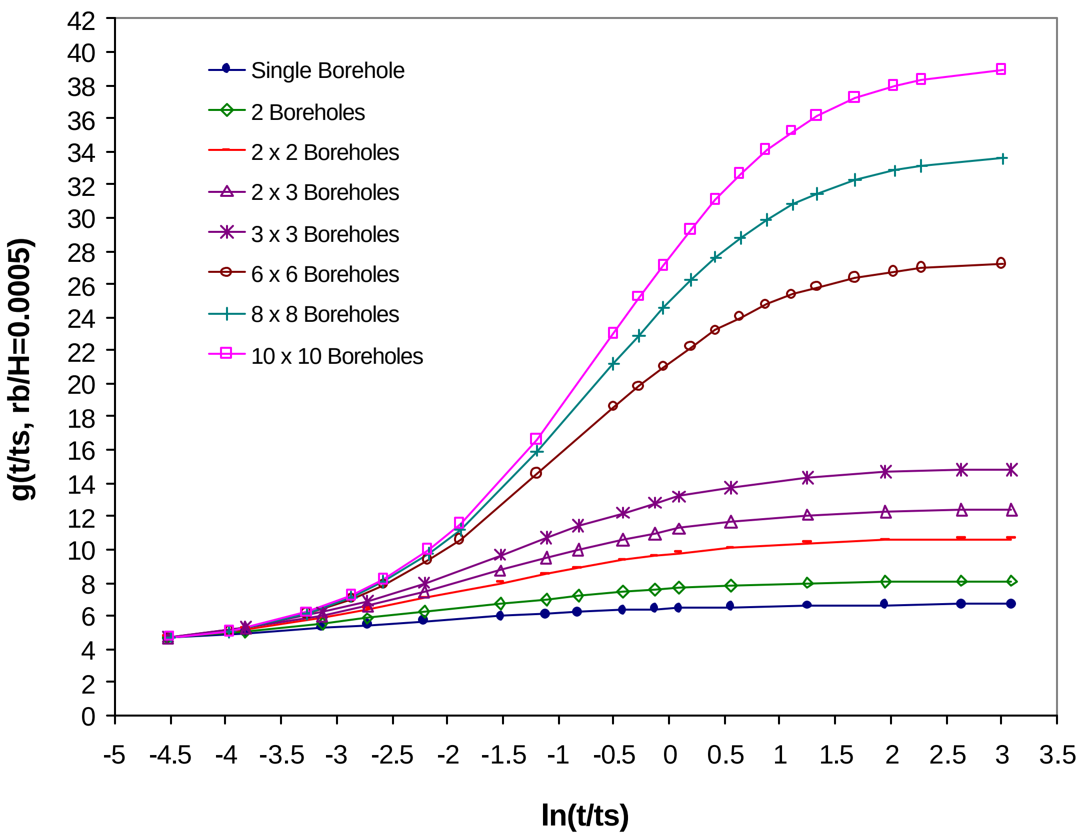



*Figure 2: Temperature response factors (g-functions) for various multiple borehole configurations compared to the temperature response curve for a single borehole.*

The detailed numerical model used in developing the long time-step g-functions approximates the borehole as a line source of finite length, so that the borehole end effects can be considered. The approximation has the resultant problem that it is only valid for times estimated by Eskilson to be greater than $\frac{5r_{Borehole}^2}{a}$. For a typical borehole, that might imply times from 3 to 6 hours. However, much of the data developed by Eskilson does not cover periods of less than a month. (For a heavy, saturated soil and a 250 ft (76.2 m) deep borehole, the g-function for the single borehole presented in Figure 2 is only applicable for times in excess of 60 days.) However, for design purposes, it is highly desirable to account for peak load conditions. A simple approximation is described below.

## METHODOLOGY

The design methodology is based partly on the g-functions developed by Eskilson, partly on a simple heat pump model that represents the ratios of the heat rejected to the ground to cooling provided and heat extracted from the ground to heating provided, and partly on a simple analytical approximation for the response of the ground loop heat exchanger to a single peak heat extraction or rejection pulse. The heat pump model and analytical approximation are discussed below, before the overall procedure is described.

### Application of Eskilson's Model

Eskilson's model only determines the temperature at the borehole wall. For sizing purposes, the entering fluid temperature to the heat pump is of interest. In order to determine the EFT, first the average fluid temperature inside the borehole must be determined; then the EFT may be determined. The temperature of the fluid inside the pipes inside the borehole is determined using a thermal resistance. (The thermal capacitance of the pipe, fluid, and grout are neglected.) The borehole resistance is the sum of the convective resistance at the pipe wall, the conductive resistance of the pipe, and the conductive resistance of the grout. The convective resistance is calculated with the Dittus-Boelter correlation. The conductive resistance of the pipe is determined with Fourier's law. The conductive resistance of the grout filling the borehole is determined from the shape factor correlations developed by Paul (6). Further details regarding the borehole resistance calculation may be found in Yavuzturk and Spitler (7). Once the borehole resistance has been determined, the average fluid temperature in the borehole may be determined as:

$$T_f = T_{borehole} + Q_i R_{TOTAL} \qquad (2)$$

Where:

$T_{borehole}$ = average borehole wall temperature in (°C )
$T_f$ = average fluid temperature in (°C )
$Q_i$ = current heat rejection pulse (W/m)

Then, once the average fluid temperature in the borehole has been determined, the entering fluid temperature to the heat pump may be found from:

$$T_{entering} = \frac{\dot{q}_{rejection,net}}{2\dot{m}c_p} + T_f \tag{3}$$

Where:

$\dot{q}_{rejection,net}$ = the net heat rejection rate (W),
$\dot{m}$ = the mass flow rate of the working fluid (kg/s)
$c_p$ = specific heat of the working fluid (kJ/kg K),
$T_{entering}$ = the entering fluid temperature to the heat pump (°C).

### Heat pump model

A very simple water-to-air heat pump model has been developed. In cooling mode, the ratio of heat rejection to the ground to cooling provided is given by:

$$\frac{\dot{q}_{rejection}}{\dot{q}_{cooling}} = a + bT_{entering} + cT_{entering}^2 \tag{4}$$

Where:

$\dot{q}_{rejection}$ = the heat rejection rate (W),
$\dot{q}_{cooling}$ = the building cooling load met by the heat pump(s) (W),
$a,b,c$ = coefficients determined by an equation fit of manufacturer's catalog data,
$T_{entering}$ = the entering fluid temperature to the heat pump (C).

In heating mode, the ratio of heat extraction from the ground to heating provided is given by:

$$\frac{\dot{q}_{extraction}}{\dot{q}_{heating}} = u + vT_{entering} + wT_{entering}^2 \tag{5}$$

Where:

$\dot{q}_{extraction}$ = the heat extraction rate (W),
$\dot{q}_{heatng}$ = the building heating load met by the heat pump(s) (W),
$u,v,w$ = coefficients determined by an equation fit of manufacturer's catalog data,
$T_{entering}$ = the entering fluid temperature to the heat pump (C).

The building cooling loads and heating loads are determined in advance by a building simulation program. The loads are assumed to be met by the heat pump or heat pumps, but since the entering fluid temperatures are not known *a priori*, they are determined simultaneously with the heat extraction and rejection rates.

### Analytical approximation for the peak pulse

While Eskilson's g-functions are suitable for long (1 week or longer) heat rejection/extraction pulses, they are not intended to be used for shorter periods, such as hourly fluctuations. For most buildings, the cooling or heating load for a peak design day would vary approximately sinusoidally. As an approximation, the peak load is represented as a rectangular pulse with a user-specified duration. Based on comparisons with the more-detailed simulation model presented below, a three-hour duration pulse is suggested.

Using the user-specified peak load on the heat pumps, a peak heat rejection or extraction pulse is determined. The response to the peak pulse is estimated with a simple analytical approximation to the line-source model:

$$\Delta T_{borehole} = \frac{Q_{rejection,peak}}{4 p\, k} \left\{ \ln\left( \frac{4a\, t}{r_b^2} \right) \right\} \qquad (6)$$

Where:

$Q_{rejection,peak}$ = heat rejection rate, above monthly average heat rejection rate (W/m)
a = ground thermal diffusivity ($m^2/s$)

Then, the peak entering temperature may be determined from Equations 2 and 3. This approximation is no better than the g-function might be, if it were calculated for shorter time steps. More detailed models of short time step response are described by Yavuzturk and Spitler (7).

## Operation of the Model

The design methodology requires that the user provide the following information:

- monthly heating and cooling loads on the heat pump or heat pumps, typically determined by a building energy analysis program;
- monthly peak heating and cooling loads, again on the heat pumps and typically determined by a building energy analysis program;
- information about the heat pump or heat pumps, from which the relationship between the entering fluid temperature to the heat pump and the heat rejected to the ground for a given cooling load and the heat extracted from the ground for a given heating load can be determined;
- thermal properties of the ground;
- geometric configuration of the ground loop heat exchanger;
- borehole diameter, U-tube diameter, grout thermal properties;
- thermal properties of the working fluid.

Assuming a given borehole depth, and the above information, the average fluid temperature in the borehole at the end of each month, the EFT at the end of each month, and the actual heat rejection rate for each month are determined simultaneously. Then, the responses to the peak pulses are determined for each month, and the resulting peak entering fluid temperatures to the heat pump(s) for each month are determined.

The program also has a sizing mode where the minimum borehole depth that will meet user-specified minimum and maximum peak temperatures is determined by searching with the simulation until the depth is found that is constrained by either the minimum or maximum peak entering fluid temperature.

## EXAMPLE

## Input Data

In order to provide an example design calculation using GLHEPRO, loads and ground thermal properties for a sample building has been provided by Morrison (8). The building is a 2500 $m^2$ office building designed to the Canadian Model National Energy Code for Buildings. It is located in Ottawa, Ontario, Canada. The proposed location of the borefield is beneath the 24.4 m x 48.8 m parking lot.

The monthly building cooling and heating loads and the monthly peak loads (block loads) are detailed in Table 1.

Table 1 Summary of Building Loads

| Month | Monthly Heating Load (kW-hr) | Monthly Cooling Load (kW-hr) | Monthly Peak Heating Load (kW) | Monthly Peak Cooling Load (kW) |
|---|---|---|---|---|
| 1 | 47908.9 | 43.4 | 166.8 | 5.6 |
| 2 | 32854.3 | 94.1 | 155.0 | 8.5 |
| 3 | 23011.1 | 0.0 | 137.2 | 0.0 |
| 4 | 10438.2 | 2215.7 | 120.8 | 88.8 |
| 5 | 1961.3 | 6369.3 | 77.4 | 112.3 |
| 6 | 200.8 | 19384.2 | 24.6 | 153.3 |
| 7 | 27.5 | 27445.5 | 14.4 | 197.2 |
| 8 | 79.1 | 26119.3 | 25.8 | 151.8 |
| 9 | 1167.6 | 11191.1 | 74.7 | 145.7 |
| 10 | 8727.4 | 2676.4 | 128.1 | 99.6 |
| 11 | 18944.6 | 39.0 | 136.6 | 21.7 |
| 12 | 37938.2 | 68.0 | 162.1 | 12.0 |

Other details, again specified by Morrison, are:

- The Heat transfer fluid: 20% ethanol
- Pipe material: 1-1/4" HDPE, Schedule 40
- Borehole diameter: 150 mm
- Borehole grout: Bentonite - 30% solids

Correlations for heat pump coefficient of performance (COP) in heating mode and energy efficiency ratio[1] (EER) in cooling mode as a function of entering fluid temperature were also provided. The resulting curves are shown in Figures 3 and 4.

[1] Energy Efficiency Ratio is a mixed-units measure of heat pump efficiency in cooling mode, used in the U.S. It is defined as Btu/hr of cooling provided per watt of power required. The COP for cooling mode can be found from the EER by multiplying it by the conversion factor 0.291 W / 1 Btu/hr.

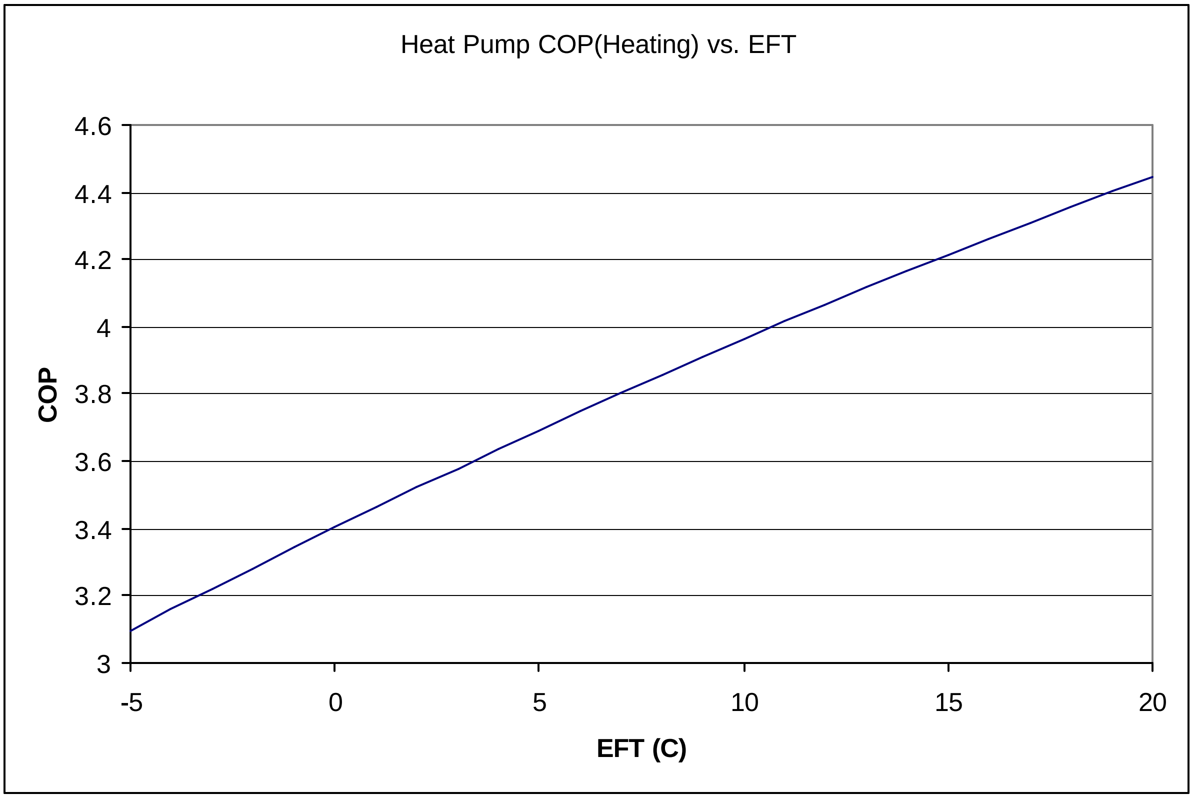



Figure 3 Heat Pump COP in Heating Mode

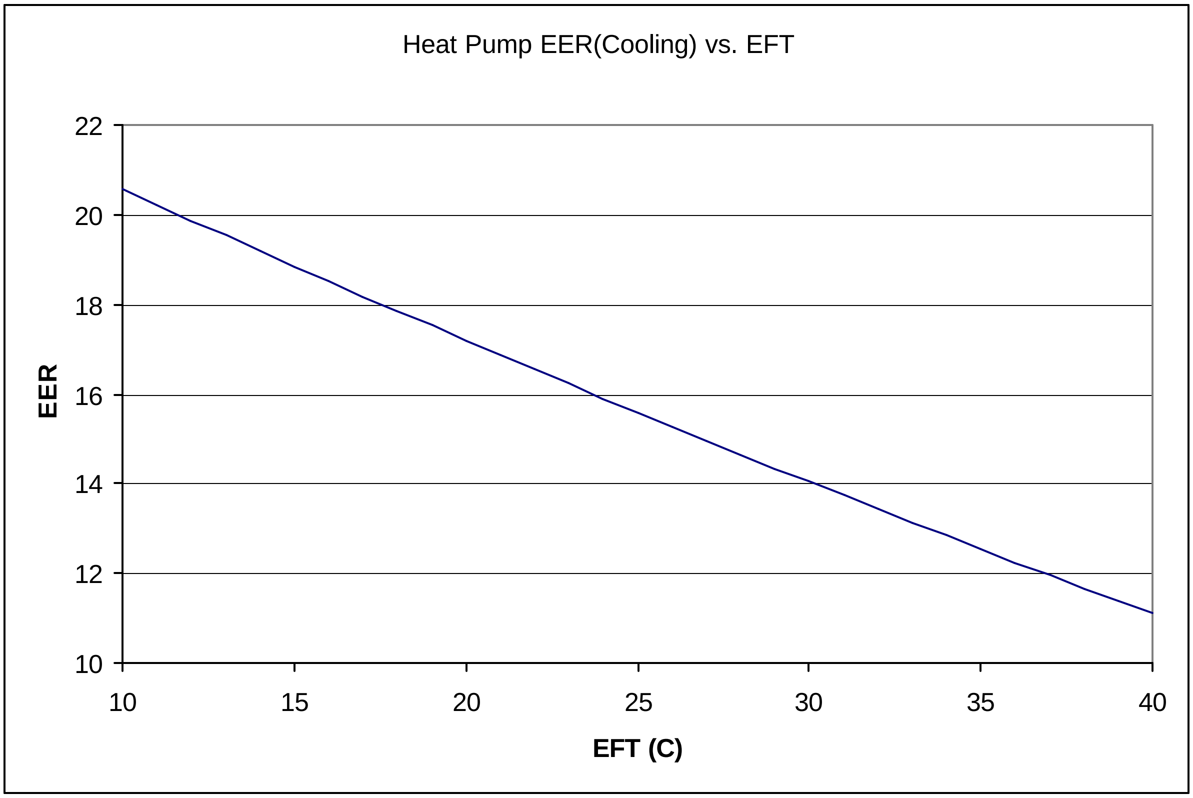



Figure 4 Heat Pump EER

## Input Procedure

Once the input data have been gathered, they can be entered into GLHEPRO. A short discussion of the input procedure, illustrated by a few screen shots are included below to give the reader an idea of how the program works. The program is controlled from the main dialog box shown in Figure 5. In this case, most of the information required by the program has been entered already. The active borehole depth is still to be required. Details such as borehole radius, borehole spacing, undisturbed ground temperature, and fluid flow rate are entered directly here. Borehole geometry and heat pump both must be selected from a library. User-editable libraries are available for the ground thermal properties, heat transfer fluids, and heat pumps. The borehole thermal resistance can be entered directly, or calculated using another dialog box.

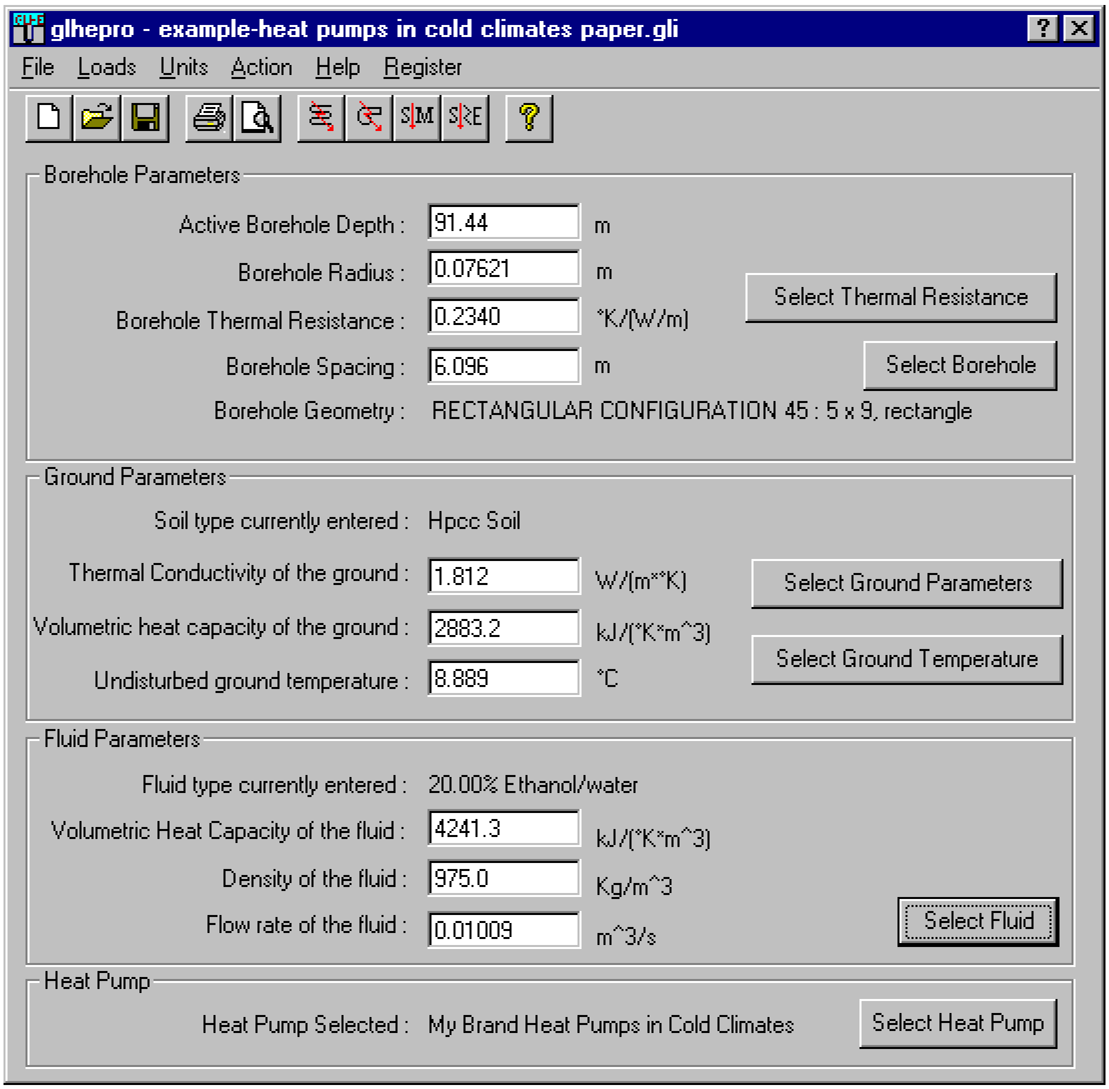
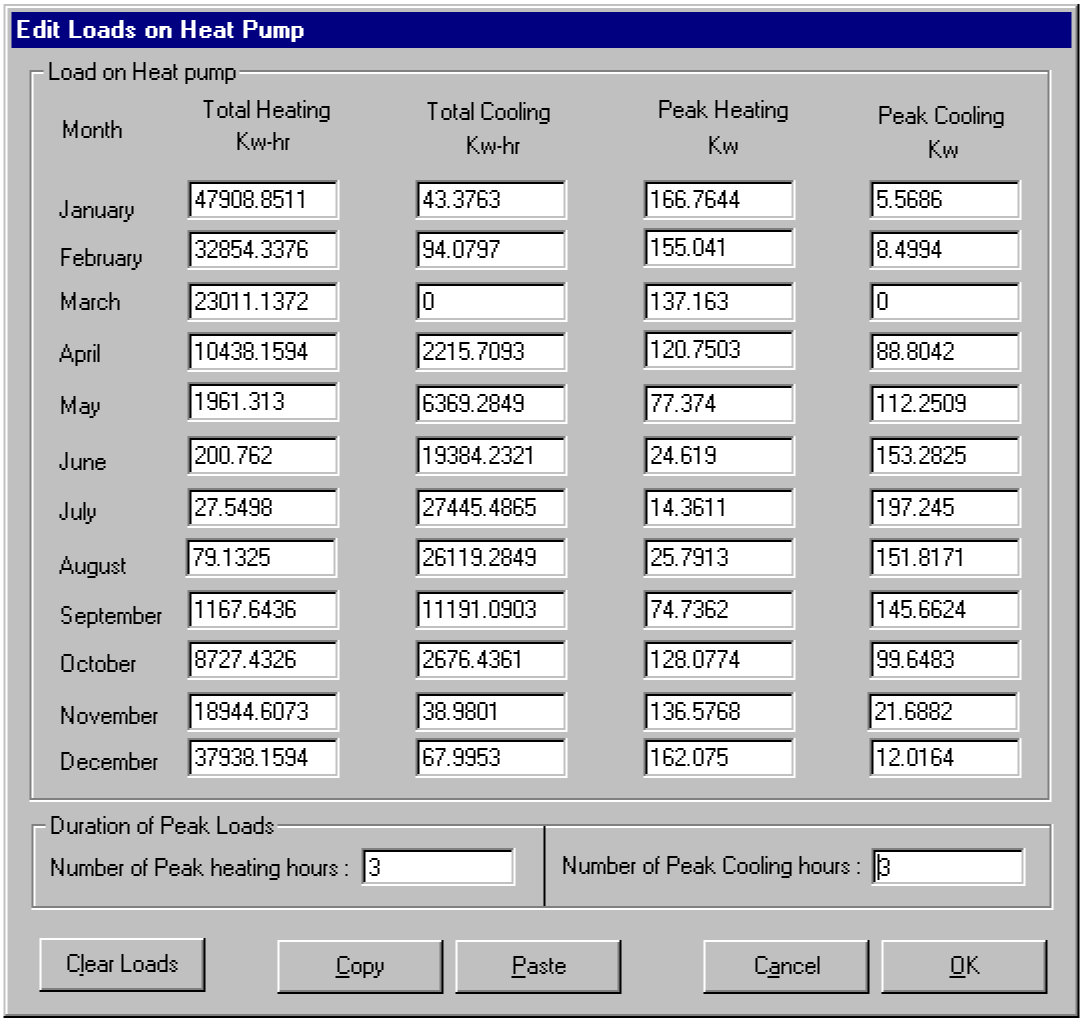



Figure 5 Main Dialog Box of GLHEPRO

Once the program has been started, the building loads are entered. GLHEPRO can read loads directly from the BLAST and Trane System Analyzer building energy analysis programs. Alternatively, the loads can be pasted in from a spreadsheet, which was the procedure used in this case. They are pasted into the heat pump loads dialog box, shown in Figure 6.



Edit Loads on Heat Pump

Load on Heat pump

| Month | Total Heating Kw-hr | Total Cooling Kw-hr | Peak Heating Kw | Peak Cooling Kw |
|---|---|---|---|---|
| January | 47908.8511 | 43.3763 | 166.7644 | 5.5686 |
| February | 32854.3376 | 94.0797 | 155.041 | 8.4994 |
| March | 23011.1372 | 0 | 137.163 | 0 |
| April | 10438.1594 | 2215.7093 | 120.7503 | 88.8042 |
| May | 1961.313 | 6369.2849 | 77.374 | 112.2509 |
| June | 200.762 | 19384.2321 | 24.619 | 153.2825 |
| July | 27.5498 | 27445.4865 | 14.3611 | 197.245 |
| August | 79.1325 | 26119.2849 | 25.7913 | 151.8171 |
| September | 1167.6436 | 11191.0903 | 74.7362 | 145.6624 |
| October | 8727.4326 | 2676.4361 | 128.0774 | 99.6483 |
| November | 18944.6073 | 38.9801 | 136.5768 | 21.6882 |
| December | 37938.1594 | 67.9953 | 162.075 | 12.0164 |

Duration of Peak Loads

Number of Peak heating hours : 3 | Number of Peak Cooling hours : 3

Clear Loads | Copy | Paste | Cancel | OK

Figure 6 Heat Pump Loads Dialog Box

As discussed before, the program uses a simple approximation for the peak loads. They are represented by the user as a square-wave type pulse, specified by giving the peak cooling and heating load for each month, and the number of hours for which the peak applies. The default number of 3 hours was chosen based on a comparison to the detailed short time-step model for a few cases. Never the less, this approach is not completely general, and an improved algorithm is a topic for future research.

The borehole thermal resistance is determined using the borehole thermal resistance calculator provided as part of the program. The program assumes that if IP units are being used, piping will be described in standard North American sizes; if SI units are being used, piping will be described in European DIN sizes. Since, in this case, North American standard sizes were specified, the program mode was changed from SI to IP units to determine the borehole thermal resistance. (When switched between units, all entries are automatically translated, so that switching back and forth causes no problems.) The borehole thermal resistance dialog box is shown in Figure 7. Most of the entries are close to self-explanatory. The borehole spacing follows Paul's shape factors; the "B" spacing is generally assumed reasonable for a U-tube that is inserted into the borehole without any spacers. The "C" spacing can only be achieved with a spacer that forces the two pipes against the borehole wall.

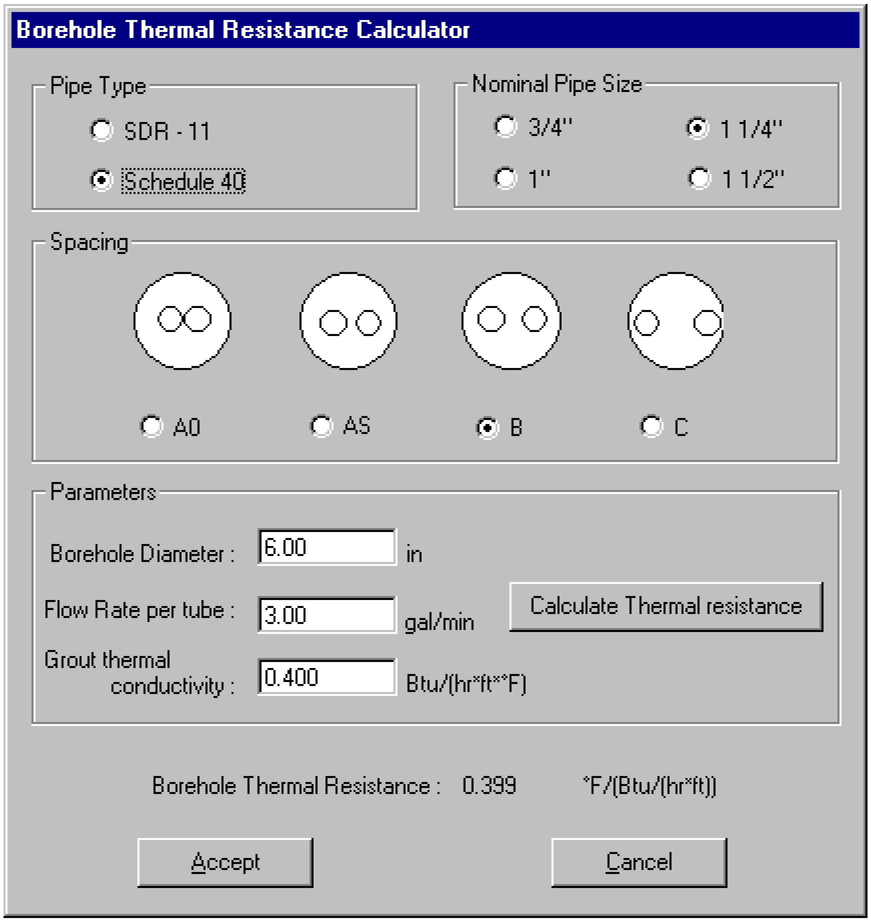



Figure 7 Borehole Thermal Resistance Calculator Dialog Box – IP version

The borehole configuration is selected from a large (but finite) number of potential arrangements of multiple boreholes. These configurations include lines, "L"s, open rectangles, and rectangles. In this case, with consideration given to the geometry, a rectangular configuration of 5 boreholes by 9 boreholes is chosen on a 6.1 m spacing.

Although each library has a slightly different interface, the fluid library might be considered reasonably typical. Different fluid types and concentrations are available. Ethanol was not included in the distribution library, so it was added to the user library. It can now be selected using the dialog box shown in Figure 8.

The ground thermal properties were determined based on a weighted average of the values provided by Morrison. Since the weighted average depends on the depth, a few iterations were required to find a consistent conductivity, thermal diffusivity, and depth.

For real building designs, heat pumps are usually chosen from the library. In the event that the heat pump is not in the library, it can be added by entering catalog data, from which the correlations described above in the Heat Pump Model section can be determined. In this case, the correlations given by Morrison were used to develop pseudo-catalog data, which was then used to determine the necessary GLHEPRO style correlations.

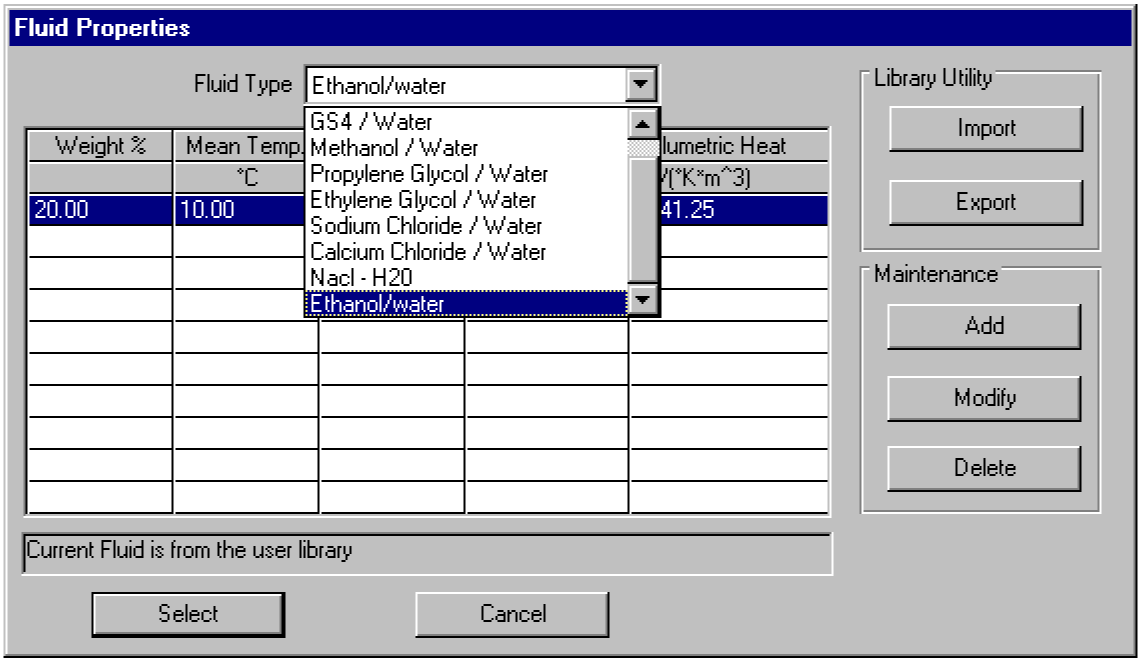



Figure 8 Fluid Properties Library

## Design Procedure and Results

Once all necessary input data have been entered, the user can proceed with the design. In GLHEPRO this is done by choosing the GLHE Size option. Once this has been selected, the user will see the dialog box shown in Figure 9.

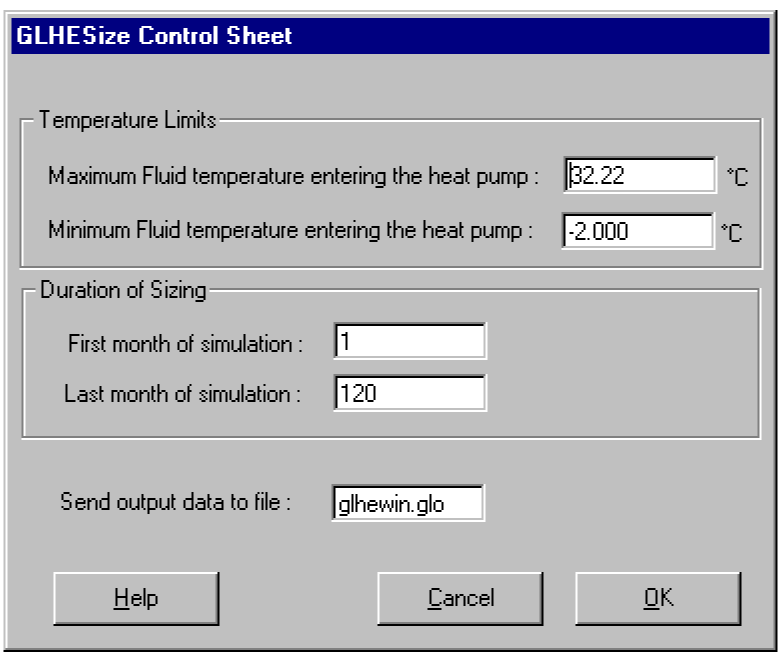



Figure 9 GLHE Size Dialog Box

At this point, the user has several choices that are very important to the outcome of the design. Either the minimum or maximum entering fluid temperature will control the borehole depth, while also affecting the overall energy consumption. The narrower the temperature band, the more efficiently the heat pumps will run. However, since the ground loop heat exchanger will be larger with a narrower temperature band, pumping energy consumption may be increased. Investigation of the tradeoffs is beyond the scope of this paper. Kavanaugh and Rafferty [9] have presented some metrics for pumping energy costs.

In this case, we have initially selected a maximum entering fluid temperature (EFT) to the heat pump of 32ºC and a minimum EFT of -2ºC. The minimum EFT is selected based on the freezing point of the ethanol mixture being about -11ºC. Under design heating conditions, a $\Delta T$ of 4ºC is expected. Therefore, a design minimum EFT of -7ºC might be permissible, except that is preferable to have some margin of safety, say 5ºC, which brings us to a design minimum EFT of -2ºC. However, whenever there is a relatively small difference between the undisturbed ground temperature and the limiting design EFT, the design will tend to be very sensitive to the limiting design EFT. In this case, there is less than an 11ºC difference, and, as will be shown below, the result is very sensitive to the minimum design EFT.

The length of the design period can also be very important. For cooling dominated buildings typical of much of the U.S., the annual heat rejection exceeds the annual heat extraction. When this occurs, the entering fluid temperature rises from year to year. For this building, there is relatively little change, as the annual heat rejection and annual heat extraction are reasonably balanced.

For our initial design constraints, the program recommends that the 45 boreholes be 84 m deep, as shown in Figure 10.

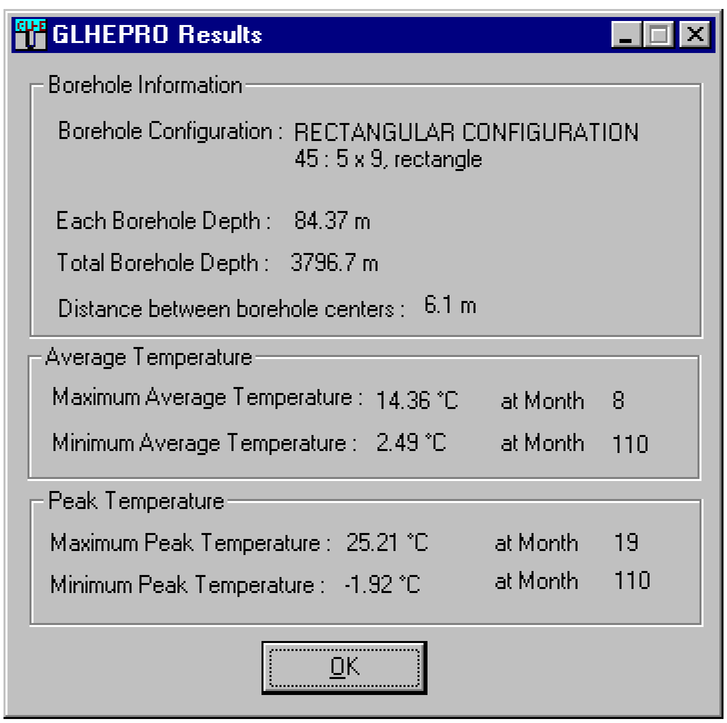



Figure 10 Summary of Results

Additional results are provided in an output file. These have been plotted in Figure 11 to show the peak maximum and minimum entering fluid temperatures for each month. The fact that the annual heat rejection and extraction are closely balanced can be inferred from the fact that the annual peaks change very little from year to year.

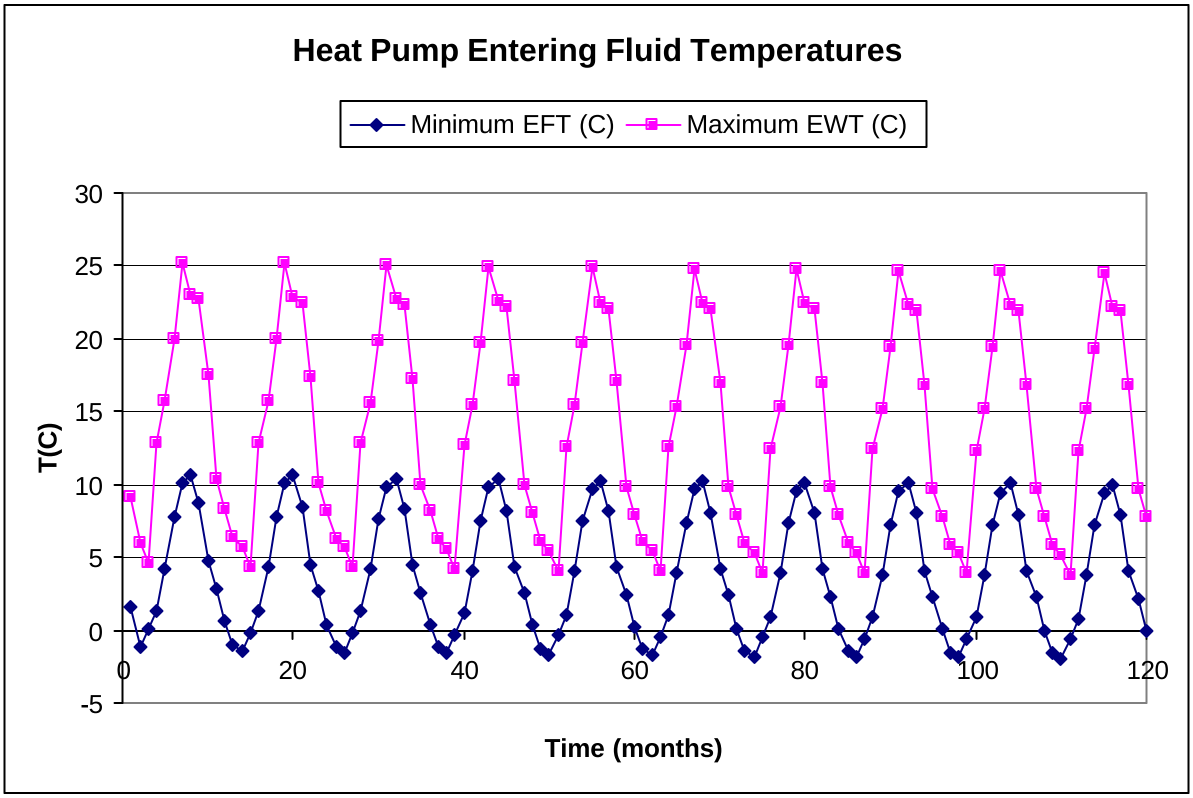



Figure 11 Monthly heat pump entering fluid temperatures

It is also useful to examine the sensitivity of the design to the design parameters. In this case, the design is highly sensitive to the minimum entering fluid temperature. A series of sizes were calculated for a range of minimum entering fluid temperatures. This relationship is illustrated in Figure 12. For this building, a slightly lower design minimum EFT, say just 4ºC lower, will allow a significantly smaller and less expensive ground loop heat exchanger. It would be well worth the designer's time to refine the design accordingly.

## CONCLUSION

A method for simulating the response of the ground to a building with a ground source heat pump system has been presented. The method takes into account monthly building heating and cooling loads, heat pump characteristics, borehole characteristics and configuration, fluid thermal properties, and ground thermal properties. A program in which this methodology has been implemented has been presented. The program, while powerful in its analysis and design capabilities, none the less requires intelligent use. As can be inferred from the example, it is quite possible to develop a working design that meets a design specification, yet not really have an optimal design.

As a topic for future research, development of design tools which can automatically optimize the design while accounting for all of the interactions should be pursued. In addition, although not discussed in this paper, additional validation and testing of this and other programs would be useful.

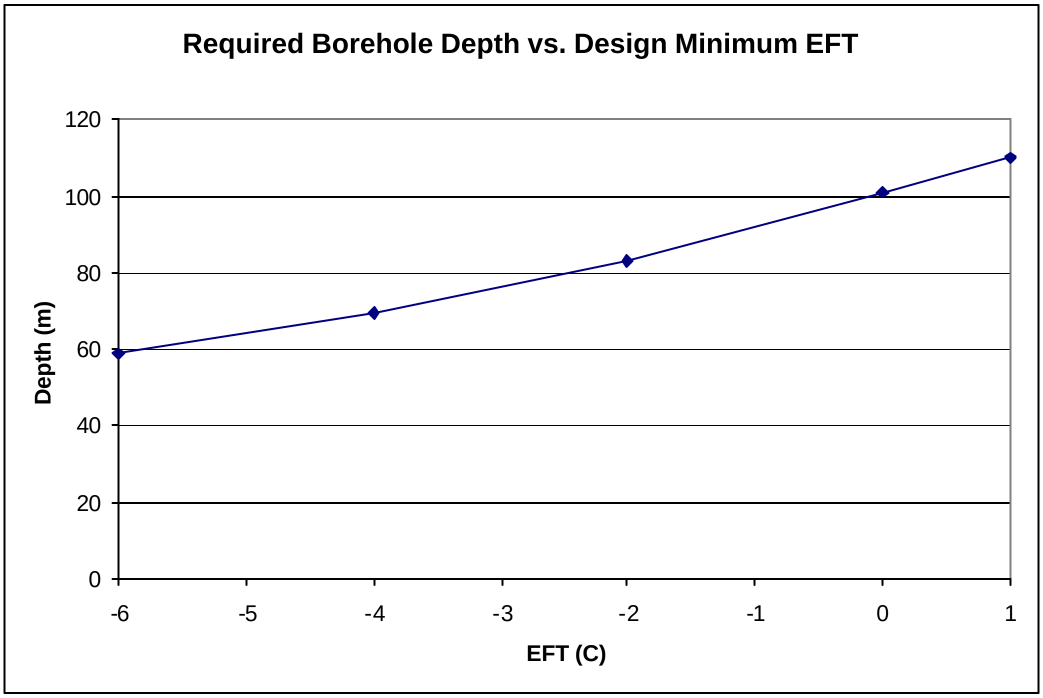



Figure 12 Sensitivity of GLHE size to Design Temperature

## ACKNOWLEDGMENTS

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