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MARTIN MARIETTA

Horizontal Ground-Coil Heat Exchanger Theoretical and Experimental Analysis

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HORIZONTAL GROUND-COIL HEAT EXCHANGER THEORETICAL AND EXPERIMENTAL ANALYSIS

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NOMENCLATURE

C	specific heat, J/(kg·°C) [Btu/(lb·°F)]
DT	one-half amplitude of annual surface temperature, °C (°F)
h	convective heat transfer coefficient, W/(m^2·°C) [Btu/(h·ft^2·°F)]
K	thermal conductivity, W/(m·h·°C) [Btu/(h·ft^2·°F)]
L	latent heat, J/kg H_2O (Btu/lb H_2O)
M	moisture content, kg H_2O/kg dry soil (lb H_2O/lb dry soil)
N_{Nu}	Nusselt number $= 2\ hr_0/K_f$
N_{Pr}	Prandtl number $= \mu C_f/K_f$
N_{Re}	Reynolds number $= 2\ Vr_0\rho_f/\mu$
r	radius, m (ft)
R	boundary between soil frozen and nonfrozen regions, m (ft)
T	temperature, °C (°F)
TA	annual average ground surface temperature, °C (°F)
t	time, h
t_0	time of the year, h
V	fluid velocity, m/h (ft/h)
x	distance along the ground coil, m (ft)
z	depth, m (ft)

GREEK LETTERS

ρ	density, kg/m^3
θ	angular direction, defined in Eq. 3.3
ϕ	phase angle, radian
α	thermal diffusivity $= K/\rho C_p$, m^2/h (ft^2/h)
μ	fluid viscosity, kg/(m·h) [lb/(ft·h)]
ψ	angular direction, defined in Eq. 5.4

SUBSCRIPTS

0	pipe inside wall	l	lower
1	pipe outside wall	u	upper
2	backfill region boundary	s	soil region
b	thermal backfill region	sf	soil frozen region
f	fluid	u	upper coil
i	initial	F	farfield
p	coil		

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EXECUTIVE SUMMARY

Ground-coil heat pump (GCHP) systems have long been regarded as having excellent potential for both reduced peak load and energy conservation. Past research work has provided a rich resource of useful test data and experience. However, it is also generally recognized that the development of modeling techniques for the GCHP has remained relatively stagnant for the past three decades.

Ground-coil design is still based mainly on the application of line-source theory, which requires the specification of line-source strength, which has to be estimated. This method works well for those areas in which there have been previous installations and operating experience. In other instances, this method tends to significantly overdesign the ground coil. With other air-conditioning systems becoming more efficient, this practice of excessive overdesign definitely will adversely impact the GCHP's economic competitiveness. It is clear that new models to more realistically describe ground-coil operation are needed for future ground-coil design.

The ORNL ground-coil program began in 1980. The fundamental concept was to be more rigorous in the theoretical analysis underlying development of mathematical models for different types of ground coils. Only through the understanding of heat and mass transfer mechanisms between fluid flow, the coil wall, and the soil can important design factors, many of them ignored by the line-source approach, be studied.

In this report, three horizontal ground-coil models are presented: (1) a horizontal single coil with a radially symmetrical temperature profile and soil moisture freezing effect; (2) a horizontal single coil with nonsymmetrical soil temperatures around the coil; and (3) horizontal double coils, one on top of the other in the same trench, with nonsymmetrical soil temperatures around the coils and with thermal interference effects.

Model 1 is designed to check the effect of soil moisture freezing around the coil. Parametric studies utilizing this model revealed that unless the coil inlet fluid temperature is much lower than the soil moisture freezing point, the amount of latent heat released will be very small compared with the total energy absorbed by the coil. Model 2 enables simulation of the effect of ground surface heat transfer with the ambient air. Model 3 is used to study the effect of two coils being buried in the same trench. It is concluded from field experimental results that this arrangement will absorb about 50% more energy from the ground over a single coil for the same trench length, thus reducing trenching cost.

All three models have been well validated with the field experimental data provided by Brookhaven National Laboratory and The University of Tennessee. The average error of simulating the daily energy absorbed from the ground is only 16%, on the conservative side, from the measured values. It is not possible to compare the ORNL models to line-source models on the basis of energy absorption/rejection because this parameter is

required input for line-source models. Comparison on the basis of predicted ground temperatures, however, reveals that ORNL models match the data better in spite of the fact that line-source models are given the exact heat rejection/absorption rate as input. Considering the application of line-source theory, which cannot accurately assess the level of overdesign or underdesign of ground coil, ORNL models are at least one step ahead.

Computer codes for the three models are listed in the report. The codes are easy to use and do not require the knowledge of solving partial differential equations. All codes are available on floppy disks for personal computer (PC) application or on tape for mainframe computer application.

Although these models simulate much more realistically ground-coil operation than the traditional line-source applications, they also require much more computer time to simulate coil operation. Therefore, at present, these models are probably more suitably used as references by which to check the coil designs based on the line-source method. However, with anticipated improvements in PC speed, these models should be more practical for coil design purposes in the future.

ABSTRACT

Ground-coupled heat pump systems have long been recognized for their high potential for energy conservation. However, the design of the ground-coil heat exchanger is still largely based on line-source theory, which was developed for heat pump ground-coil application back in the 1940s. Although this theory is easy to use, many important factors in ground-coil design have to be excluded because of the limitations of the theory. New models to better predict ground-coil performance are needed.

Based on energy balance, three ground-coil models were developed: One incorporates a radially symmetrical temperature profile and a soil freezing effect around the coil; one includes a three-dimensional ground temperature distribution caused by heat transfer between the ground surface and ambient air; and one contains ground heat transfer and thermal interference effects. All three models have been validated with the field experimental data provided by Brookhaven National Laboratory and by The University of Tennessee. The maximum error in calculated energy exchange between coil and ground is <16%, on the conservative side, compared with the measured values.

One section of this report includes a comparison of (1) a line-source theory model, (2) a modified line-source theory model, and (3) one of the ORNL models. All three models were used to simulate the same field experiment. The results indicated that the ORNL model is much better than the other two. Finally, some possible future work involving mass transfer induced by the soil temperature gradient is discussed.

The computer codes, which are easy to use, are included in the appendices, along with sample calculations. These codes can be used for ground-coil design purposes or for checking the coil design with other methods.

1. INTRODUCTION

Ground-coupled heat pump (GCHP) systems have long been recognized for their potential in energy conservation and in the reduction of power peak load. Much theoretical and experimental work in this field has been accomplished, a small part of which is represented in refs. 1–10. However, no comprehensive ground-coil heat exchanger analysis has been derived so far because of the complex nature of the problem. Several major difficulties are encountered:

1. the lack of knowledge of soil thermal conductivity and diffusivity, both of which are highly dependent on the soil moisture content in a given location;
2. moisture migration, which results when a temperature gradient is imposed in the soil;
3. ice formation around the coil, with the attendant release of latent heat and a step change in soil thermal properties in the frozen region;
4. the effect of seasonal temperature variation at depths below the ground surface;
5. possible thermal resistance due to lack of intimate contact of the coil with the soil;
6. the effect of the ground-coil size and material; and
7. the effect of coil cyclic operations.

Earlier researchers, from the 1930s to the 1950s, considered GCHP systems for winter application only. Most ground coils for field experiments were of copper tubing with refrigerant expanded directly into the coil.[5,10,11] It was understood that ground-coil performance analysis was a complicated problem;[7] however, the lack of high-speed computers made the detailed numerical analysis of these problems impossible. Most modeling efforts were centered around line-source theory by treating the ground coil as a line source buried in an infinite medium[4,12] or in a semi-infinite medium.[10,13] The problems involved in this approach are that (1) the strength of the line source has to be estimated, which makes line-source theory application more or less empirically dependent; (2) the fluid temperature in the coil changes continuously, which means that the line-source strength will not be constant, as required by line-source theory; and (3) the initial ground temperatures are not uniform. For example, the ground temperature at 1.2 m (4 ft) below the surface varied from 10 to 1.7°C (50 to 35°F) over the winter in the Long Island, N. Y., area.[14] This seasonal ground temperature variation will definitely have a significant impact on the heat transfer performance of ground coils.

The above discussion indicates that a simple approach to a complex problem will result in excluding many important factors.

Research work in GCHP systems was almost completely halted from the mid-1950s to the early 1970s because of the low cost of energy. When the work was resumed, the ground trenching costs had declined, and installation techniques had improved considerably. The replacement of metal tubing with plastic coil is particularly interesting because plastic coil, if the material is selected correctly, can form leakproof joints easily. Also, plastics do not have corrosion problems, and they are much cheaper than metal tubing. Use of plastic tubing has become common practice in this field today. However, up to now there has not been much improvement in theoretical analysis; most of the new theoretical developments were centered around line-source theory. Metz[15] used the line-source approach, dividing the ground into blocks for ground-coil heat transfer calculations. The computer code treated surface temperature effects by incorporating Kusuda and Achenbach's correlation[16] into the code. It could also handle thermal interference from the adjacent parallel coil legs by the mirror-image method. By superimposing a negative source on a positive one, the code could simulate heat pump on/off cyclic operation. The strength of the line source was based on the house load. The computer code is fast and easy to use; however, it has not been validated fully thus far.

Kalman's approach[17] treated the heat transfer problem as one dimensional. The coil was assumed buried in an infinite medium, with farfield soil temperature varied as a function of time and coil burial depth.

Bose, Parker, and McQuiston[18] used the mirror-image method to treat a ground coil buried in a semi-infinite medium. Two possibilities were discussed: (a) a constant surface temperature and (b) an adiabatic surface. Both cases are incorrect because the ground surface is neither adiabatic nor isothermal.

Claesson and Dunard[19] wrote an extensive description of extracting heat from the horizontal ground coils. However, most of the work again concerned buried pipes with a constant heat extraction rate, which is incorrect because of the continuous change in fluid temperature along the coil.

Most of the recent analytical work has basically involved the application of line-source theory. So far, none of the line-source models have been validated satisfactorily with experimental field data. Thus, field experience is still a crucial factor in ground-coil design using the line-source approach.

At Oak Ridge National Laboratory (ORNL), we felt that only through an appreciation of the fundamental principles of soil heat and mass transfer could one derive the model properly. The basic concept, therefore, was to be more rigorous in the theoretical analysis underlying the development of mathematical models for different types of ground coils. The models should include as many important factors as possible, such as fluid properties, flow rate, coil size, coil material, coil length, coil burial depth, soil properties, coil cyclic operation, soil freezing, seasonal ground temperature variation, etc. The resulting models were to be validated with laboratory and field experimental results. Once validated, the models could be used for ground-coil design.

The ORNL ground-coil modeling program has been roughly divided into three phases. Phase 1 concerned ground coils involving heat transfer with constant farfield temperatures, which was suitable for deep-well, tube-in-tube-type ground heat exchanger analyses. This phase of work has been completed.[20,21] A mathematical model was derived and solved numerically. The computer model results were validated with the laboratory test data taken at different operating conditions.

Phase 2 concerned ground coils involving heat transfer with soil freezing and with seasonal ground temperature variation. It was decided first to check the effect of soil freezing. Since soil freezing is advantageous to ground-coil performance because of the release of latent heat, the thermal storage effect, and an increase in soil thermal conductivity in the frozen soil region, it could be very important in affecting the overall system performance. The soil freezing model with radially symmetrical temperature distribution has been completed, and the numerical solution has been partially validated.[22] The model shows that, unless the ground-coil inlet fluid temperature is much lower than the soil moisture freezing temperature, the effect of soil freezing around the coil is relatively minor. Since the fluid temperature in the ground coil would be kept above −4°C (25°F) in the applications we were interested in, it was concluded that soil freezing was not important enough to warrant further study. However, the situation could change if a low-temperature water-source heat pump, operating at very low fluid temperature with improved efficiency, were developed. Our attention was then focused on the case of the horizontal ground coils with seasonal ground temperature variation. Since ground-coil performance is dependent on the ambient ground temperature, inclusion of the effect of seasonal ground temperature variation would enable us to simulate ground-coil operation more realistically. This part of the work was completed, and the computer simulation results were validated by field measurements to a very satisfactory degree.[23] This model provides a three-dimensional ground temperature distribution, which may be particularly useful if environmental impact analyses of ground-coil operation are desired. The study was then focused on the thermal interference effects of ground-coil operation. Ground-coil installation contractors can cut costs by putting more than one coil into the same trench. One of the field experiments[24] indicated that two coils per trench was the most efficient. Putting more than two coils in the same trench would not greatly improve system performance. Therefore, it was decided to model the two-coil thermal interference case. A mathematical model was derived and solved numerically. The model was validated with the field experimental data.

Phase 3 work treats the case of ground-coil heat transfer coupled with soil moisture migration. This part of the research is directed toward summer operation of the horizontal ground-coil heat exchanger. Soil moisture migration has been studied extensively in agricultural irrigation and in power company buried cable fields.[25,26] The effect of soil moisture migration is to dry out the soil around the ground coil. Since soil thermal conductivity is a strong function of soil moisture content, soil moisture migration could severely decrease the ground-coil capacity. It could also induce a contact resistance for clay-type soil by creating a gap between the soil and the coil which otherwise would be filled with moisture.

It was concluded at ORNL, however, that GCHP systems probably would not be competitive with high-efficiency air-source heat pump systems for meeting summer cooling loads. Therefore, this phase of the work was halted for the time being. So far, only the mathematical model with radially symmetrical temperature and moisture profiles has been completed.

In this report, the phase 2 work is described in detail. The mathematical models based on energy balance are shown, and the validation of the models and the parametrical studies are presented and discussed. The computer codes, which are written for personal

computer application and which can be used for ground-coil design, are included in Apps. B, C, and D.

The ground-coil models presented in this report represent a conceptual break from the traditional line-source theory. Although ORNL ground-coil models consume more computer time, they provide a more realistic simulation of ground-coil operation. As of now, the models probably are best used as a check on ground-coil designs based on line-source theory. However, because of progress in the area of computer speed, we are very optimistic that our models will soon be practical for use directly in ground-coil design.

2. GROUND-COIL MODEL WITH SOIL FREEZING

2.1 INTRODUCTION

The ground-coil model with soil freezing was developed to check the effect of soil freezing around the coil. The model is two-dimensional with a radially symmetrical soil temperature profile and with a cylindrical region of soil frozen around the coil when freezing occurs. The following assumptions were made to simplify the analysis:

1. the soil is homogeneous;
2. the soil thermal properties are constant but not necessarily identical in the frozen and nonfrozen regions;
3. the fluid temperature and velocity are uniform at any coil cross section;
4. the coil is buried deep enough that the distance between the ground surface and the coil can be considered as farfield;
5. only a single coil is in the ground; and
6. the effect of ground temperature variation happens only at farfield and at the coil burial depth and the effect is radially symmetrical.

For winter operation, assumptions 1 and 2 are close to the real ground conditions because the top layer of ground is saturated with moisture. The fluid is well mixed because of the large coil length-over-diameter ratio, allowing assumption 3 to be made. Field experiments by Freund and Whitlow[27] indicated that thermal penetration caused by the coil was not more than 1 m (3 ft). Since coils are usually buried at least that deep, assumption 4 is also true. The coils are usually buried at least 2 m (6 ft) apart so that thermal interference will not occur,[27] and therefore a single-unit analysis is adequate for the system (assumption 5). Assumption 6 is not strictly true, but it simplifies the model from three-dimensional to two-dimensional. However, the error is probably small if the average farfield temperature from the surface to twice the coil burial depth is close to the farfield temperature at coil burial depth.

2.2 THEORETICAL DEVELOPMENT

Under the assumptions made in Sect. 2.1, the following equations can be derived for the system shown in Fig. 1.

(a) Energy balance in the fluid within the tube and tube inner wall:

$$-V\frac{\partial T_f}{\partial x} + \frac{2K_p}{r_0\rho_f C_f}\frac{\partial T_p}{\partial r}\Big|_{r_0} = \frac{\partial T_f}{\partial t} \qquad (r < r_0) \ . \tag{2.1}$$

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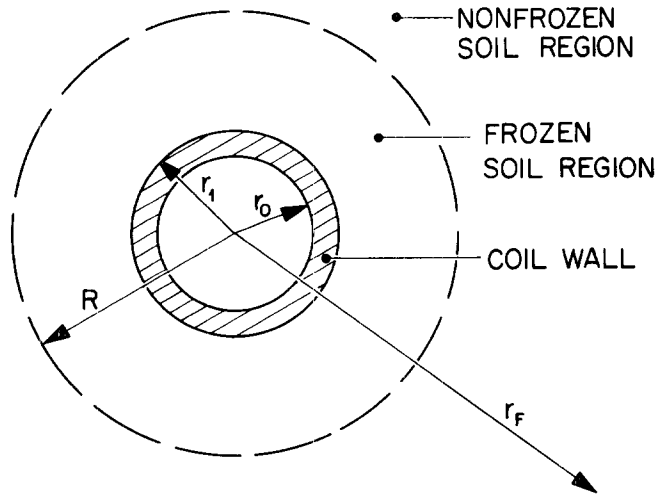

Fig. 1. Schematic of ground coil for the ground-coil model with soil freezing.

(b) Energy balance in the coil wall:

$$\frac{\partial^2 T_p}{\partial r^2} + \frac{1}{r}\frac{\partial T_p}{\partial r} = \frac{1}{\alpha_p}\frac{\partial T_p}{\partial t} \qquad (r_0 \leqslant r \leqslant r_1) \ . \tag{2.2}$$

(c) Frozen soil region:

$$\frac{\partial^2 T_{sf}}{\partial r^2} + \frac{1}{r}\frac{\partial T_{sf}}{\partial r} = \frac{1}{\alpha_{sf}}\frac{\partial T_{sf}}{\partial t} \qquad (r_1 \leqslant r \leqslant R) \ . \tag{2.3}$$

(d) Nonfrozen soil region:

$$\frac{\partial^2 T_s}{\partial r^2} + \frac{1}{r}\frac{\partial T_s}{\partial r} = \frac{1}{\alpha_s}\frac{\partial T_s}{\partial t} \qquad (R \leqslant r \leqslant r_f) \ . \tag{2.4}$$

(e) Boundary conditions:

At $r = r_0$,

$$h(T_p - T_f)|_{r_0} = K_p \frac{\partial T_p}{\partial r}|_{r_0} \ . \tag{2.5}$$

(Information for calculating h is provided in App. A.)

At $r = r_1$,

$$K_p \frac{\partial T_p}{\partial r}\Big|_{r_1} = K_{sf} \frac{\partial T_{sf}}{\partial r}\Big|_{r_1} , \tag{2.6}$$

$$T_{sf} = T_p . \tag{2.7}$$

At $r = R$ (boundary between soil frozen and nonfrozen regions),

$$K_{sf} \frac{\partial T_{sf}}{\partial r}\Big|_R - K_s \frac{\partial T_s}{\partial r}\Big|_R = \rho_s ML \frac{dR}{dt} , \tag{2.8}$$

$$T_{sf} = T_s = 0°\text{C } (32°\text{F}) . \tag{2.9}$$

[The 0°C (32°F) can be replaced by the actual soil moisture frozen temperature if it is known.]

At $r = r_F$ (farfield),

$$T_s = T_F(t) = TA - DT \times \exp\left(-z\sqrt{\frac{\pi}{8766\alpha_s}}\right) \times \cos\left(\frac{2\pi t_0}{8766} - \phi - z\sqrt{\frac{\pi}{8766\alpha_s}}\right) . \tag{2.10}$$

Equation 2.10 is the Kusuda and Achenbach correlation.[16] If there is a known ground temperature profile at different depths over the winter heating season, Eq. 2.10 should be replaced by the known profile.

Initial conditions ($t = 0$):

$$T_f = T_{fi}(x) ,$$

$$T_p = T_{pi}(x) ,$$

$$T_s = T_{si}(x) ,$$

where T_{fi}, T_{pi}, and T_{si} are known functions of x and r. For the coil to start operating, T_{fi}, T_{pi}, and T_{si} can be easily calculated by the Kusuda and Achenbach correlation,[16] or they can be determined by the known ground temperature profile.

Fluid inlet conditions:

$$T_f(t, x = 0) = T_{f0} ,$$

where T_{f0} is a known function of time, t, which actually represents the heat pump model. For a given water-source heat pump, with known operating conditions and inlet fluid temperature, the exit fluid temperature can be calculated easily from published data on the capacity of the heat pump. Unlike the line-source theory, in which one must specify the strength of the line source, this model needs only the ground-coil inlet fluid temperature as input. It then calculates the amount of energy exchange between the coil and the ground.

The model described so far is for the ground coil with fluid circulation. During the "off" cycle period, the fluid velocity, V, in Eq. 2.1 is zero. Because the heat capacity is very small for the fluid in the coil, Eq. 2.5 can be written in the form

$$T_f = T_p \tag{2.11}$$

at $r = r_0$.

2.3 COMPUTER MODEL

A finite-difference scheme was written to solve the mathematical model for both continuous and cyclic operation. The scheme consists of four simultaneous partial differential equations that describe the temperature distribution in the fluid, pipe, frozen soil region, and nonfrozen soil region and the ice growing rate. These equations are coupled radially by the boundary conditions at the surface interfaces and longitudinally by the flow of the fluid in the ground coil. The computer program uses an explicit solution of a finite-difference approximation to this system of equations to calculate the temperature at fixed nodal points in the fluid, pipe, and nonfrozen ground. Since the interface between frozen and nonfrozen ground is a moving boundary, the nodal points in the frozen soil zone are not fixed with respect to time. A fixed longitudinal spacing of nodes is used, and an unequal spacing of nodes in the nonfrozen ground is permitted. Two time steps are used. The first is quite small and is used for the fluid coil wall and frozen soil region because the wall and iced region usually are very thin. The second time step, which is substantially larger, is used in the nonfrozen soil region.

The output data are the fluid and coil temperatures along the coil, the soil temperatures at nodal points, the energy exchange between the fluid and the coil, the energy flow from the soil to the coil, the radius of the soil frozen region along the coil, and all the input items.

The computer program has been designed to be easy to use and does not require that the user be familiar with the partial differential equations involved. The input data requirements are as follows:

1. the physical properties (density, specific heat, and thermal conductivity) of the materials used for the coil;
2. length and inside and outside diameters of the coil;
3. soil density, specific heat, and thermal conductivity for both frozen and nonfrozen states and moisture content by volume;
4. fluid density, specific heat, flow rate, and convective heat transfer coefficient;

5. number of longitudinal nodes and number and spacing of nodes in the grid for the nonfrozen soil region;
6. heat pump on/off cyclic schedule, which can vary as a function of time; and
7. the quantities used in Kusuda and Achenbach's correlation:[16]
   a. time of year, in hours (January 1, 0 h, is the starting time);
   b. coil burial depth;
   c. yearly average ground surface temperature variation;
   d. the amplitude of the yearly ambient temperature variation; and
   e. the soil phase angle as specified by Eq. 2.10 or the known ground temperature profile at depths over the heat pump operating season.

There are also options that allow a uniform initial temperature distribution in the ground or one that varies in radial direction (still should be axisymmetrical). The user can also specify the inlet water temperature as a function of time. The output from the program consists of a printed summary of the temperature distribution at fixed time intervals and also the sensible and latent capacity of the heat exchanger. Appendix B lists the program and a sample calculation.

2.4 MODEL VALIDATION

The model was used to simulate the field test results provided by Brookhaven National Laboratory (BNL).[14] The fluid and ground temperatures were provided as daily averages. The heat pump total "on" time, daily energy absorbed from the ground, and average daily coil flow rates were also provided.

The following list provides the properties of the coil, soil, and fluid and weather information:

- coil length = 152.5 m (500 ft),
- coil burial depth = 1.2 m (4 ft),
- coil size = 4.09-cm (1.61-in.) ID and 4.65-cm (1.83-in.) OD,
- coil material = medium-density polyethylene,
- coil thermal conductivity = 0.46 W/(m·°C) [0.266 Btu/(h·ft·°F)],
- coil specific heat = 2174 J/(kg·K) [0.52 Btu/(lb·°F)],
- fluid = water-ethylene glycol (20% by weight) mixture,
- soil type = sandy with 10% moisture content by volume,
- soil thermal conductivity = 1.731 W/(m·°C) [1 Btu/(h·ft·°F)],
- soil thermal diffusivity = 0.0036 m^2/h (0.03875 ft^2/h),
- flow rate = 0.927 m^3/h (4.081 gpm) average during "on" time,
- yearly average temperature, TA = 10.232°C (50.42°F),
- amplitude of yearly temperature variation, DT = 12.759°C (22.97°F), and
- phase angle, ϕ = 0.352 radian.

The thermal properties of the fluid were taken from the *ASHRAE Handbook*.[28] The farfield temperature was allowed to vary as indicated by Kusuda and Achenbach's correlation (Eq. 2.10). The ground-coil inlet fluid temperature from the test data was an

input to the computer code. The calculation of N_{Nu} (calculation of h) is discussed in App. A.

The computer simulation started on November 26, which was the starting day of the heating season. The ground-coil and fluid temperatures were assumed to be initially uniform and equal to the farfield temperature. A total of 48 days was simulated. Since only the fraction of "on" time per day was given, the computer code was set up to run with the same fraction of "on" time hourly for each day simulated.

Figure 2 shows the comparison of calculated and experimental results for 48 days of daily total energy absorption from the ground. The model predicts the test results very well.

Figure 3 shows the calculated frozen soil thickness along the coil at the end of the 46th, 47th, and 48th days. More than 13 cm (5 in.) of frozen soil had built up at the ground-coil inlet. However, even after 48 days of cyclic operation, 30 m (100 ft) of coil

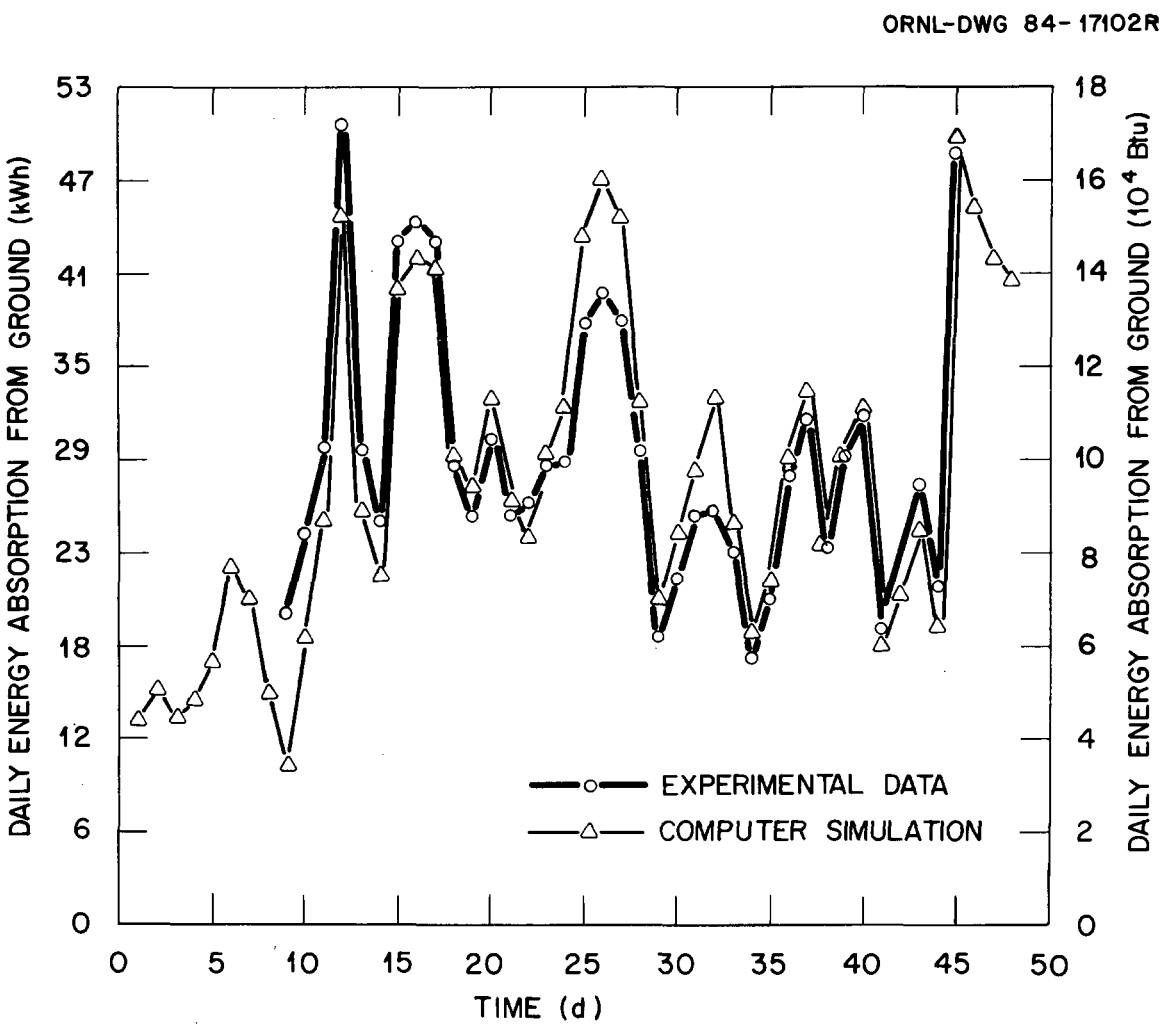

Fig. 2. Comparison between calculated and field experimental results for ground-coil daily energy absorption.

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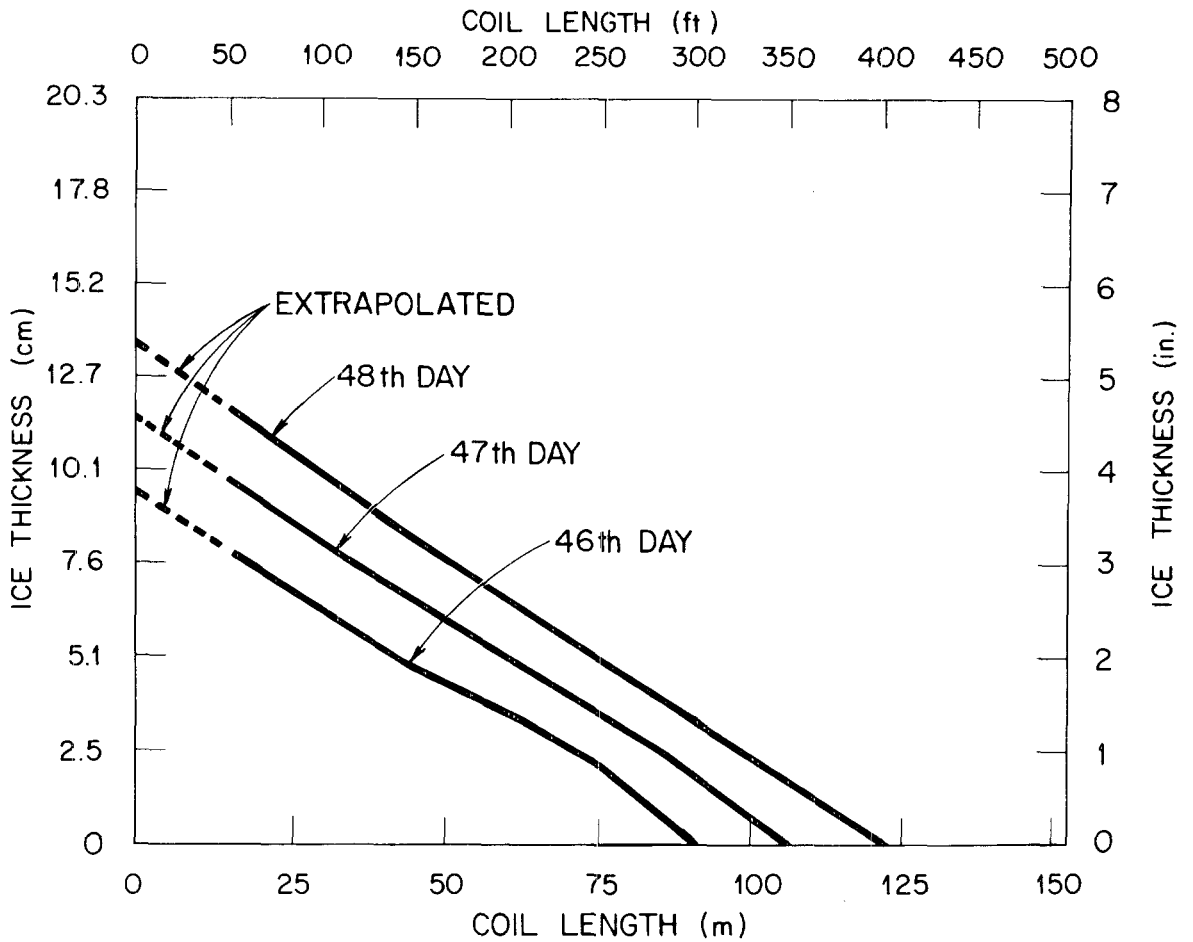

Fig. 3. Calculated frozen soil region along coil.

remained ice free. The calculated results indicate that the amount of latent heat released for this particular experiment was only 2.2% of the total energy absorbed from the ground. Although the results shown in Fig. 3 cannot be validated against the field experimental data because of the lack of soil freezing information, they did demonstrate the capability of the model.

2.5 PARAMETRIC STUDIES

Because this model was designed to check the effect of soil freezing around the coil, the only parameter to be studied was the fluid inlet temperature.

As a basis for comparison, a base run was completed with the following material and operating conditions:

1. 10-h continuous operation;
2. 2.5-cm (1-in.) nominal size high-density polyethylene pipe;

3. 91.4-m (300-ft) coil length;
4. 2.27-m^3/h (10-gpm) flow rate;
5. mixture of water and 20% ethylene glycol by weight for the fluid;
6. 18.3% moisture content by total soil weight, with 1.03 W/(m·°C) [K = 0.596 Btu/(h·ft·°F)] in the nonfrozen soil region and 1.56 W/(m·°C) [2.7 Btu/(h·ft·°F)] in the frozen region (these are the thermal conductivity readings for Northway silt loam);[29]
7. −3.2°C (26.3°F) inlet fluid temperature and 3.8°C (38.8°F) farfield and initial ground temperatures; and
8. 1.22-m (4-ft) farfield radius.

Figure 4 shows the effect of inlet fluid temperature. When the inlet fluid temperature is lowered to −12.2°C (10°F), the total energy absorbed by the lower inlet fluid

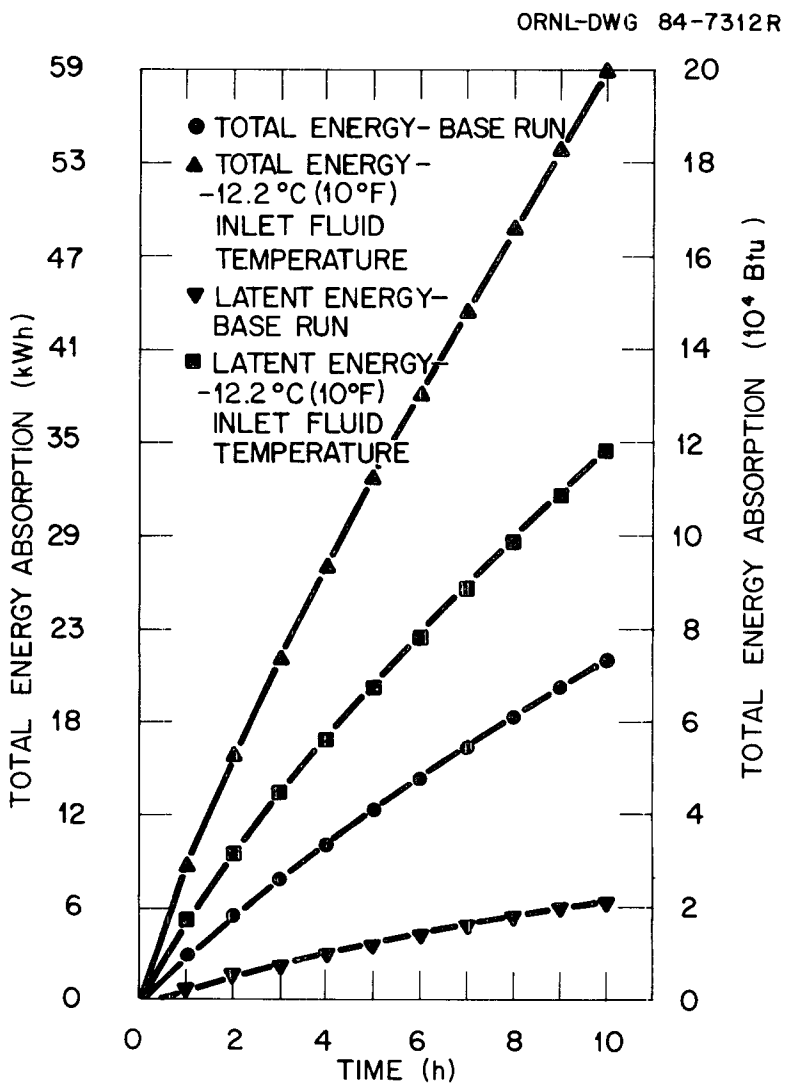

Fig. 4. Effect of coil fluid inlet temperature on ground-coil performance.

temperature case is 2.7 times higher. At the base inlet temperature of −3.2°C (26.3°F), the latent heat due to phase change is 30.6% of the total energy absorbed. However, when the inlet fluid temperature is lowered to −12.2°C (10°F), the latent heat absorbed increases to 63.9%. In other words, the increase in energy absorbed is due mainly to the increase of latent heat. Since for most ground-coil designs the fluid inlet temperature to the heat pump would not be lower than −4°C (25°F) in order to prevent excessive heat pump capacity and efficiency losses, the effect of icing around the coil would be small. However, the situation might change if a heat pump with high efficiency at a very low inlet fluid temperature were developed.

3. GROUND-COIL MODEL WITH SEASONAL GROUND TEMPERATURE VARIATION AT DEPTHS

3.1 INTRODUCTION

One of the most troublesome problems in ground-coil design is to estimate the effect of seasonal ground temperature variation at various depths. As a result, this important factor has been ignored in most ground-coil models. Metz[15] did include this effect in his model. However, with the ground being divided into different blocks of sizes considerably larger than the coil size, the heat transfer between the coil and the ground was oversimplified. Besides, once the strength of the line source was chosen, the seasonal ground temperature variation affected only the ground temperature distribution and not the amount of energy exchange between the coil and the ground. Common sense tells us that the seasonal ground temperature variation will affect ground-coil performance. The model presented here incorporates this effect as one of the factors affecting ground-coil operation. The difficult part was to set up a farfield boundary condition that was a function of time as well as depth. The ground temperature at depths has been extensively studied.[30–33] Kusuda and Achenbach[16] analyzed a total of 63 sets of data of soil temperature at various depths for a period of one to several years. By modifying the existing theories, they formed their own correlation. Kusuda and Achenbach's correlation only qualitatively predicts the ground temperatures. Nevertheless, for ground-coil design, their correlation is well suited to forming the variable farfield boundary conditions. However, if the ground temperature variation at different depths is known at the coil burial site over the heat pump operating season, it should be used to replace the Kusuda and Achenbach correlation.

The soil freezing effect was not included in this model because soil freezing affects ground-coil performance only slightly. The design will be somewhat conservative if this effect is neglected. Another reason is the difficulty involved in numerically predicting the shape of the soil frozen region, which will not be cylindrical because of the nonsymmetrical boundary conditions. Since the soil thermal properties in frozen and nonfrozen regions are usually not equal to each other, the irregular soil freezing front, which is a moving boundary, is very difficult to determine, even numerically.

However, the effect of thermal backfilling material is included in the model. The main advantages of having thermal backfilling are to minimize contact resistance between coil and soil, to maintain a high thermal conductivity value even at very dry ground conditions, and to reduce the effect of moisture migration due to decreased heat flux.

The model was solved numerically and was validated by field experimental data provided by BNL[14] for winter operation and by The University of Tennessee (UT)[34] for summer operation. It was found for the UT test data that the soil moisture migration for summer coil operation does not become serious until near the end of cooling season.[34]

Since the validation was for the months of June and July 1984, the effect of moisture migration should be negligible, and thus the field experimental results could be used for computer simulation.

The model is based on the same assumptions mentioned in Sect. 2.1 except that the heat transfer is no longer radially symmetrical. However, it is assumed that the heat transfer up to the coil outside wall is radially symmetrical. Since the coil diameter is usually not more than 5 cm (2 in.) and the wall thickness is not more than 0.35 cm (0.14 in.), this assumption will probably cause only a small error in the calculated ground-coil performance.

3.2 THEORETICAL DEVELOPMENT

With the above assumptions, the following equations can be derived for the system shown in Fig. 5.

Heat exchange between the fluid and coil inside wall:

$$-V\frac{\partial T_f}{\partial x} + \frac{2K_p}{r_0 \rho_f C_f}\frac{\partial Tp}{\partial r}\Big|_{r_0} = \frac{\partial T_f}{\partial t} \quad , \tag{3.1}$$

where conductive heat transfer in fluid is neglected.

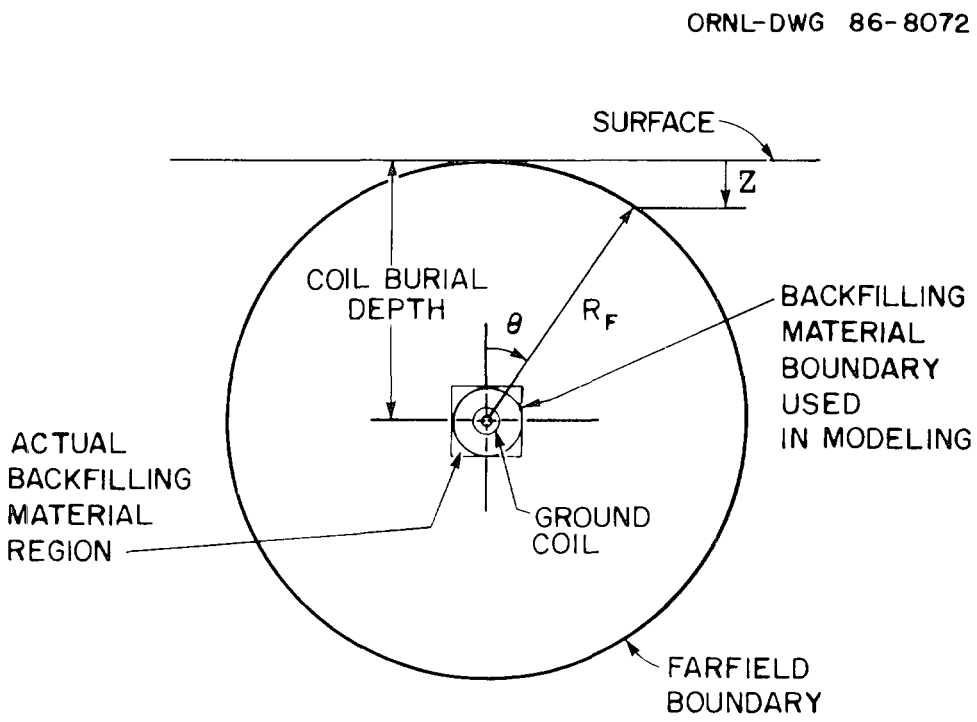

Fig. 5. Schematic of ground coil for the ground-coil model with seasonal ground temperature variation at depths.

Heat transfer in the coil wall:

$$\frac{\partial^2 T_p}{\partial r^2} + \frac{1}{r}\frac{\partial T_p}{\partial r} = \frac{1}{\alpha_p}\frac{\partial T_p}{\partial t} \qquad (r_0 \leqslant r \leqslant r_1) \ . \tag{3.2}$$

Heat transfer in the backfilled zone:

$$\frac{\partial^2 T_b}{\partial r^2} + \frac{1}{r}\frac{\partial T_b}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T_b}{\partial \theta^2} = \frac{1}{\alpha_b}\frac{\partial T_b}{\partial t} \ . \tag{3.3}$$

Heat transfer in the soil:

$$\frac{\partial^2 T_s}{\partial r^2} + \frac{1}{r}\frac{\partial T_s}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T_s}{\partial \theta^2} = \frac{1}{\alpha_s}\frac{\partial T_s}{\partial t} \ , \tag{3.4}$$

where heat transfer along the coil (x direction) in Eqs. 3.2 through 3.4 is neglected because of the low thermal conductivity values of the plastic coil and the soil and the long distance in the x direction.

Boundary conditions:

At $r = r_0$,

$$h(T_p - T_f)|_{r_0} = K_p \frac{\partial T_p}{\partial r}|_{r_0} \ . \tag{3.5}$$

At $r = r_1$,

$$T_b = T_p \ . \tag{3.6}$$

Equation 3.6 is acceptable for coil winter operation where no contact resistance between the soil and the coil exists.

$$2\pi K_p \frac{\partial T_p}{\partial r}|_{r_1} = K_s \int_0^{2\pi} \frac{\partial T_b}{\partial r}|_{r_1} d\theta \ . \tag{3.7}$$

At $r = r_2$,

$$T_s = T_b \ . \tag{3.8}$$

$$K_b \frac{\partial T_b}{\partial r}|_{r_2,\theta} = K_s \frac{\partial T_s}{\partial r}|_{r_2,\theta} \ . \tag{3.9}$$

At $r = r_F$,

$$T_{sF} = TA - DT \times \exp\left(-z\sqrt{\frac{\pi}{8766\alpha_s}}\right)$$

$$\times \cos\left(\frac{2\pi t_0}{8766} - \phi - z\sqrt{\frac{\pi}{8766\alpha_s}}\right) , \tag{3.10}$$

where Eq. 3.10 is the correlation of Kusuda and Achenbach[16] and ϕ is the phase angle of the earth temperature cycle, below grade, in radians. Equation 3.10 should be replaced by the known ground temperature profile at depths, if such data exist.

Initial conditions ($t = 0$) are

$$\begin{aligned} T_f &= T_{fi}(x) , \\ T_p &= T_{pi}(x,r) , \\ T_b &= T_{bi}(x,r,\theta) , \\ T_s &= T_{si}(x,r,\theta) , \end{aligned} \tag{3.11}$$

where T_{fi}, T_{pi}, T_{bi}, and T_{si} are known functions of x, r, and θ. For the coil to start operating, T_{fi}, T_{pi}, T_{bi}, and T_{si} can be easily calculated by Eq. 3.10 or can be easily determined from the ground temperature profile at depths if it is available.

The fluid inlet condition is

$$T_f(t,x = 0) = T_{f0}(t) , \tag{3.12}$$

where $T_{f0}(t)$ is a known function of time, t, which represents the heat pump operation, as described in Sect. 2.2.

The model described so far is for the ground coil with fluid circulation. During the "off" cycle period, the fluid velocity, V, in Eq. 3.1 is zero. Since the thermal capacity of the fluid is small, Eq. 3.5 can be written in the form

$$T_f = T_p . \tag{3.13}$$

3.3 COMPUTER MODEL

The computer code is similar to the one described in Sect. 2.3, except for the input of the spacing in the angular direction.

Output from the program consists of a printed summary of a nonradially symmetrical ground temperature profile at fixed time intervals and the capacity of the heat exchanger coil.

3.4 MODEL VALIDATION

3.4.1 Winter Operation

The model was used to simulate the field test results provided by BNL.[14] The fluid and ground temperatures were provided as daily averages, along with the heat pump total "on" time, daily energy absorbed from the ground, and coil flow rates.

Properties of the coil, soil, and fluid are the same as those in Sect. 2.4.

The convective heat transfer coefficient between fluid and wall was calculated. App. A shows the calculation of N_{Nu}.

Forty-four days were simulated, starting on day number 329 (November 26, 1981), the day the heating season really began. Since only the fraction of "on" time per day was given in the experimental data, the computer code was set up to run the same fraction of "on" time per hour.

Figure 6 shows the simulation of the daily energy absorbed from the ground. The simulation had to begin on the same day the heat pump started operating because the past coil operating history was important to coil performance. After the first nine days, the

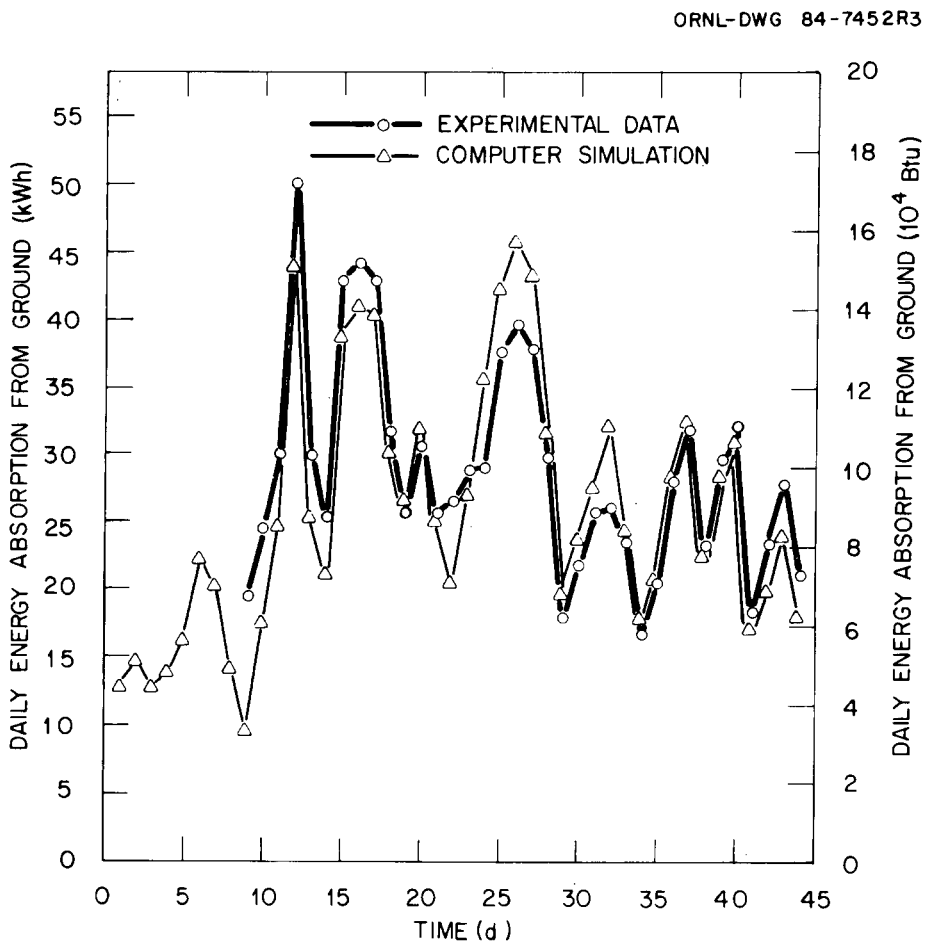

Fig. 6. Simulation of daily energy absorption.

computer code predicted field experimental results very well. Figure 7 shows the simulation of the coil exit fluid temperature during the "off" cycle period. The simulation indicated the same trend as the data, but the computer-calculated values were for the most part about 1°C (1.8°F) higher than the test results. There are two reasonable explanations: (1) The boundary condition when fluid is stopped, Eq. 3.13, incorrectly forces the fluid temperature to equal the coil inside wall temperature; and (2) the exact cycling schedule was not given, which is an important factor in determining the fluid temperature. Detailed analysis of boundary conditions when fluid flow stops involves natural convection in a long horizontal coil. Because the model predicted the daily energy absorption from the ground well, which is most important in designing the ground coil, further analysis of the heat transfer problem during the heat pump "off" cycle was not warranted for this study.

Figure 8 shows the calculated ground temperature distribution after 42 days of simulation. Although no experimental data are provided for comparison, the figure represents a very realistic ground temperature distribution because it is similar to the temperatures measured by Smith[35] and by Johnson et al.[36]

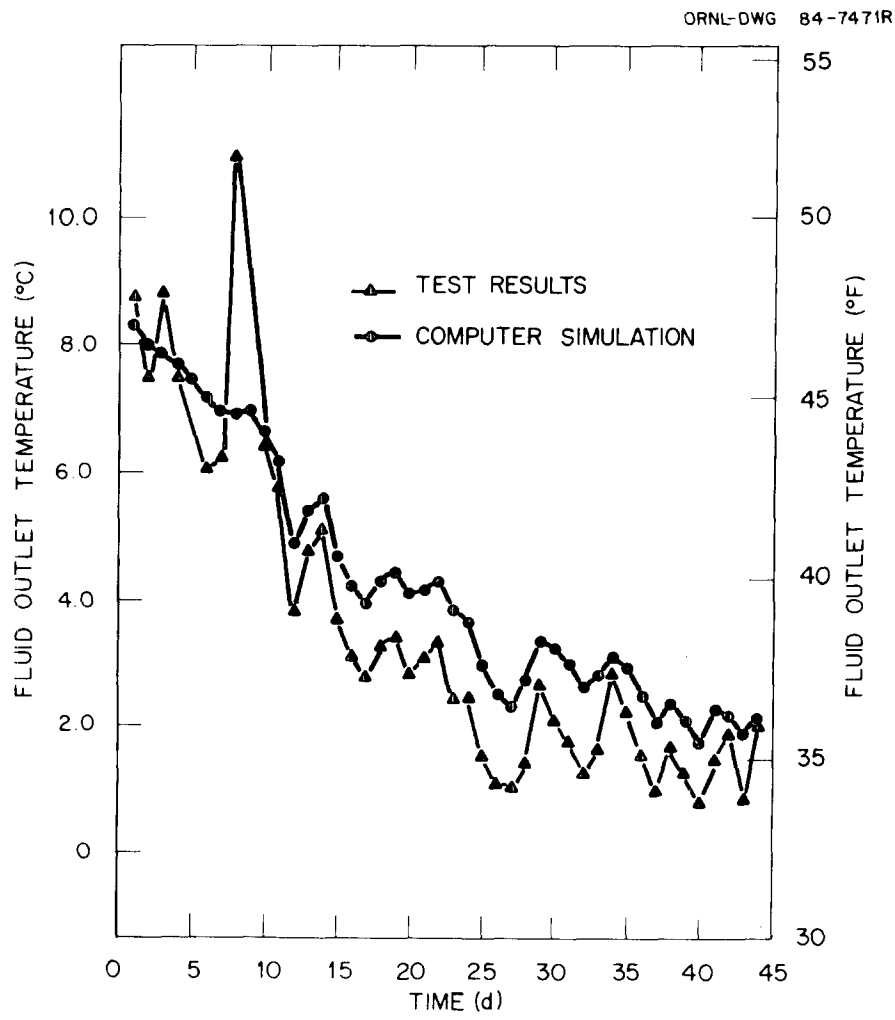

Fig. 7. Simulation of ground-coil fluid temperature at coil exit.

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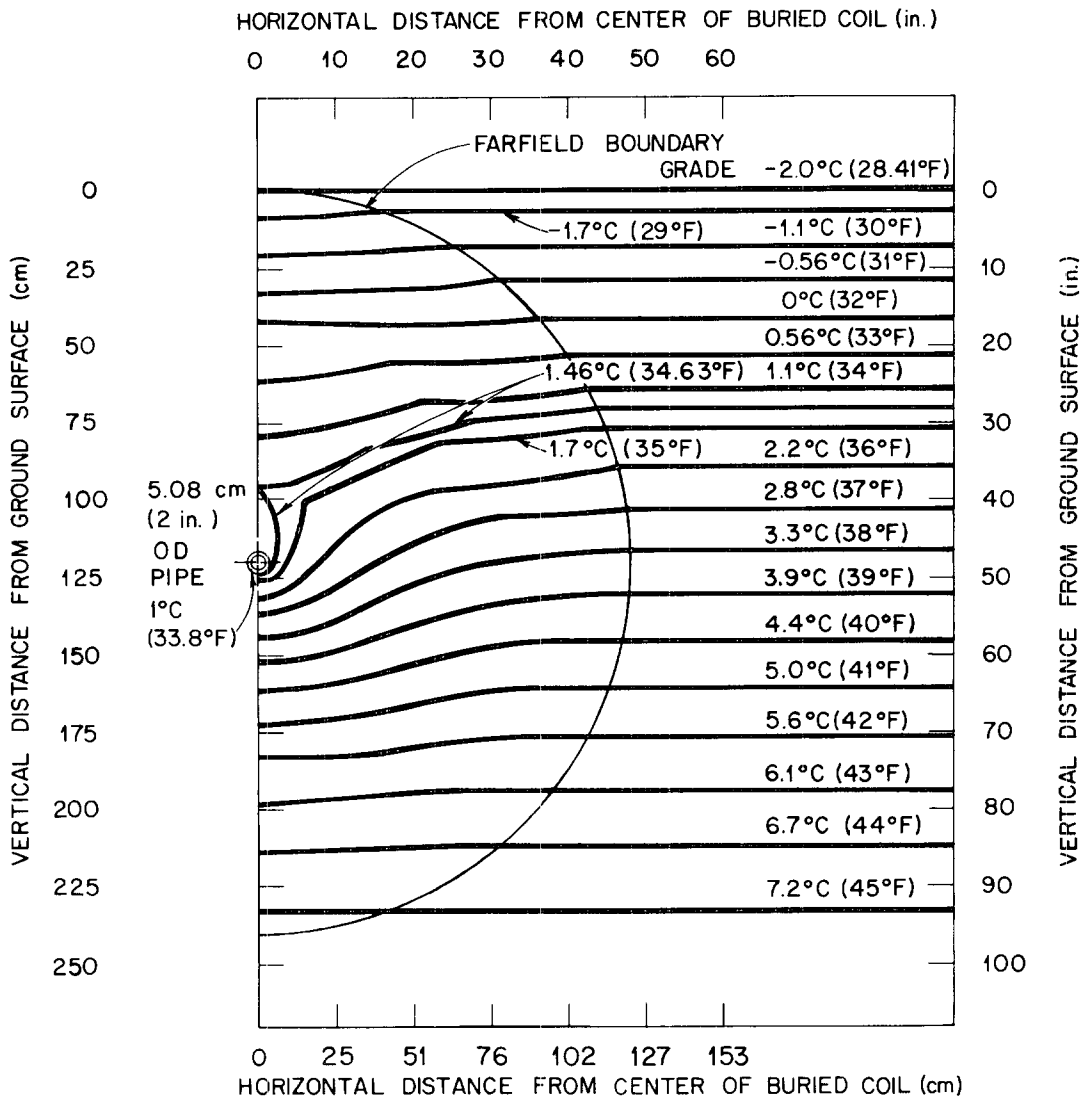

Fig. 8. Calculated ground temperature distribution around coil.

3.4.2 Summer Operation

The model was used to simulate the field test results collected for UT's TECH site ground-coil experiment.[34] Heat pump hourly fraction of "on" time was determined by the fraction of compressor power consumption in the hour divided by compressor power consumption at steady-state operation. Hourly ground-coil inlet fluid temperature was provided as an input item to the computer code. A total period of 32 days was simulated.

Properties of the coil, soil, and fluid were as follows:

- coil length = 213 m (700 ft),
- coil burial depth = 1.2 m (4 ft),

- coil size = 3.5 cm (1.38 in.) ID and 4.22 cm (1.66 in.) OD,
- coil material = high-density polyethylene,
- coil thermal activity = 0.46 W/(m·°C) [0.266 Btu/(h·ft·°F)],
- coil specific heat = 2174 J/(kg·°C) [0.52 Btu/(lb·°F)],
- fluid = water–methanol (20% by weight) mixture,
- thermal conductivity of fluid = 0.351 W/(m·K) [0.203 Btu/(h·ft·°F)],
- specific heat of fluid = 4109 J/(kg·°F) [0.982 Btu/(lb·°F)],
- soil type = partially saturated clay,
- soil thermal conductivity = 0.5624 W/(m·K) [0.325 Btu/(h·ft·°F)],
- soil thermal diffusivity = 0.002226 m^2/h (0.02396 ft^2/h),
- flow rate = 1.915 m^3/h (8.43 gpm),
- yearly average temperature, TA = 15.6°C (60°F),
- amplitude of yearly temperature variation, DT = 11.1°C (20°F), and
- phase angle, ϕ = 0.44.

The thermal properties of the fluid (thermal conductivity, viscosity, density, and specific heat) were taken from the International Critical Tables.[37] At 38°C (100°F), N_{Re} is equal to 18,957, which is in the turbulent region, and N_{Pr} = 11.85. The N_{Nu} was then calculated from the following formula (see App. A):

$$N_{Nu} = 0.0155 N_{Pr}^{0.5} N_{Re}^{0.83} \quad . \tag{3.14}$$

A value of N_{Nu} equal to 189 was used throughout the analysis, during the heat pump "on" period.

The farfield ground temperature at depths calculated by Kusuda and Achenbach's correlation[16] was too low compared with the experimental data. The amplitude of the annual temperature variation was increased by 8.3°C (15°F) and the time of the year was also changed from 3744 to 4350 (t_0 in Eq. 3.10) in order to better match the calculated and measured temperatures over the simulated period.

Figure 9 shows the comparison of daily energy exchange between coil and ground. The calculated results slightly underpredict the experimental data, particularly in times where heat pump "on" time was long. Because the trench was backfilled with sand around the coil to eliminate the contact resistance between the coil and the soil, the thermal conductivity of sand should be programmed into the computer code. For simplicity, only the thermal conductivity of clay was accounted for. This partly explains why the code underpredicted the test results, because the thermal conductivity of sand is much higher than that of clay.[34] However, when the effect of sand is included, it can be seen from Fig. 9 that the prediction is improved, except for the first eight days. This is because the UT ground coil had been operated for some time, whereas the computer simulation assumed that the coil had just started operating.

Figure 10 shows the simulation of ground-coil fluid outlet temperatures. The model almost matched the measured temperatures exactly when the heat pump was on. However, there was considerable deviation when the heat pump was cycled off. If was found that the ground-coil exit fluid temperature was measured inside the house and thus approached room temperature during the "off" period, while the model assumed that the entire coil was underground and that the fluid approached the ground temperature.

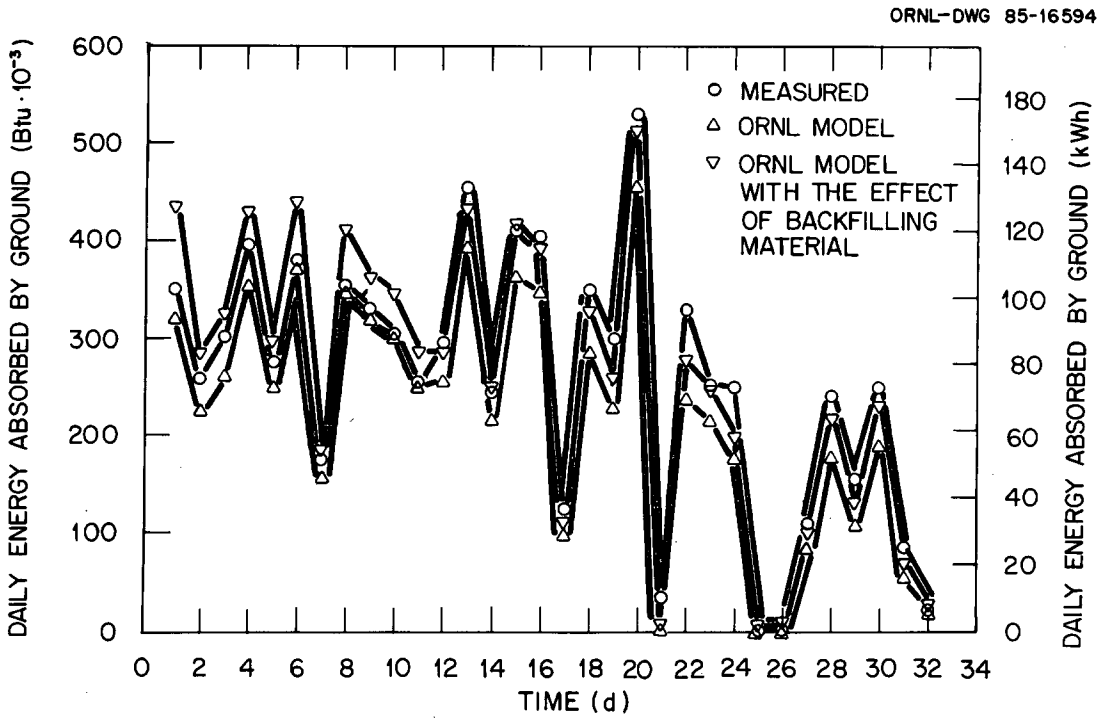

Fig. 9. Comparison of measured and calculated daily energy exchanged between coil and ground.

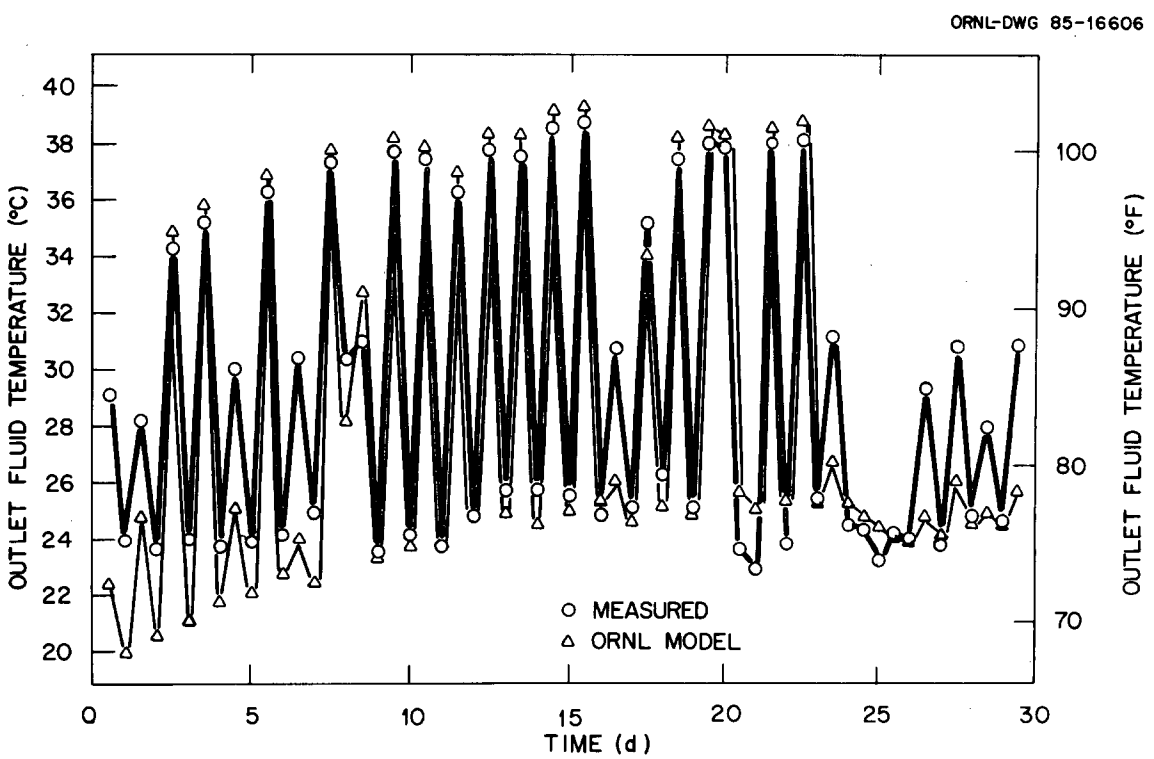

Fig. 10. Comparison of measured and calculated ground-coil exit fluid temperatures.

3.5 PARAMETRIC STUDIES

For comparison, a base run was made with 15-day continuous operation and a fluid inlet temperature of 0°C (32°F). Because this model is basically for ground-coil winter operation, all the other operating conditions and the fluid and coil material properties, size, and length were the same as those of the BNL data indicated in Sect. 3.4.1.

Figure 11 shows the effect of soil thermal conductivity, K_s. When K_s was reduced by 50%, the total energy absorbed from the ground was decreased by 23%. When K_s was doubled, a 20% increase in energy absorption was achieved. Although this parameter generally is not adjustable, it must be defined first.

Figure 12 shows the effect of ground-coil wall thermal conductivity, K_p. When K_p was reduced from 0.46 W/(m·°C) [0.266 Btu/(h·ft·°F)] (base case) to 0.189 W/(m·°C) [0.109 Btu/(h·ft·°F)] [the thermal conductivity of polyvinyl chloride (PVC)], the ground-coil capacity was reduced by 12.3%. When a thin-wall metal coil was assumed, the coil performance increased by 7.7%. Past experience indicates that copper coil joints, in

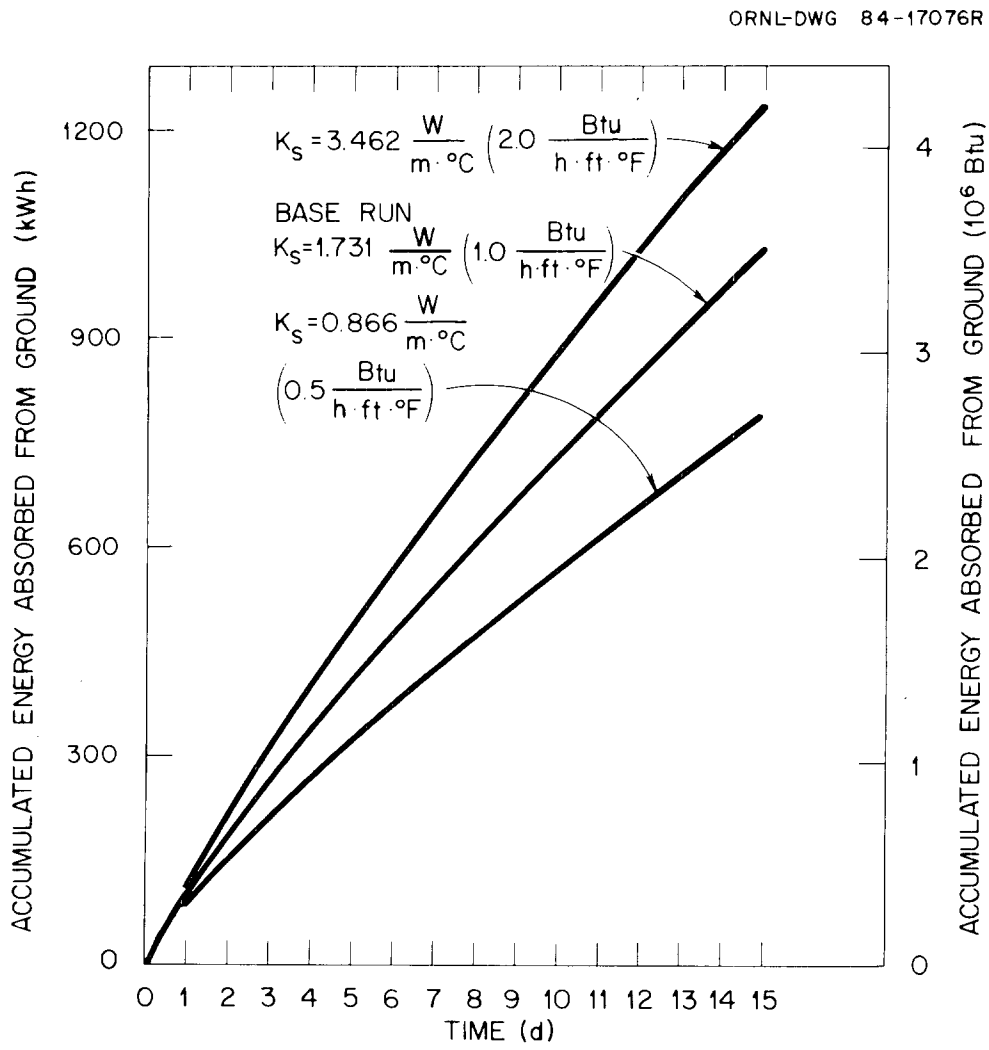

Fig. 11. Effect of soil thermal conductivity, K_s, on total energy absorption.

addition to being more costly, are difficult to solder and often become a source of fluid leakage. In contrast, high-density polyethylene pipe (or polybutylene pipe) is very flexible, easy to weld, and costs much less.

Figure 13 shows the effect of coil length. When the coil length was reduced by 50% from 152.4 to 76.2 m (500 to 250 ft), the coil capacity dropped 44.5%. When the length was increased by 50% to 228.6 m (750 ft), the coil capacity increased 31%. These figures indicate that the coil length is a very important factor to be considered in design.

Figure 14 shows the effect of coil burial depth. The deeper the burial depth, the less fluctuation occurs in the surrounding soil temperature and the better the coil performs. When the coil burial depth is increased from 1.22 m to 1.52 and 1.83 m (4 to 5 and 6 ft), the coil capacity increases 13.1% and 23.4%, respectively.

Figure 15 shows the effect of three backfilling materials: clay, sand, and a fluidized mixture {K = 3.334 W/(m·K) [1.926 Btu/(h·ft·°F)]}. It can be seen that for a period of 32 days, the fluidized mixture exchanged 47% more energy than the clay backfill and 23% more than the sand.

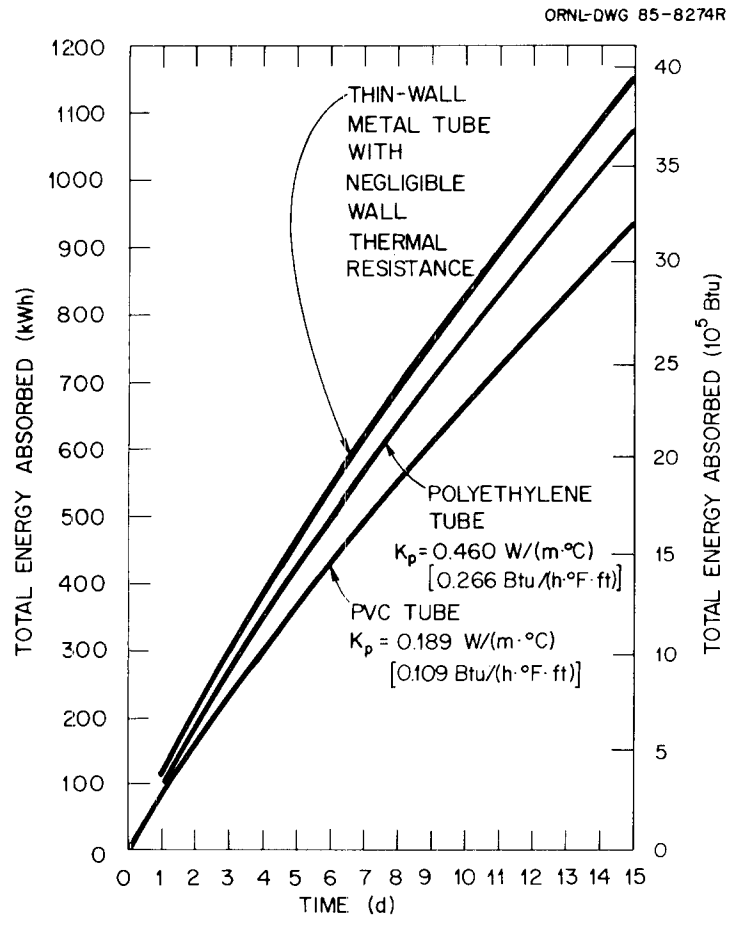

Fig. 12. Effect of coil wall material on total energy absorption.

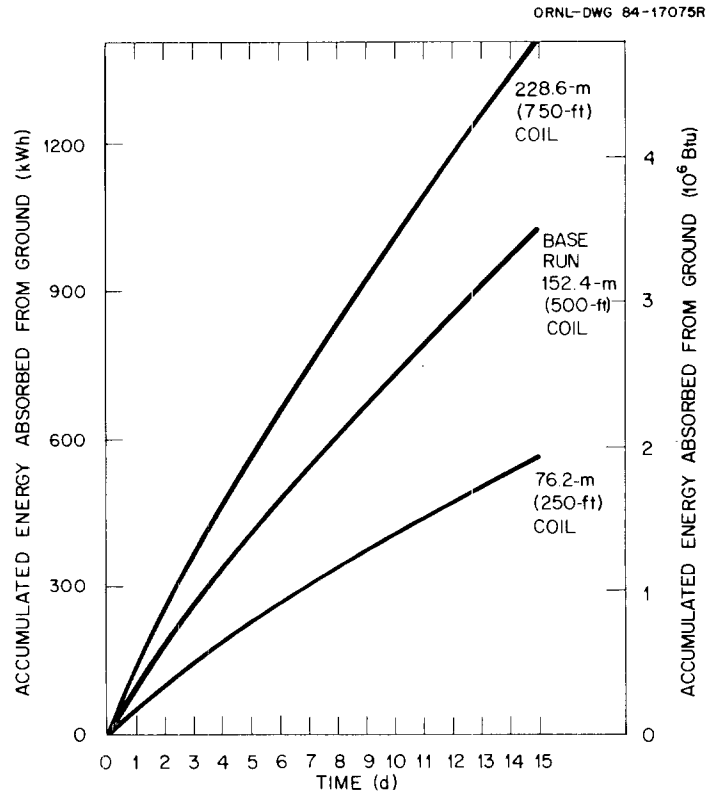

Fig. 13. Effect of coil length on total energy absorption.

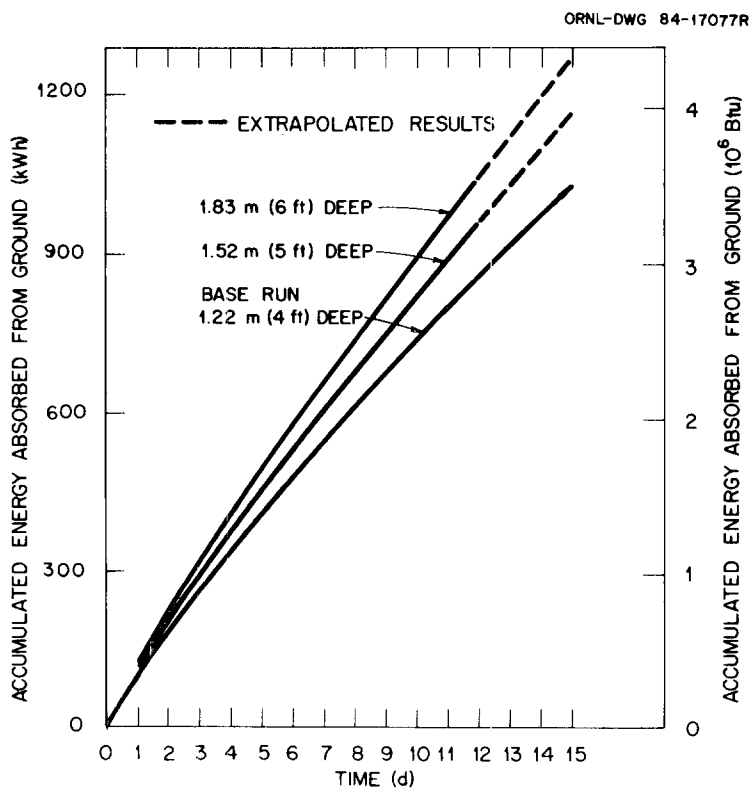

Fig. 14. Effect of coil burial depth on total energy absorption.

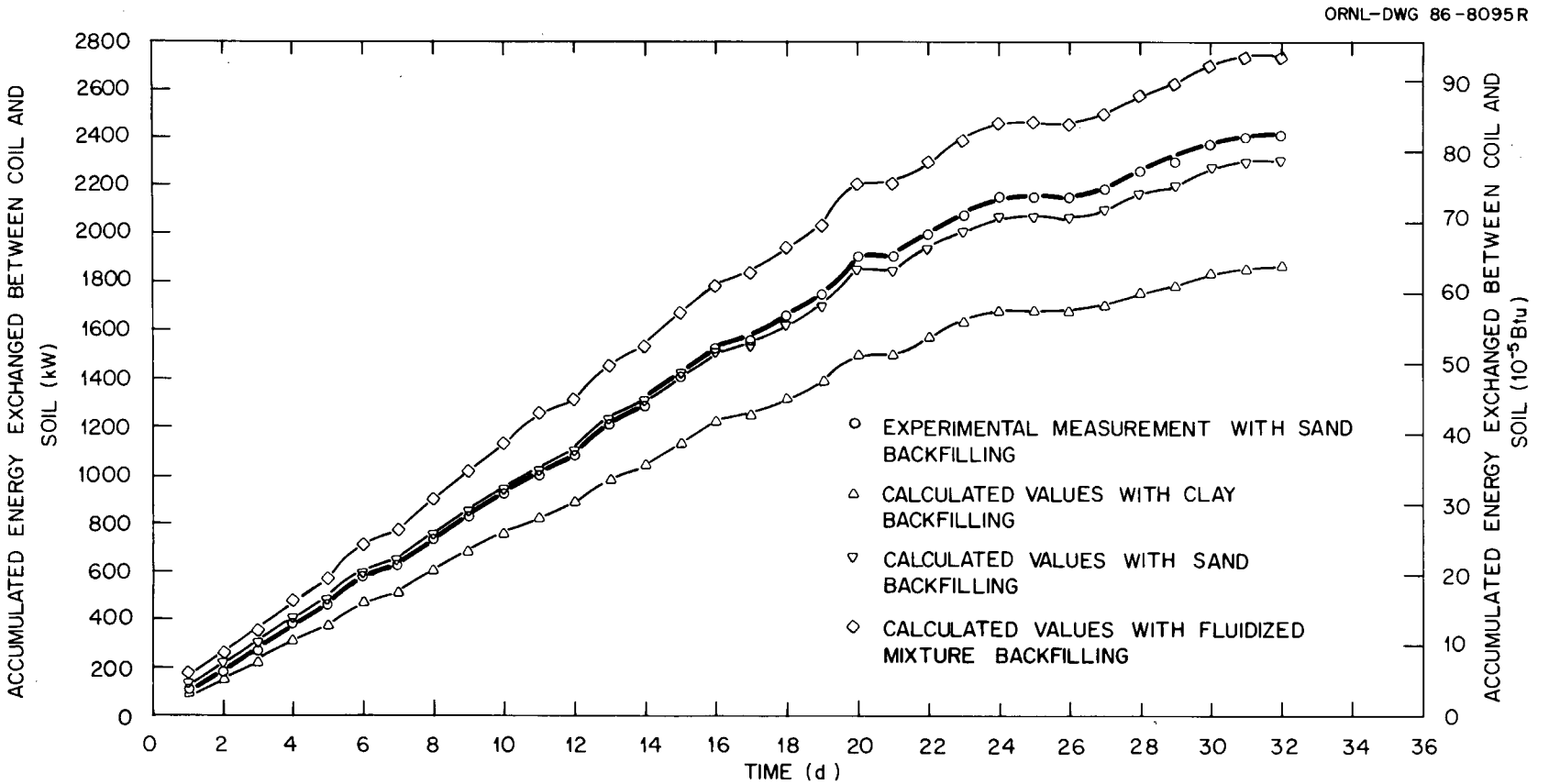

Fig. 15. Accumulated energy exchange between coil and soil for three different types of backfilling materials.

4. COMPARISON OF GROUND-COIL MODELS

Many ground-coil models available today are based on line-source theory. The ORNL models are probably the first ones to explain ground-coil operation in mathematical detail. Therefore, it was interesting to compare our model with others by simulating the same field experiments performed by BNL and UT.

Three models were selected for comparison: (1) the ORNL model with seasonal ground temperature variation, (2) the BNL model with a modified line-source approach,[15] and (3) a simple line-source model.[17] For the BNL and simple line-source models, other than ground and coil properties, the heat exchange rate between the coil and the soil from the experiment was treated as an input item. In addition, the BNL model also required the coil burial depth, the number of coil parallel legs, the heat pump cycling schedule, and the variable farfield boundary conditions. The input for the ORNL model was described in detail in Sect. 2.4.

For simple line-source application, the only item that can be compared is the soil temperatures at different distance away from the coil center. For the BNL model, fluid inlet and exit temperatures can also be checked.

4.1 SIMULATION OF WINTER OPERATION

All three models were used to simulate the BNL field experimental data[14] for a period of 43 days.

Figure 16 compares the soil temperature profile at coil burial depth as calculated by the three models. The line-source model predicts a somewhat lower temperature profile than the ORNL and BNL models. However, no experimental data were available for comparison, except the measured farfield temperature, which was somewhat higher than the calculated farfield temperatures. Because Kusuda and Achenbach's correlation[16] does not predict the daily farfield ground temperature fluctuation, it is not surprising to have this kind of temperature deviation.

Figure 17 compares the calculated coil fluid inlet temperatures, as determined by the BNL model, with the measured ones. The BNL model closely predicts the fluid inlet temperature, partly because the exact energy exchange between the coil and the ground is input from the experimental data to the BNL model. For the ORNL model, the fluid inlet temperature is an input item.

Figure 18 compares the calculated ground-coil exit fluid temperatures with the experimental data. The ORNL model slightly overpredicts and the BNL model underpredicts the test results. However, if we observe the exit and inlet fluid temperature difference, the ORNL model's calculation is closer to the experimental data than the BNL model's.

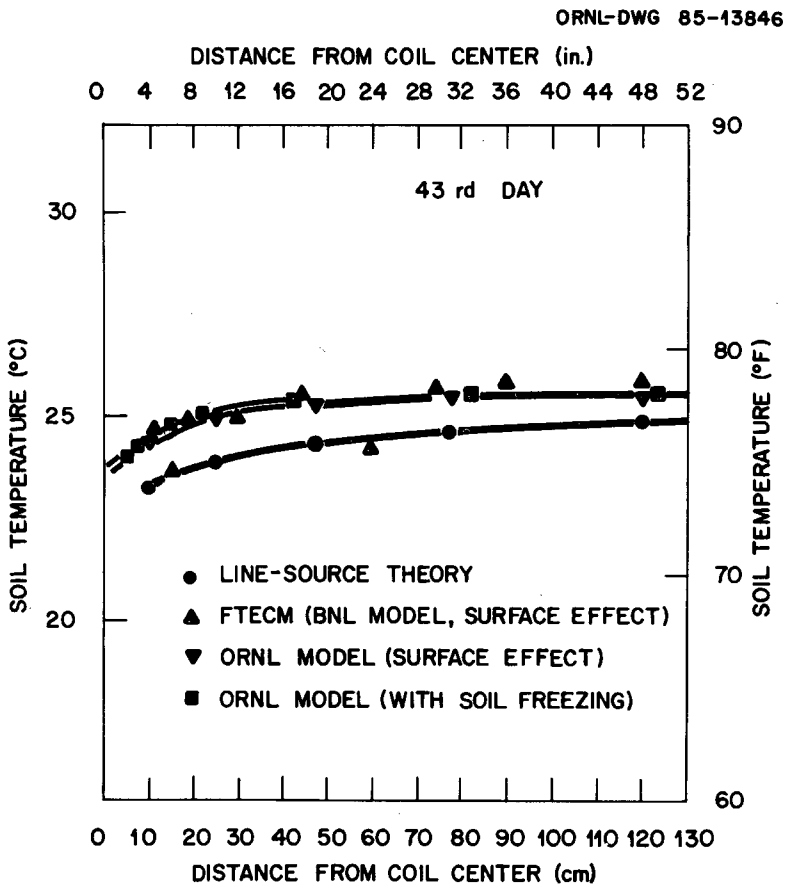

Fig. 16. Comparison of the soil temperature profile as calculated by different ground-coil models.

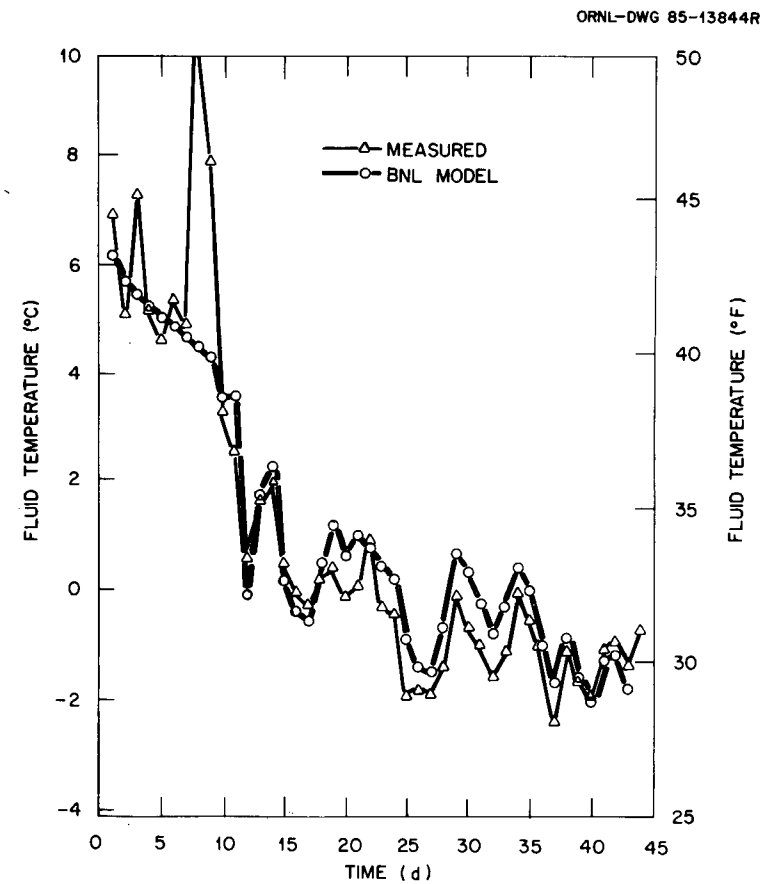

Fig. 17. Comparison of measured fluid inlet temperatures with those calculated by the BNL model.

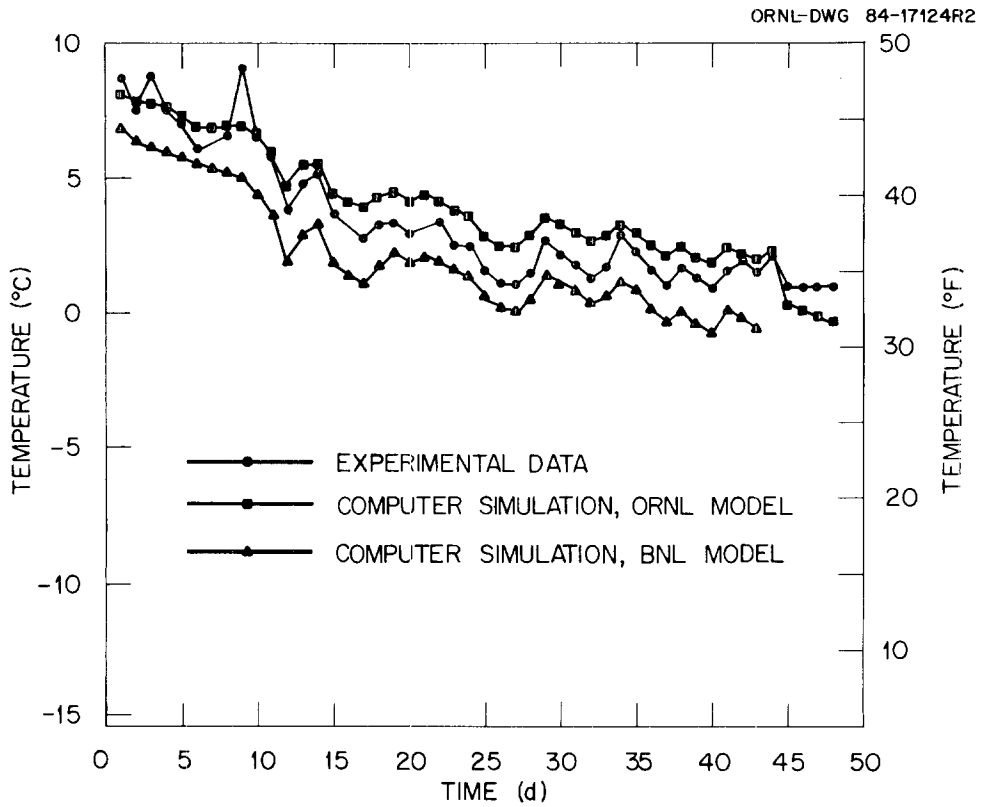

Fig. 18. Comparison of measured and calculated ground-coil fluid exit temperatures.

4.2 SIMULATION OF SUMMER OPERATION

All three models were used to simulate the UT summer field experiment.[34]

Figure 19 shows soil temperature as calculated by the three models compared with measured values at a 7.62-cm (3-in.) distance from the coil wall at the midpoint of the coil. It can be seen that all three models underpredict the experimental results. One reason for this discrepancy is that the coil was backfilled with sand to eliminate the possible contact resistance. At the beginning of the cooling season, the measured thermal conductivity of sand is much higher than that of clay.[34] Taking the sand into account in the ORNL model, the prediction is much closer to the test results. However, for the line-source and BNL models, it is not very easy to add the effect of sand backfilling into the models.

Figure 20 shows the fluid inlet temperature simulation by the BNL model. Again, the match is very good. This fluid inlet temperature is an input item in the ORNL model.

Figure 21 compares the fluid exit temperatures as calculated by the ORNL and BNL models with the measured ones. The ORNL model results match the fluid exit temperatures almost exactly when the heat pump is on. When the heat pump cycles off, both the BNL and ORNL models underpredict the test data because the coil fluid exit temperature was measured indoors and thus approached house indoor temperatures during off periods.

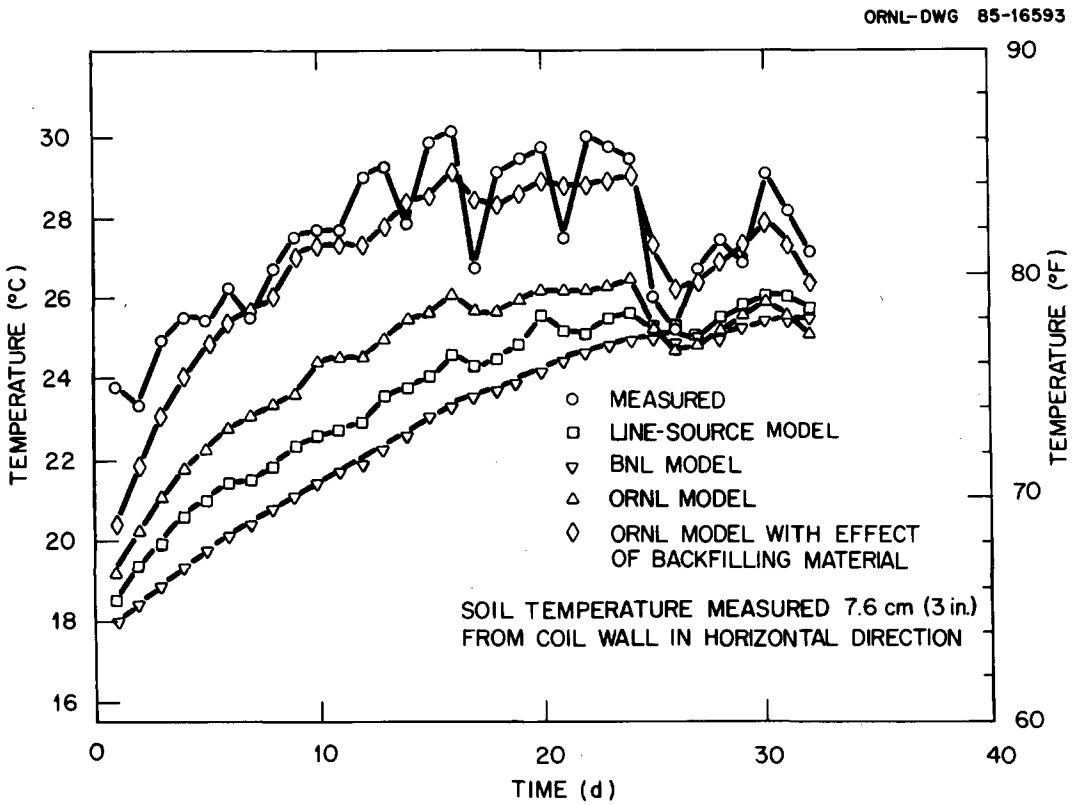

Fig. 19. Comparison of measured soil temperatures with those calculated by the line-source model, the BNL model, and the ORNL model (both with and without the effect of the backfilling material).

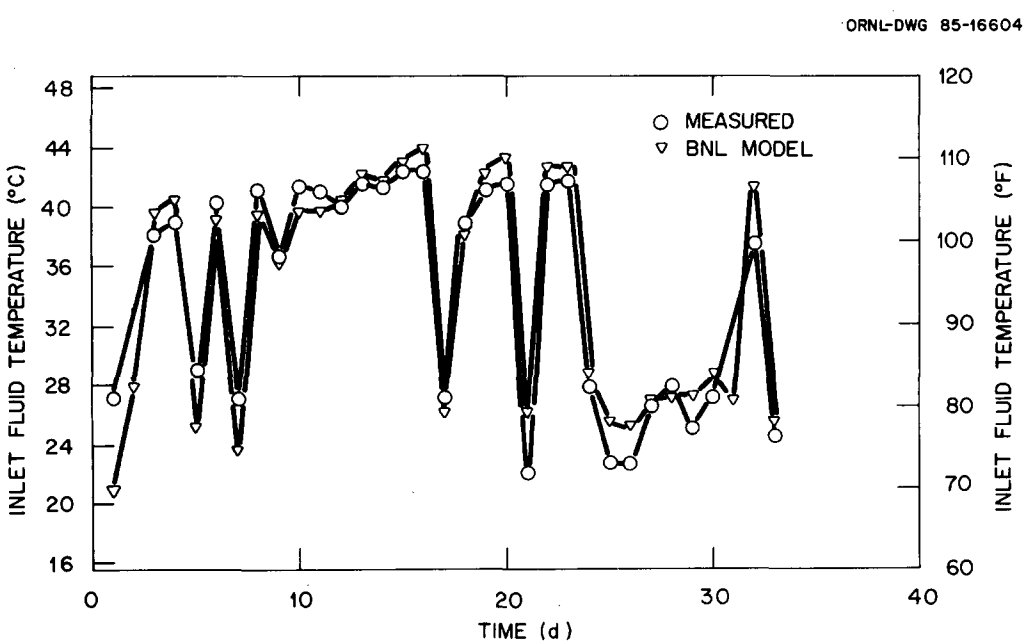

Fig. 20. Comparison of measured fluid inlet temperatures with those calculated by the BNL model.

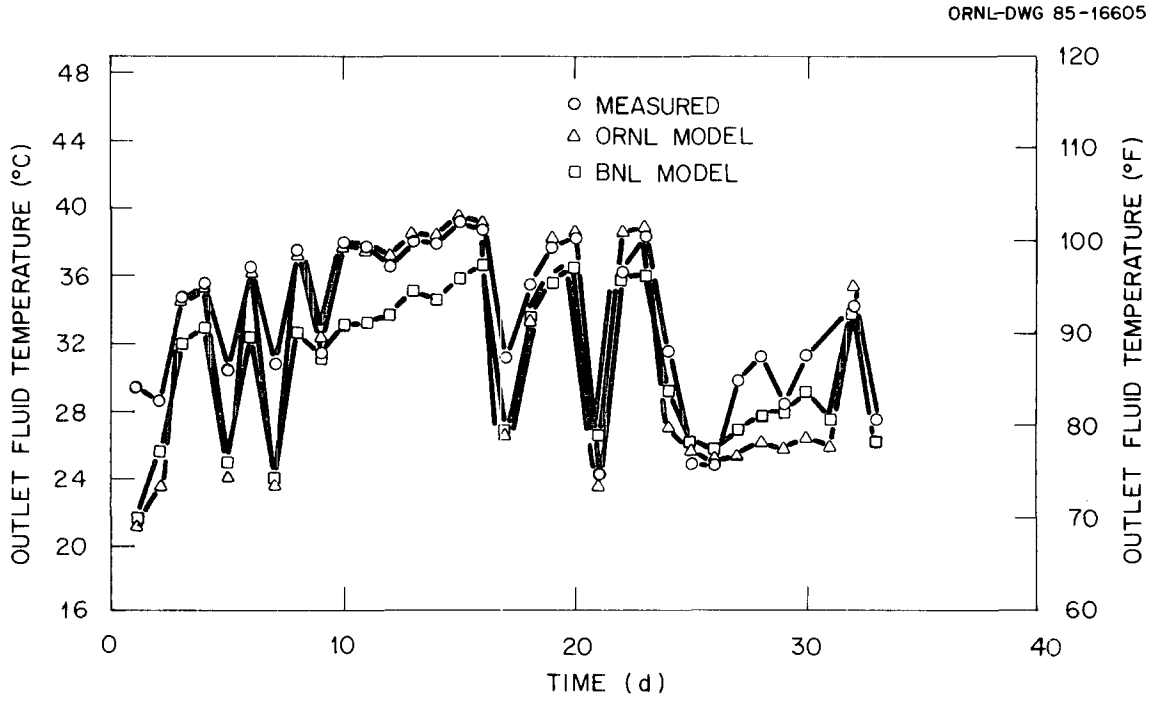

Fig. 21. Comparison of measured fluid outlet temperatures with those calculated by the ORNL and BNL models.

5. GROUND-COIL MODEL WITH THERMAL INTERFERENCE

5.1 INTRODUCTION

Thermal interference problems will occur when ground-coil legs are buried too close to each other. Previously, these types of problems have been treated almost exclusively by superposition of solutions. The mirror-image method is probably the only method used in solving horizontal ground-coil thermal interference problems.[19] However, the assumptions used for mirror-image application are somewhat questionable: (1) The ground temperature should be uniform initially; (2) the ground surface and farfield temperatures should be kept constant; and (3) the strength of each coil leg could be different but must be constant along the coil. Although none of these three assumptions is true, this problem has not been studied seriously because, in horizontal ground-coil heat exchanger design, past experience indicates that the effect of thermal interference is a minor one for most designs because of the wide distance between coil legs. However, it has been found that by burying multicoils in the same trench the trenching cost could be cut drastically,[24] thus making horizontal GCHP systems more competitive. For proper design of multiple coils in a single trench for GCHP systems, the thermal interference problem needs to be studied.

ORNL has completed the mathematical model for two coils per trench, one located above the other. The model has been solved numerically and has been validated with field experimental results.

5.2 THEORETICAL DEVELOPMENT

The model for two coils per trench is based on energy balance. Figure 22 shows the schematic of the coil arrangement. The following assumptions were made to simplify the analysis:

1. The soil is homogeneous and the soil thermal properties are constant.
2. The fluid temperature and velocity are uniform at any coil cross section.
3. The temperature distributions in both coil walls are radially symmetrical.
4. The coils are buried deep enough so that a circular farfield boundary could be formed, with the center located on the lower coil and with Z_2 as the radius.

For winter operation, assumption 1 is close to the real ground conditions because the ground top layer is usually saturated with moisture. Assumption 2 is also true because of the large coil length-over-diameter ratio. The coil wall is usually very thin. With the well-mixed fluid flow, assumption 3 would cause a negligible error in coil wall temperature calculation. Since Z_1 is usually >0.9 m, assumption 4 would be a good assumption for a single coil.[27] For a two-coil arrangement, there are not enough field experimental data to confirm this assumption. However, except for the part of the soil on top of the top coil, the

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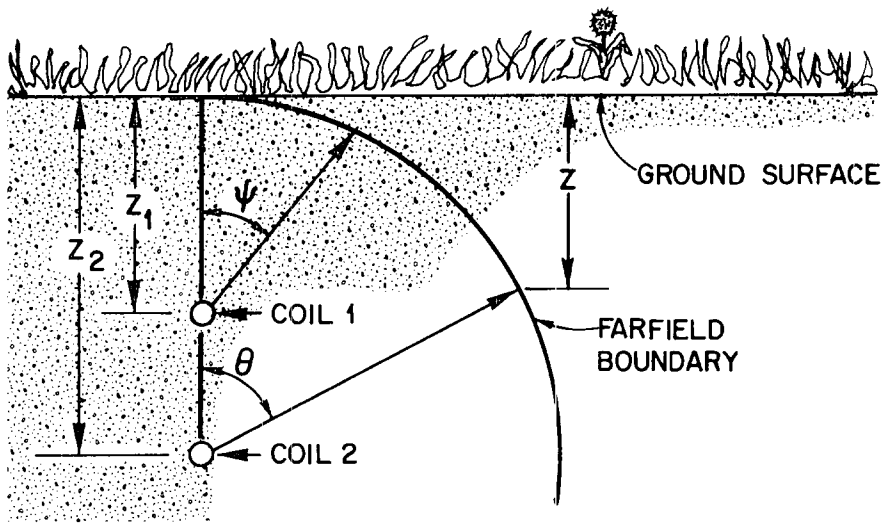

Fig. 22. Schematic of two-coil arrangement.

distance from the top coil to the farfield boundary is between Z_1 and Z_2. Since Z_2 is usually not less than 1.5 m, assumption 4 is probably true for most parts of the soil region around the two coils.

The following mathematical model is derived for the coil arrangement shown in Fig. 22.

Upper coil:

(a) Fluid:

$$-V\frac{\partial T_{fu}}{\partial x} + \frac{2K_p}{r_{1u}\rho_f C_{pf}}\frac{\partial T_{pu}}{\partial r}\Big|_{r_0} = \frac{\partial T_{fu}}{\partial t} \tag{5.1}$$

(b) Coil wall:

$$\frac{\partial^2 T_{pu}}{\partial r^2} + \frac{1}{r}\frac{\partial T_{pu}}{\partial r} = \frac{1}{\alpha_p}\frac{\partial T_{pu}}{\partial t} \tag{5.2}$$

(c) Boundary conditions:

At $r = r_{1u}$,

$$h(T_{pu} - T_{fu}) = K_{pu}\frac{\partial T_{pu}}{\partial r_u}\Big|_{r_{1u}} . \tag{5.3}$$

At $r = r_{2u}$,

$$2\pi K_{pu} \frac{\partial T_{pu}}{\partial r}\Big|_{r_{2u}} = K_s \int_0^{2\pi} \frac{\partial T_s(r,\psi)}{\partial r}\Big|_{r_{2u}} d\psi \tag{5.4}$$

and

$$T_s = T_{pu} \ . \tag{5.5}$$

Equation 5.5 assumes that there is no contact resistance between the coil and the soil, which is true for ground-coil winter operation, where the voids between the soil and the coil would be filled by moisture.

Lower coil:

(d) Fluid:

$$V \frac{\partial T_{fl}}{\partial x} + \frac{2K_p}{r_{1l}\rho_f c_{pf}} \frac{\partial T_{pl}}{\partial r}\Big|_{r_{1l}} = \frac{\partial T_{fl}}{\partial t} \ . \tag{5.6}$$

(e) Coil wall:

$$\frac{\partial^2 T_{pl}}{\partial r^2} + \frac{1}{r}\frac{\partial T_{pl}}{\partial r} = \frac{1}{\alpha_p}\frac{\partial T_{pl}}{\partial t} \ . \tag{5.7}$$

(f) Soil:

$$\frac{\partial^2 T_s}{\partial r^2} + \frac{1}{r}\frac{\partial T_s}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T_s}{\partial \theta^2} = \frac{1}{\alpha_s}\frac{\partial T_s}{\partial t} \ . \tag{5.8}$$

(g) Boundary conditions:

At $r = r_{1l}$,

$$h(T_{pl} - T_{fl}) = k_{pl} \frac{\partial T_{pl}}{\partial r}\Big|_{r_{1l}} \ . \tag{5.9}$$

At $r = r_{2l}$,

$$2\pi K_{pl} \frac{\partial T_{pl}}{\partial r}\Big|_{r_{2u}} = K_s \int_0 \frac{\partial T_s}{\partial r}\Big|_{r_{2l}} d\theta \tag{5.10}$$

and

$$T_s = T_{pl} \ , \tag{5.11}$$

where Eq. 5.11 assumes that no contact resistance exists between the coil and the soil.

At $Z = Z_1$, $\theta = 0$,

$$T_s = T_{pu} \ . \tag{5.12}$$

At $r = r_F$ (farfield),

$$T_{sF} = TA - DT \times \exp\left(-Z\sqrt{\frac{\pi}{8766\alpha_s}}\right) \times \cos\left(\frac{2\pi t_0}{8766} - Z\sqrt{\frac{\pi}{8766\alpha_s}} - \phi\right) , \tag{5.13}$$

where Eq. 5.13 is the Kusuda and Achenbach correlation[16] for ground temperature profile. The measured ground temperature profile, if available, should be used to replace Eq. 5.13.

(h) Initial conditions ($t = 0$):

$$\begin{aligned} T_{fu} &= T_{fui}(x) \ , \\ T_{pu} &= T_{pui}(r,x) \ , \\ T_{fl} &= T_{fli}(x) \ , \\ T_{pl} &= T_{pli}(r,x) \ , \\ T_s &= T_{si}(r,x,\theta) \ , \end{aligned} \tag{5.14}$$

where T_{fui}, T_{pui}, T_{fli}, T_{pli}, and T_{si} are known functions of x, r, and θ. For the coil to start the operation, these initial temperatures can be easily calculated by Eq. 5.13 or from the ground temperature profile if it is known.

(i) Fluid inlet conditions:

$$T_f(t, x = 0) = T_{f0}(t) \ , \tag{5.15}$$

where T_{f0} is a known function of time, t, which actually represents the heat pump model as described in Sect. 2.2.

The model described so far is for the ground coil with circulating fluid. During the "off" cycle period, the fluid velocity is 0. Since the heat capacity of the fluid in the coil is very small, Eqs. 5.3 and 5.9 can be written in the form, at $r = r_{1u}$,

$$T_{fu} = T_{pu} \tag{5.16}$$

and, at $r = r_{1l}$,

$$T_{fl} = T_{pl} \ .$$

Since the above equations are all of low order, they are relatively easy to solve numerically. A finite-difference computer code based on the above model was written.

5.3 MODEL VALIDATION AND DISCUSSION

The computer code based on the ground-coil model with thermal interference was used to simulate the field test results provided by UT.[38] The hourly fluid and farfield ground temperatures [up to 3.05 m (10 ft) below the surface] were provided. The hourly fraction of heat pump "on" time was determined by the fraction of heat pump power consumption over that at steady-state operation. Hourly energy absorbed from the ground and the coil fluid flow rate were also provided. Figure 23 shows the coil layout. It can be seen that part of the layout is two-coil trench and the rest is single-coil trench. This ground-coil setup made the computer simulation more difficult. The code was modified to include the simulation of the single-coil section.

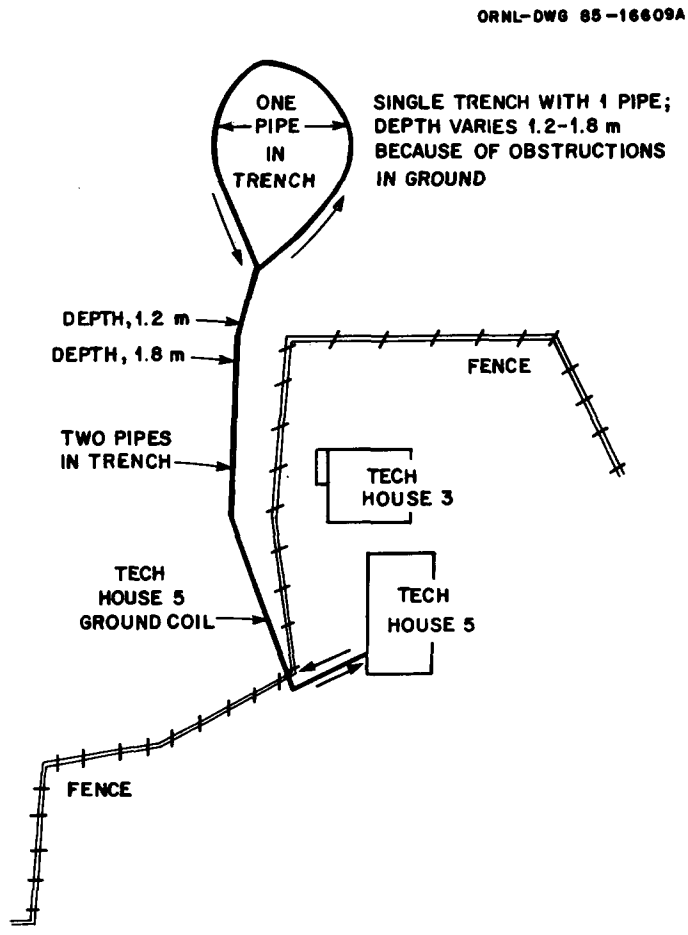

Fig. 23. Plan view of the UT TECH house horizontal ground-coil layout.

The following list provides the properties of the coil, soil, and fluid:

- coil length = 116-m two-coil trench and 116-m single-coil trench (380 ft);
- coil burial depth = two-coil section: 1.22 m (4 ft) top coil and 1.83 m (6 ft) lower coil; single-coil section: 1.52 m (5 ft);
- coil size = 4.09-cm (1.61-in.) ID and 4.83-cm (1.90-in.) OD;
- coil material = polybutylene;
- coil thermal conductivity = 0.216 W/(m·K) [0.125 Btu/(h·ft·°F)];
- coil specific heat = 2174 J/(kg·K) [0.52 Btu/(lb·°F)];
- fluid = water;
- thermal conductivity of fluid = 0.351 W/(m·k) [0.26 Btu(h·ft·°F)];
- specific heat of fluid = 4184 J/(kg·K) [1.0 Btu/(lb·°F)];
- soil = saturated clay;
- soil thermal conductivity = 2.181 W/(m·k) [1.26 Btu/(h·ft·°F)];
- soil thermal diffusivity = 0.0035 m^2/h (0.03763 ft^2/h); and
- flow rate = 1.522 m^3/h (6.67 gpm).

The fluid flow entered the top ground coil and exited at the lower coil.

A total of 28 days was simulated. Figure 24 shows the comparison of calculated and measured daily energy absorbed from the ground. The maximum deviation of calculated values from the measured ones is about 16% on the conservative side. Figure 25 shows the calculated and measured fluid temperatures at the coil exit position. It can be seen that the match is good until the heat pump "off" period becomes long. Since the fluid temperatures were measured indoors, once the heat pump was off, the fluid temperature started approaching room temperature. However, the model still considers that the fluid temperature can only approach ground temperature, which is much lower than the room temperature. Figure 25 also indicates that calculated fluid temperatures are generally lower than measured ones. One explanation is that the ground temperatures at different depths are actually higher than the measured farfield temperatures. Because part of the coil is buried alongside the house, as shown in Fig. 23, the effect of the house on the ground temperature should be considered. This also explains why the calculated daily energy absorption from the ground is conservative compared with the measured values.

Figure 26 shows the calculated soil temperature distribution after 28 days of coil operation in the two-coil section. It clearly indicates the thermal interference effect. Although the temperature profile cannot be validated because of the lack of field experimental data, it does indicate the ability of the computer code.

Figure 27 shows the energy absorbed from the ground by each coil section. Since the single-coil section has the same trench length as the two-coil section, it can be used to estimate the improvement of the coil performance due to an extra coil laid in the same trench by comparing the total energy exchange in the single-coil section to that of the two-coil section. Figure 27 indicates that the two-coil section, for 28-day operation, can absorb 60% more energy than the single-coil section. However, this figure is expected to drop when coil operation continues beyond 28 days because the thermal interference effect becomes more serious. This result is very consistent with the field experimental data reported by Hughes et al.[24]

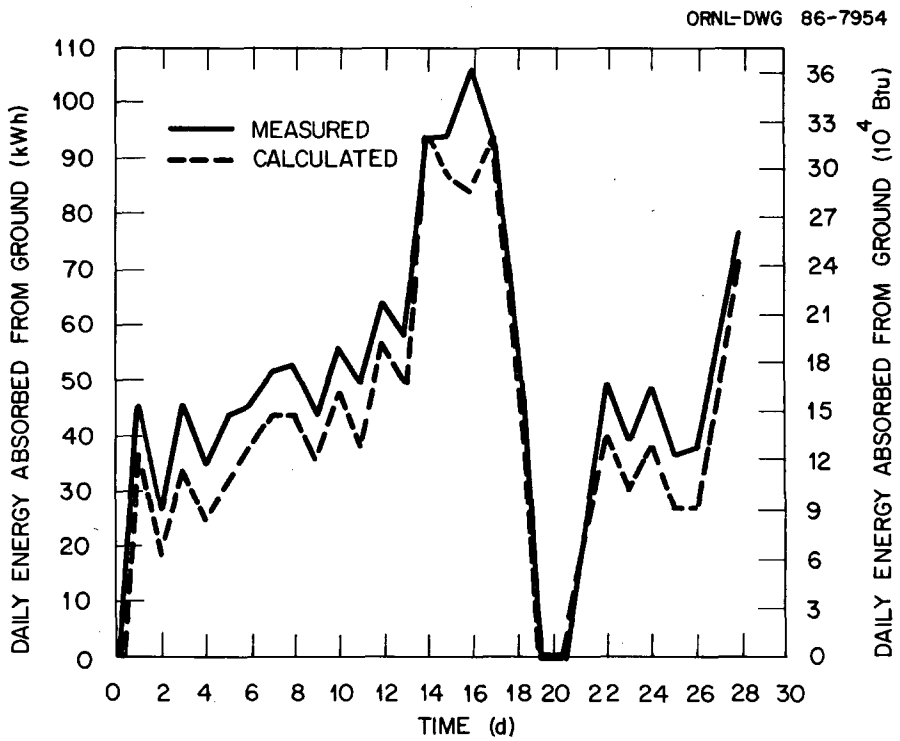

Fig. 24. Comparison of measured and calculated daily energy absorption from the ground.

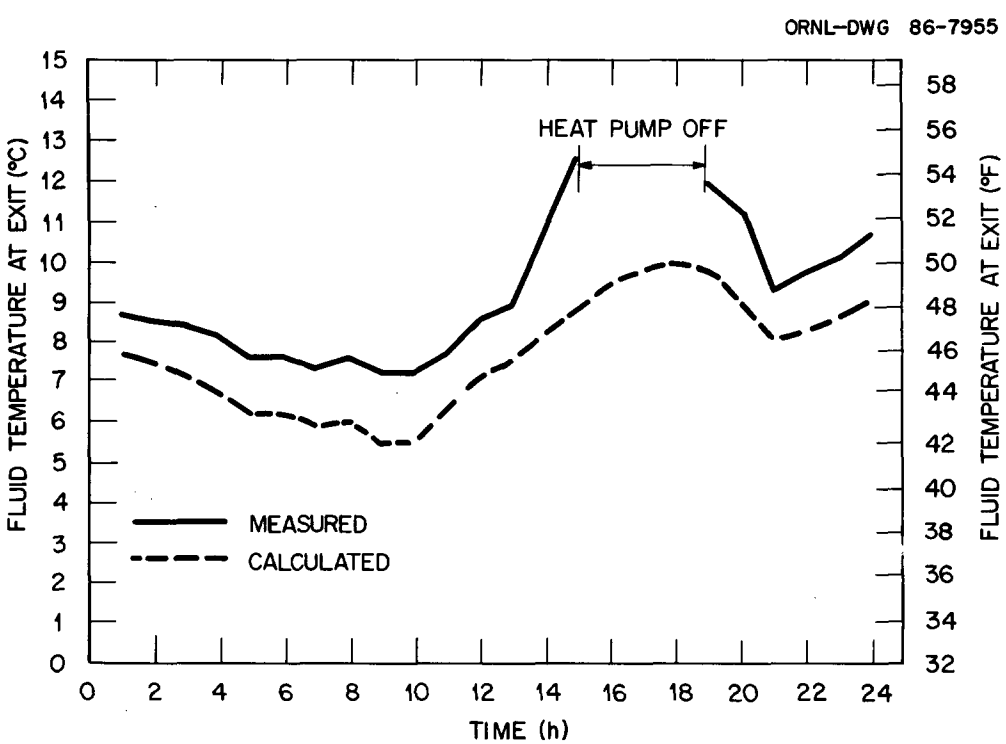

Fig. 25. Comparison of measured and calculated fluid temperatures at coil exit.

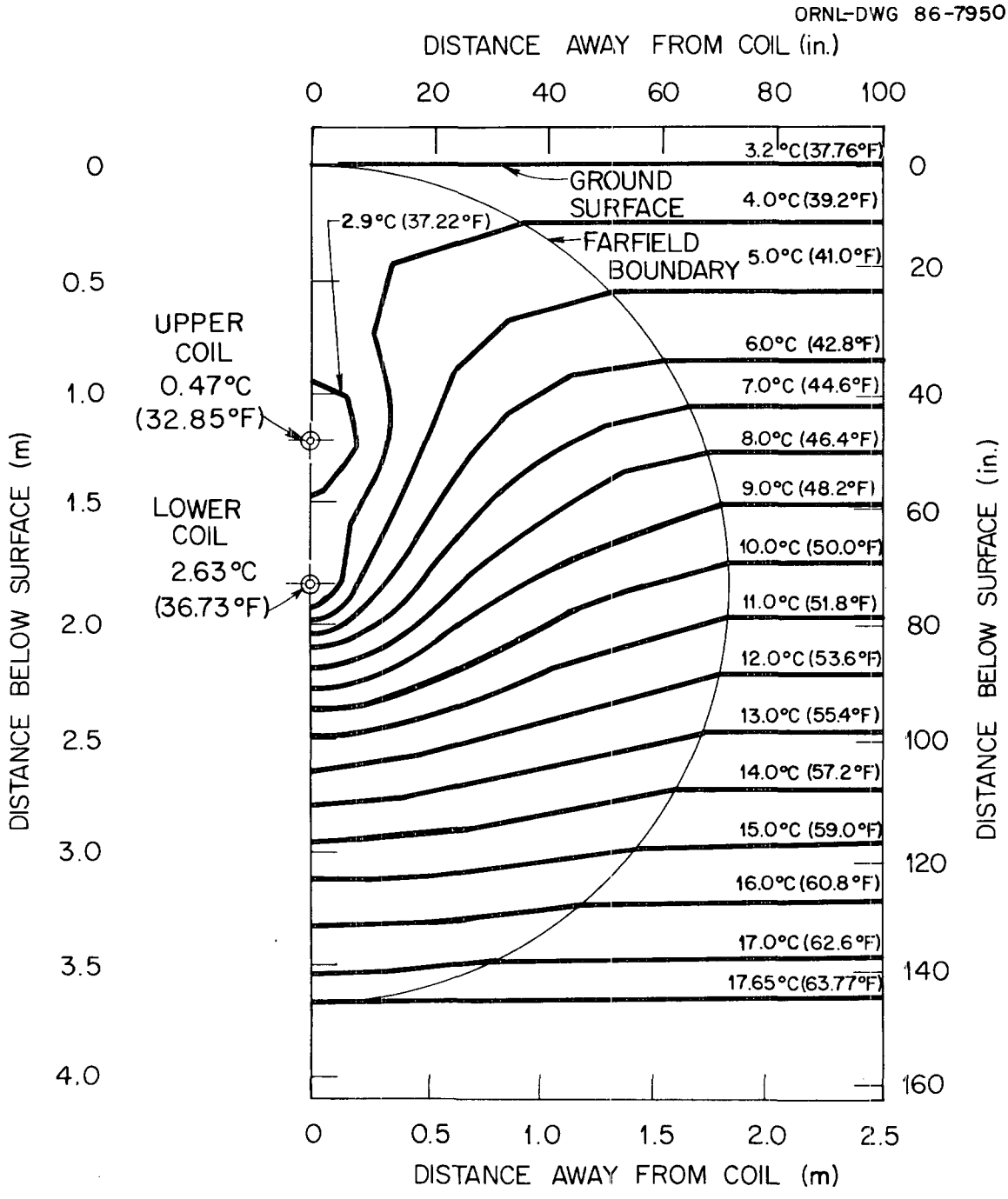

Fig. 26. Calculated ground temperature distribution after 28 days of coil operation.

Figure 28 shows the effect of coil performance if the inlet fluid location is switched from the upper coil to the lower coil. The total energy absorbed was reduced by almost 25%, which is mainly due to the ineffective use of the upper coil.

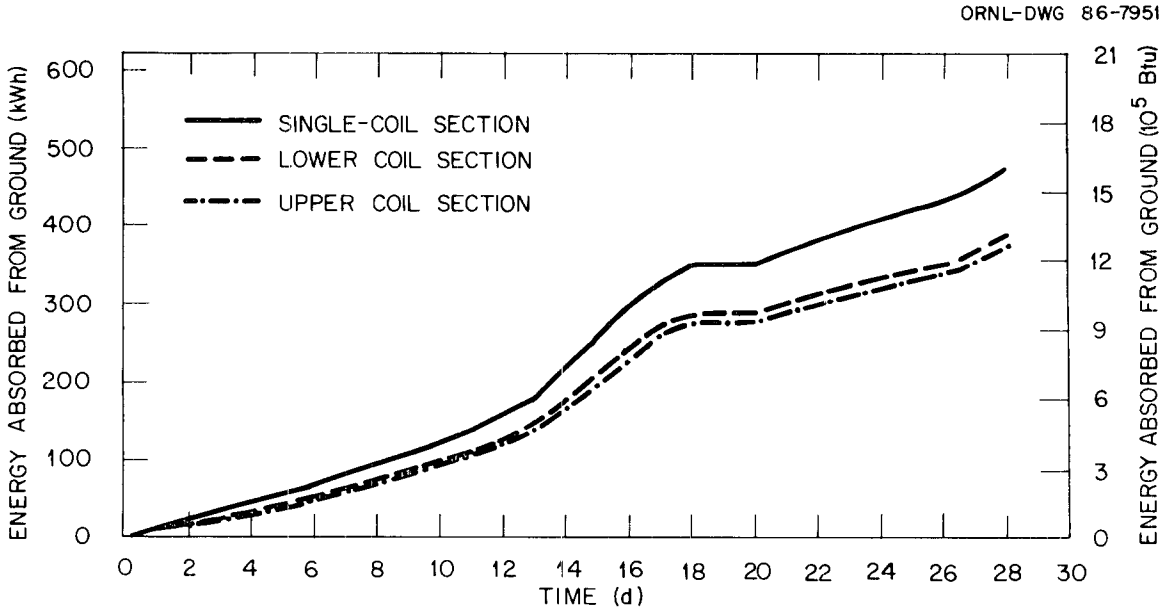

Fig. 27. Energy absorption from the ground by each section of coil.

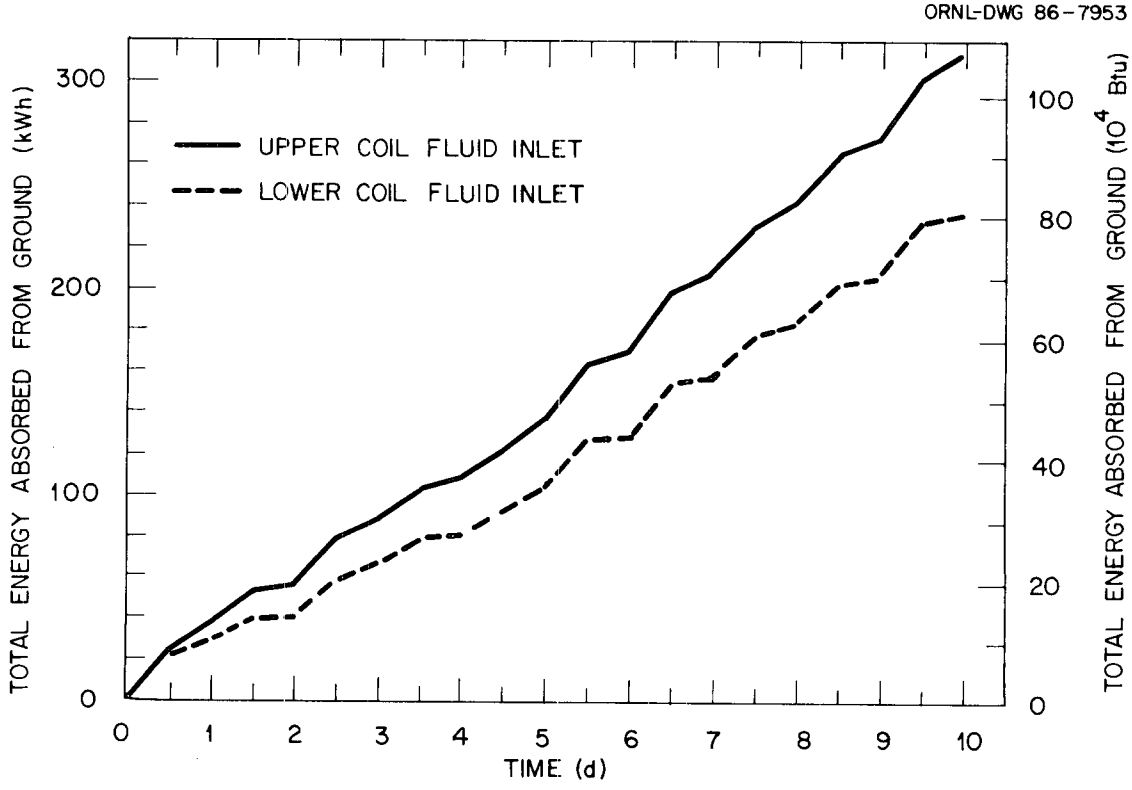

Fig. 28. Comparison of calculated total energy absorption from the ground with different fluid inlet positions.

6. DISCUSSION

6.1 MODEL WITH SOIL FREEZING EFFECT

Of the three validated models presented in this report, this model was used to check the importance of icing around the coil. The parametric study indicated that, if the ground-coil fluid inlet temperature is much lower than 0°C (32°F), the increase in total energy absorbed from the ground is largely due to the latent heat from freezing of the soil moisture. However, the existing preference in ground-coil design is to limit the fluid temperature to the heat pump to not lower than −4°C (25°F) in order to avoid excessive heat pump capacity drop. If the −4°C (25°F) coil fluid exit temperature is one of the design criteria, the effect of soil freezing around the coil is likely to be very small.

6.2 MODEL WITH EFFECT OF VARIABLE FARFIELD BOUNDARY CONDITIONS AND BACKFILLING MATERIAL

This model (having seasonal ground temperature variation) will provide a three-dimensional temperature distribution that will more realistically simulate ground-coil operation. The effect of backfilling material can be analyzed with this model.

6.3 MODEL WITH THERMAL INTERFERENCE

This model can be used to estimate the overall ground-coil performance improvement if two coils are buried in the same trench.

6.4 PARAMETRIC STUDIES

The parametric study using the model with variable seasonal ground temperature provides some useful guidelines for future design.

1. Soil thermal conductivity is an important factor in designing the coil. Even though we have no control over this factor, its value must be known for proper coil design.

2. The use of plastic tubing (polyethylene or polybutylene) as the ground coil has become common practice for several reasons: (1) plastic tubing does not corrode, (2) tube joints can be easily welded together (leakproof plastic welding is an important improvement over soldering metal joints), and (3) plastic tubing is two to three times cheaper than copper tubing for the same tube size. The parametric study showed that using thin-wall metal tubing increases coil performance by only 7.7% over polyethylene tubing after 15 days of continuous operation. The performance improvement is not enough to offset the other advantages of plastic tubing over metal.

3. Coil burial depth is a factor of concern. Theoretically, the deeper the coil is buried, the better the coil performs, as indicated in parametric studies. However, for the northern part of the United States, where the winter heating load is very high, the coil cannot be buried so deep that the ground temperature penetration in summer would be insufficient to melt the frozen soil region built up during the winter season. A permafrost region around the coil could result. This model does not take into account the soil freezing effect. However, after a 1-year simulation period with this model, a review of the ground temperature distribution should provide a good idea of whether a permafrost region around the coil is possible or likely.

4. Probably the greatest uncertainty in this study is the calculation of the convective heat transfer coefficients in the transitional flow region, $2{,}200 < N_{Re} < 10{,}000$. For most ground-coil winter operation, N_{Re} from time to time will fall into this flow region. Very little research work has been accomplished in this respect because of the unstable nature of the outcome of the fluid flow. From the available publications, the calculated N_{Nu} varies from 25 to 55.9. Figure 23 indicates that the N_{Nu} has very little effect on the overall heat transfer between fluid and ground until N_{Re} drops into the laminar flow region, where the thermal resistance between the fluid and coil wall becomes influential. This indicates that the main thermal resistance is from the ground.

5. The selection of thermal backfill material becomes very important if summer cooling load is heavy. The backfill material should minimize the contact resistance between coil and soil and should maintain a high thermal conductivity, even at very dry ground conditions.

6. Coil length is the most important factor in ground-coil design. As a matter of fact, the choices of coil material, size, and fluid are limited. The entire ground-coil design is centered on figuring out what the coil length should be.

7. For the two-coil trench, the fluid should enter the upper coil, not the lower one; otherwise, coil performance will deteriorate.

8. Thermal interference in the two-coil trench downgrades each coil's performance. However, if the energy absorbed by the two coils is added together, they outperform the single-coil trench by exchanging 50 to 60% more energy with the ground for the same trench length.

6.5 COMPARISON OF ORNL, BNL, AND LINE-SOURCE MODELS

The comparison of three different ground-coil models (ORNL, BNL, and line source) by simulating the same field experimental data provided some interesting results. As far as soil radial temperature distribution at the coil burial depth is concerned, the simple line-source model calculates lower temperature levels (more conservative) than other models. However, the line-source model is too simplified; except for the soil temperatures, it does not provide any other information. The BNL model provides a quick calculation and includes the most important factors but is difficult to understand. Furthermore, it is difficult to use, that is, to sort out the arrangement of the "blocks" of the ground. The heat

transfer activity is most sensitive at the area nearest the coil. In the BNL model, because of the limited number of blocks, the temperature profile around the coil is not adequately represented. In predicting the soil temperature distribution and fluid exit temperature, the ORNL model clearly outperforms the other two models. Furthermore, the ORNL model describes the operation of the ground coil in much more detail mathematically than do the other models.

For the same reason, the ORNL model takes much more computer time for execution than the others. However, there is a fundamental difference between the ORNL model and other models based on line-source theory. The ORNL model, based on the fluid inlet temperature to the ground coil, calculates the amount of energy exchanged between the coil and the ground. Other models require as input the amount of energy the ground will offer, and the ground temperature change is calculated accordingly. We think it is much easier and more accurate to calculate the fluid exit temperature from the heat pump, based on house load, heat pump fluid inlet temperature, and flow rate, than to estimate the amount of energy the ground will offer. Besides, the ORNL model is more flexible than the others. The effect of sand backfilling, for example, can be easily added to the ORNL model but is more difficult for the other models.

As for the thermal interference problem, it has not been studied extensively. Most ground-coil designs with thermal interference are based on the superposition of line-source solutions, a method that has its limitations. Now that there is evidence that a two-coil trench will cut the trenching cost drastically,[24] the ORNL model could be very useful as a tool to study the effect of coil thermal interference.

7. FUTURE WORK

To date, ORNL has completed the advanced ground-coil models for a deep-well tube-in-tube-type ground heat exchanger, horizontal coil with variable farfield boundary conditions, horizontal coil with soil freezing effect, and dual horizontal coils in the same trench with thermal interference.

The most frequent criticism of ORNL models is that they take too much computer time. Consequently, it is claimed that the ORNL model is not practical to use at present unless a mainframe computer is available. One way to cut the computer time is to simplify the model, but that could cause an unacceptable decrease in accuracy. Using an approximate solution in calculating the ground temperature distribution might be one possible method of reducing the time required.

Finally, a good ground-coil model should be able to simulate winter and summer operations. Summer operation, however, involves possible moisture migration and contact resistance between the coil and the soil. So far, very little research work has been accomplished in soil moisture migration caused by ground-coil heat pump operation. Limited data on contact resistance have been reported by Svec, Goodrich, and Palmer.[39] To include contact resistance in the model is a very simple matter. However, modeling soil moisture migration is quite complicated. Research work in buried electrical cable and agricultural fields has yielded many models that include moisture migration as a result of heat dissipation to the ground.[25,26,40–42] However, most of these models are for constant flux and radially symmetrical temperature distributions, which deviate from true ground-coil heat pump operating conditions, such as "on/off" cyclic operation. For areas where summer cooling load dominates, a ground-coil design model should include the moisture migration effect because the soil thermal properties are heavily dependent on moisture content. The only alternative is to design the system very conservatively. This would make GCHP systems less competitive with other cooling systems in those regions. ORNL has completed a ground-coil mathematical model that includes the effect of moisture migration in a radially symmetrical temperature field. We think that additional effort is needed if the cooling performance of GCHP systems is to be effectively analyzed.

8. CONCLUSIONS

Three validated ground-coil models were discussed, one to account for the effect of soil freezing around the coil, one to account for the effect of seasonal ground temperature variation, and one to account for the effect of thermal interference. From a study of these models, the following conclusions are drawn:

1. Unless the coil fluid inlet temperature is much lower than 0°C (32°F), the effect caused by soil freezing is likely to be small.
2. Soil thermal properties are an important factor in ground-coil performance, and they should be determined prior to coil design.
3. Using plastic coil, such as polyethylene tubing, will not reduce the coil capacity greatly but will prevent corrosion and leak problems and will cost much less than metal tubing.
4. The effect of coil burial depth can be studied using the ORNL computer program. The deeper the coil is buried, the better the coil performs. However, caution should be exercised to avoid creating a permafrost region around the coil if the coil is buried too deep and the winter heating load is high.
5. Fluid flow in the coil should not be in the laminar region to avoid a high thermal film resistance between the coil wall and fluid, which could considerably reduce the amount of energy exchange.
6. The selection of thermal backfill material is very important if summer cooling load is heavy.
7. Thermal interference will downgrade the performance of coils in the same trench. However, the overall performance of the two-coil trench is better than that of the single-coil trench arrangement by 50 to 60% for the same trench length (depending on the length of the coil operating period).

A comparison of the ORNL model and the other two ground-coil models, representing simple and modified line-source approaches, was made by simulating the same field experimental results. The ORNL model clearly outperformed the other models; however, it also consumes more computer time than the other models. Because computers are becoming faster and smaller, it is expected that the ORNL model will be more widely accepted in the near future. For the time being, the ORNL model can be effectively used as a reference to check ground-coil designs by other models.

The analysis of heat pump ground coils will not be completed, however, until full analysis of summer ground-coil operation is possible. Because GCHP systems have long been recognized as being more suitable for winter operation because of favorable ground

conditions, it is concluded that this kind of system is more suitable for the northern part of the United States. Based on this conclusion, the analysis of ground-coil summer operation, involving possible moisture migration and contact resistance, will have to be postponed until field experiments indicate that GCHP systems are economically competitive with alternative types of cooling systems.

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Appendix A

CALCULATION OF CONVECTIVE HEAT TRANSFER COEFFICIENT IN TRANSITIONAL FLOW REGION

For ground-coil winter operation, the fluid temperature is usually very low. The high fluid viscosity, from time to time, will lower the flow N_{Re} so that the fluid flow will be in the transitional region ($2{,}200 < N_{Re} < 10{,}000$). For the BNL winter field test data used in this report, the fluid temperature varied from 7.2 to −3.9°C (45 to 25°F). N_{Re} varied from 2,500 to 3,500, and N_{Pr} varied from 27.5 to 1.3. Publications about the calculation of the convective heat transfer coefficient in this flow region are very rare because of the region's unstable nature. Jacob[1] did mention some research work in this field and suggested that, for $3{,}500 \leqslant N_{Re} \leqslant 11{,}000$,

$$N_{Nu} = 0.0067(N_{Re})(N_{Pr})^{0.2}\left(\frac{\mu_f}{\mu_0}\right)^{0.14} . \tag{A.1}$$

Based on their experimental results, Donne and Bowditch[2] suggested that, when the soil length-over-diameter ratio increased, the flow tended to change from laminar to turbulent. Since this ratio for this study is very high (on the order of 3,000), we assumed that N_{Nu} was along the path of the prolongation of the turbulent region. Then, from Kays,[3] either

$$N_{Nu} = 0.0155 N_{Re}^{0.83}\ N_{Pr}^{0.5} \qquad (N_{Pr} < 20) \tag{A.2}$$

or

$$N_{Nu} = 0.0118 N_{Re}^{0.9} N_{Pr}^{0.3} \qquad (N_{Pr} > 20) \tag{A.3}$$

can be used.

From the above equations, N_{Nu} varied from 55.9 for fluid temperature at 7.2°C to 32.4 at −3.9°C. *VDI-Warmeatlas*[4] provides some information about estimating N_{Nu} in the transitional flow region. Based on the above reference, N_{Nu} was found to be 25 when $N_{Re} = 2500$ and $N_{Pr} = 27.5$. Figure A.1 indicates the effect of N_{Nu} on the total energy exchange between the fluid and the ground. It can be seen that there is only a 3% difference in total energy absorption from the ground when N_{Nu} varies from 55.9 to 25 over a three-day period of continuous operation. However, when $N_{Nu} = 4.363$ (for laminar flow with a constant heat rate),[3] there is a 33% decrease in total energy exchange.

The above analysis indicates that the main thermal resistance is from the ground. Unless the fluid flow is in the laminar region, the convective film resistance seems to have little effect on the heat exchange between the fluid and the ground. Because the fluid temperature through the coil during the operation rose no more than 2.8°C (5°F), the effect of changing N_{Re} and N_{Pr} along the coil on the amount of heat exchange between the fluid and the soil is negligible. For the rest of the study, N_{Nu} was then taken as a constant equal to 55.9.

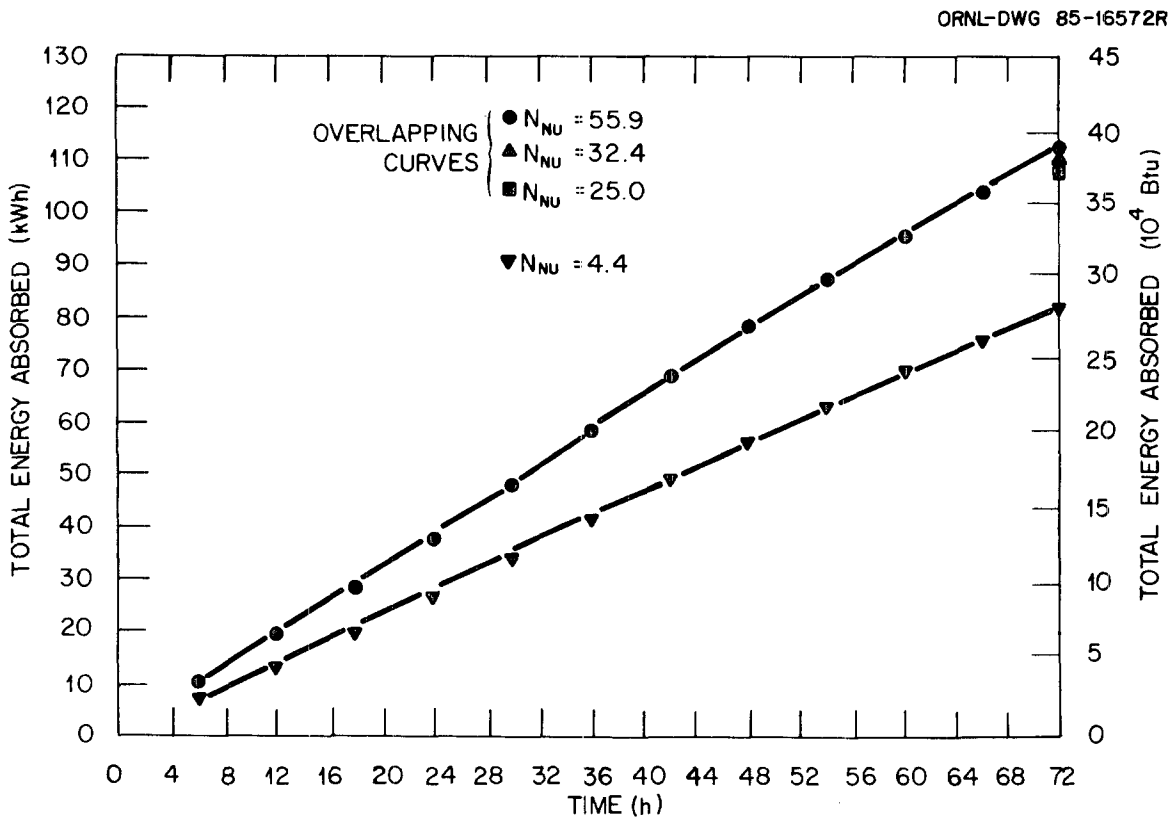

Fig. A.1. Effect of N_{Nu} on total energy absorption.

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Appendix B

GROUND-COIL MODEL WITH SOIL FREEZING EFFECT

B.1. Computer Code Listing

```
C
C       THIS CODE IS STORED IN NAME: FREEZE.F7
C       THIS CODE IS FOR GROUND COIL MODEL WITH RADIALLY SYMMETRICAL
C       TEMPERATURE PROFILE AND SOIL FREEZING EFFECT
C
      IMPLICIT REAL*8(A-H,O-Z)
      DOUBLE PRECISION MU1,MU2,MU3,LATENT,MOIST
      INTEGER DAYS,HOURS,MINUTE,SECOND
      LOGICAL OLDATA,STOP
      DIMENSION U(20,2),T(10,20,2),F(10,20,2),
     &          S(10,20,2),RR3(20)
      DIMENSION DEPTH(20),C1R(10),C2R(10),C3R(10),D1R(10),D2R(10),
     &   E1R(10),E2R(10),DRFZ(20),DRSOIL(5),DELTAR(20),RF(10),
     &   R3(20),ETA1(10),ETA2(10),SHALF(10),WEIGHT(10,2),SOIL(10),
     &   D3R(10),E3R(10)
C
      DATA PI /3.141592654D0/
C
C
C
C  RHOF=DENSITY OF FLUID: PB/FT3
C  CPF=SPECIFIC HEAT OF FLUID: BTU PER PB PER F
C  RK1 = THERMAL CONDUCTIVITY OF COIL WALL: BTU/HR/FT/F
C  RK2 = THERMAL CONDUCTIVITY OF SOIL FROZEN REGION: BTU/HR/FT/F
C  RK3 = THERMAL CONDUCTIVITY OF SOIL NON-FROZEN REGION: BTU/HR/FT/F
C  RHO1 = DENSITY OF COIL MATERIAL: PB/FT3
C  RHO2 = DENSITY OF SOIL FROZEN REGION: PB/FT3
C  RHO3 = DENSITY OF SOIL NON-FROZEN REGION: PB/FT3
C  CP1 = SPECIFIC HEAT OF COIL MATERIAL: BTU/PB/F
C  CP2 = SPECIFIC HEAT OF FROZEN SOIL: BTU/PB/F
C  CP3 = SPECIFIC HEAT OF NON-FROZEN SOIL: BTU/PB/F
C  H1 = CONVECTIVE HEAT TRANSFER COEFFICIENT BETWEEN FLUID AND COIL WALL
C        BTU PER HR PER FT2 PER F
C  LATENT = LATENT HEAT OF THE SOIL MOISTURE: BTU/PB
C  MOIST = MOISTURE CONTENT IN THE SOIL; PERCENT OF SOIL TOTAL DENSITY
C  TIMMAX = MAXIMUM PROGRAM RUNNING TIME, HOUR
C  TIMPRT = TIME INTERVAL BETWEEN DATA PRINT OUT, HOUR
C  GPM = FLUID FLOW RATE; GAL PER MIN
C  R1 = COIL INSIDE RADIUS: INCH
C  R2 = COIL OUTSIDE RADIUS: INCH
C  R3 = BOUNDARY OF SOIL FROZEN  AND NON-FROZEN REGIONS: INCH
C  R4 = FARFIELD RADIUS: INCH
C  DTIME = TIME STEP FOR FLUID AND SOIL NON-FROZEN REGION: MIN
C  PDTIME = TIME STEP FOR COIL WALL AND SOIL FROZEN REGION: MIN
C  ZMAX = LENGTH OF THE GROUND COIL: FT
C  TINFIN = DEFAULT VALUE OF INITIAL GROUND AND FLUID TEMPERATURE
C  TH2O = DEFAULT VALUE OF FLUID INLET TEMPERATURE: NOT
C         NECESSARILY CONSTANT: F
C  NZ = NO. OF NODAL POINTS IN VERTICAL DIRECTION: FT
C  NPIPE = NO. OF NODAL POINTS OF COIL WALL
C  NFREEZ = NO. OF NODAL POINTS OF SOIL FROZEN REGION
C  NSOIL = NO. OF NODAL POINTS IN SOIL NON-FROZEN REGION
C  DRSOIL = DISTANCE BETWEEN NODAL POINTS IN SOIL NON-FROZEN
C           REGION: DOES NOT NECESSARILY BE CONSTANT: INCH
```

```
C  TFREEZ = SOIL FREEZING TEMPERATURE: F
      DATA RKF, RHOF, CPF    /.36D0, 64.6D0, .925D0/
      DATA RK1, RHO1, CP1, H1/.266D0, 58.66D0, .52D0, 125.0D0/
      DATA RK2, RHO2, CP2/1.D0, 113.12D0, .2346D0/
      DATA RK3, RHO3, CP3/1.D0, 113.12D0, .2346D0/
C
      DATA LATENT, MOIST /143.5D0, .05673D0/
      DATA IOUT/6/, OLDATA/.FALSE./, STOP/.FALSE./
      DATA TIMMAX, TIMPRT /6.0D0, 6.0D0/
      DATA GPM/3.883D0/
      DATA R1,R2,R3,R4/.805D0, .912D0, 20*.912D0,120.0D0/
      DATA DTIME/20.0D-1/,PDTIME/5.0D-2/
      DATA ZMAX/500.0D0/
      DATA NZ/10/, NPIPE/2/, NFREEZ/2/, NSOIL/6/
      DATA DRSOIL/2.D0,5.D0,10.D0,12.D0,18.D0/
C     TFREEZ IS THE SOIL FREEZING TEMPERATURE
        DATA TFREEZ/32.0D0/
        DATA TE,DTE,PHASE,TYEAR/50.417D0,22.967D0,.352D0,7872.D0/
        DATA DPTH/4.0D0/
C
C       TH2O REPRESENTS GROUND COIL INLET FLUID TEMPERATURE.
C       IT ACTUALLY REPRESENTS THE HEAT PUMP MODEL.
C       TO CALCULATE TH2O, USE GROUND COIL FLUID EXIT TEMP.
C       HEAT PUMP CAPACITY, FLUID FLOW RATE, AND HOUSE LOAD
C       TO FIGURE OUT WHAT TH2O SHOULD BE.
C
C
      WRITE(IOUT,1)
1     FORMAT(2X,'GROUND COIL WITH SOIL FREEZING')
      NSOIL1=NSOIL-1
      NPM1=NPIPE-1
      NFZM1=NFREEZ-1
      NZM1=NZ-1
C
      TIME=0.
      BTUSY=0.0D0
      DZ=ZMAX/DBLE(NZ)
      HFLUX=0.
      FUSION=0.
        DRPIPE=(R2-R1)/DBLE(NPM1)
        EPS=DRPIPE
      DO 40 K=1,2
        DO 11 J=1,NZ
   DO 12 I=1,NSOIL
   Z=DPTH*DSQRT(PI/(RK3/(RHO3*CP3)*8766.D0))
   S(I,J,K)=TE-DTE*DEXP(-Z)*DCOS(PI*TYEAR/4383.D0-Z-
     &       PHASE)
12      CONTINUE
   DO 13 I=1,NPIPE
   T(I,J,K)=S(1,J,K)
13      CONTINUE
   DO 14 I=1,NFREEZ
   F(I,J,K)=T(1,J,K)
14      CONTINUE
```

```
        U(J,K)=T(1,J,K)
11      CONTINUE
   40 CONTINUE
      IF(OLDATA)READ(19,2001,END=41)TIME,BTUSY,FUSION,HFLUX,R3,
     &    T,F,S,U
   41 CONTINUE
 2001 FORMAT(7(1PE11.4))
      DZ=12.0D0*ZMAX/DBLE(NZ)
      DO 45 J=1,NZ
      DRFZ(J)=(R3(J)-R2)/DBLE(NFZM1)
   45 CONTINUE
C
C  SET VELOCITY OF FLUID
C
      VINNER=1728.0D0*(GPM*.1337D0)/(PI*R1*R1)
      DO 60 IZ=1,NZ
      DEPTH(IZ)=DBLE(IZ)*DZ/12.0D0
   60 CONTINUE
      SOIL(1)=0.0
      DO 50 ISOIL=2,NSOIL
   50 SOIL(ISOIL)=SOIL(ISOIL-1)+DRSOIL(ISOIL-1)/12.0D0
C
C   PRINT DATA
C
      WRITE(IOUT,1001)R1,R2,(R3(I),I=1,NZ),R4,ZMAX
 1001 FORMAT('0GEOMETRIC DATA :',/,
     &    5X,' R1      - INTERNAL RADIUS OF PIPE    ',5X,F7.3,
     &                                               ' INCHES',/,
     &    5X,' R2      - EXTERNAL RADIUS OF PIPE    ',5X,F7.3,
     &                                               ' INCHES',/,
     &    5X,' R3      - RADIUS OF FROZEN REGION    ',5X,10F7.3,/,
     &                                               ' INCHES',/,
     &    5X,' R4      = DISTANCE FROM PIPE TO      ',/,
     &    5X,'           UNDISTURBED SOIL           ',5X,F7.3,
     &                                               ' INCHES',/,
     &    5X,' ZMAX    - DEPTH OF WELL              ',5X,F7.3,
     &                                               ' FEET')
      R4=R2 + 12.0D0*R4
      WRITE(IOUT,1002)NPIPE,DRPIPE,NFREEZ,DRFZ,NSOIL,DRSOIL,
     &                NZ,DZ
 1002 FORMAT('0GEOMETRIC GRID :',/,
     &    5X,' NPIPE  - NUMBER OF MESH POINTS IN PIPE   ',I3,/,
     &    5X,' DRPIPE - RADIAL SPACING OF MESH POINTS    ',/,
     &    5X,'          IN PIPE                         ',F7.3,
     &                                                   ' INCHES',/,
     &    5X,' NFREEZ - NUMBER OF MESH POINTS IN        ',/,
     &    5X,'          FROZEN ZONE                     ',I3,/,
     &    5X,' DRFZ   - RADIAL SPACING OF POINTS IN      ',/,
     &    5X,'          FROZEN ZONE                      ',10F7.3,/,
     &    5X,'                                           ',10F7.3,
     &                                                   ' INCHES',/,
     &    5X,' NSOIL  - NUMBER OF POINTS IN OUTER SOIL   ',I3,/,
     &    5X,' DRSOIL - RADIAL SPACING OF POINTS IN      ',/,
     &    5X,'          OUTER SOIL                       ',5F7.3,
```

```
     &                                                  ' INCHES',/,
     &    5X,' NZ      - NUMBER OF VERTICAL MESH POINTS   ',I3,/,
     &    5X,' DZ      - VERTICAL SPACING OF POINTS       ',F7.2)
C
      WRITE(IOUT,1003)TIMMAX,TIMPRT,DTIME,PDTIME
 1003 FORMAT('0TIME PARAMETERS:',/,
     &    5X,' TIMMAX - LENGTH OF SIMULATION            ',F7.2,
     &                                                  ' HOURS',/,
     &    5X,' TIMPRT - TIMING OF PRINTED INFORMATION     ',F7.4,
     &                                                  ' HOURS',/,
     &    5X,' DTIME = TIME STEP                         ',F7.5,
     &                                                  ' MINUTES',/,
     &    5X,' PDTIME = SMALL TIME STEP                    ',F7.5,
     &                                                  ' MINUTES')
          V1FT=VINNER/12.0D0
      WRITE(IOUT,1004)GPM,V1FT
 1004 FORMAT('0PUMPING DATA:',/,
     &    5X,' GPM    - PUMPING RATE                    ',F7.3,
     &                                        ' GALLONS/MINUTE',/,
     &    5X,' BINNER - VELOCITY OF FLUID               ',F7.3,
     &                                        ' FEET/MINUTE')
C
      WRITE(IOUT,1005)TINFIN
 1005 FORMAT('0TEMPERATURE DATA:',/,
     &    5X,' TINFIN - AMBIENT SOIL TEMPERATURE       ',F7.3,
     &                                                  ' F')
      ALPHA1 = RK1/(RHO1*CP1)
      ALPHA2 = RK2/(RHO2*CP2)
      ALPHA3 = RK3/(RHO3*CP3)
C
      WRITE(IOUT,1006)
 1006 FORMAT('0MATERIAL PROPERTIES:')
      WRITE(IOUT,1007)
 1007 FORMAT('0PIPE:')
      WRITE(IOUT,1008)RK1,H1,RHO1,CP1,ALPHA1
 1008 FORMAT(
     &    5X,' CONDUCTIVITY                             ',F7.3,
     &                                  ' BTU/HR-FT-F',/,
     &    5X,' HEAT TRANSFER RATE                       ',F7.3,
     &                                  ' BTU/HR-FT2-F',/,
     &    5X,' DENSITY                                  ',F7.3,
     &                                  ' LBM/FT3',/,
     &    5X,' SPECIFIC HEAT                            ',F7.3,
     &                                  ' BTU/LBM-F',/,
     &    5X,' ALPHA                                    ',F7.5,
     &                                  ' FT2/HR')
C
      WRITE(IOUT,1009)
 1009 FORMAT('0FROZEN AREA:')
      WRITE(IOUT,1008)RK2,H2,RHO2,CP2,ALPHA2
      WRITE(IOUT,1010)
 1010 FORMAT('0SOIL:')
      WRITE(IOUT,1008)RK3,H3,RHO3,CP3,ALPHA3
C
```

```
      WRITE(IOUT,1011)RHOF,CPF
 1011 FORMAT('0WORKING FLUID:',/,
     &    5X,' RHOF   -DENSITY                          ',F7.3,
     &                                        ' LBM/FT3',/,
     &    5X,'CPF     - SPECIFIC HEAT                   ',F7.3,
     &                                        ' BTU/LBM-F')
C
C   CHANGE UNITS TO MINUTES AND INCHES
C
      TIMMAX=60.0D0*TIMMAX+TIME
      NPRINT=(60.0D0*TIMPRT+DTIME/2.0D0)/DTIME
      ZMAX=12.0D0*ZMAX
      RK1=RK1/(60.0D0*12.0D0)
      RK2=RK2/(60.0D0*12.0D0)
      RK3=RK3/(60.0D0*12.0D0)
C
      H1=H1/(60.0D0*144.0D0)
      H2=H2/(60.0D0*144.0D0)
      H3=H3/(60.0D0*144.0D0)
C
      RHOF=RHOF/1728.0D0
      RHO1=RHO1/1728.0D0
      RHO2=RHO2/1728.0D0
      RHO3=RHO3/1728.0D0
C
      ALPHA1=RK1/(RHO1*CP1)
      ALPHA2=RK2/(RHO2*CP2)
      ALPHA3=RK3/(RHO3*CP3)
C
C   SET CONSTANTS USED IN THE CALCULATIONS
C
      DTDZ=PDTIME/DZ
      BETA1=1.0D0-VINNER*DTDZ-2.0D0*H1*PDTIME/(RHOF*CPF*R1)
      BETA2=VINNER*DTDZ
      BETA3=2.0D0*H1*PDTIME/(RHOF*CPF*R1)
      A1DTDR=ALPHA1*PDTIME/DRPIPE
      GAMMA2=A1DTDR*(2.0D0/DRPIPE+1.0D0/R1)
      GAMMA3=2.0D0*A1DTDR*H1/RK1
      GAMMA1=1.0D0-GAMMA2-GAMMA3
DO 70 I=1,NPIPE
      R=R1+(DBLE(I)-1.0D0)*DRPIPE
        C2R(I)=A1DTDR*(1.0D0/DRPIPE+1.0D0/R)
        C3R(I)=A1DTDR/DRPIPE
        C1R(I)=1.0D0-C2R(I)-C3R(I)
   70 CONTINUE
      DO 72 J=1,NZ
      DRFZ(J)=(R3(J)-R2)/DBLE(NFZM1)
   72 CONTINUE
C
  777 FORMAT(1X,I3,I2,1X,9E18.11)
C
      ITIME=0
      HOURS=(TIME+.5/60.)/60.
      DAYS=HOURS/24
```

```
      HOURS=HOURS-24*DAYS
      MINUTE=TIME-60*(HOURS+24.0D0*DAYS)
      SECOND=60.*(TIME-60*(HOURS+24.0D0*DAYS)-MINUTE)
      NFZ2=(NFREEZ+1)/2
      WRITE(IOUT,1901)
 1901 FORMAT('0 DEPTH   ICE     H2O',8X,'PIPE',20X,'FROZEN REGION',7X,
     &       'SOIL',/,'   FT.  RADIUS',10X,25('-'),
     &       1X,19('-'),1X,54('-'))
C
      DO 99 J=1,NZ
      WRITE(IOUT,1902)DEPTH(J),R3(J),U(J,1),T(1,J,1),T(2,J,1),
     &  F(NFREEZ,J,1),
     &                (S(I+1,J,1),I=1,NSOIL1)
   99 CONTINUE
 1902 FORMAT(' ',F5.1,2X,F6.4,2X,F6.2,' I',2F6.2,' I',F6.2,' I',9F6.2)
      WRITE(IOUT,1902)
C
C   BEGIN TRANSIENT CALCULATIONS
C
C       SUBROUTINE BCYCLE IS TO PROVIDE HEAT PUMP CYCLIC OPERATION
C       INFORMATION
C
 1000 INOW=MOD(ITIME,2)+1
      ITHEN=MOD(ITIME+1,2)+1
      ITIME=ITIME+1
      TIME=TIME+DTIME
        CALL BCYCLE(TIME,VINNER,V1,ON)
C
C       SUBROUTINE FLUID IS TO PROVIDE GROUND COIL FLUID INLET TEMPERATURE
C
        CALL FLUID1(TIME,TH2O)
        LT=ON/DTIME
        FRACT=ON-DTIME*DBLE(LT)
        IF(LT .EQ. 0)GO TO 102
        AFRACT=1.0D0+FRACT/DTIME/DBLE(LT)
102     IF(LT .EQ. 0)AFRACT=1.0D0+ON/DTIME
        IF(TIME .GT. TIMMAX)STOP = .TRUE.
      IF(TIME .GT. TIMMAX)GO TO 2200
C
        IF(V1 .GT.1.0D-1)BTH2O=TH2O
        IF(V1 .LT. 0.1D-1)TH2O=U(1,INOW)
      DO 1300 J=1,NZ
      R3R2=R3(J)-R2
      DRFZ(J)=R3R2/DBLE(NFZM1)
      IF(R3R2 .GT. EPS)GO TO 1050
      MU1=2.0D0*RK3/RK1*A1DTDR/DRSOIL(1)
      MU3=A1DTDR*(2.0D0/DRPIPE-1.0D0/R2)
      MU2=1.0D0-MU1-MU3
      GO TO 1020
C
 1050 DRFZ(J)=(R3(J)-R2)/DBLE(NFZM1)
      MU1=2.0D0*RK2/RK1*A1DTDR*DRFZ(J)
      MU3=A1DTDR*(2.0D0/DRPIPE-1.0D0/R2)
      MU2=1.0D0-MU1-MU3
```

```
      DO 1200 I=2,NFZM1
      R=R2+(DBLE(I)-1.0D0)*DRFZ(J)
      D2R(I)=ALPHA2*PDTIME/DRFZ(J)*(1.0D0/DRFZ(J)+1.0D0/R)
      D3R(I)=ALPHA2*PDTIME/DRFZ(J)**2
        D1R(I)=1.0D0-D2R(I)-D3R(I)
 1200 CONTINUE
 1020 CONTINUE
      R=R3(J)
      DO 71 I=2,NSOIL1
   R=R+DRSOIL(I-1)
   DRAVG=(DRSOIL(I)+DRSOIL(I-1))*.5D0
        E2R(I)=2.0D0*ALPHA3*DTIME/DRSOIL(I)/DRSOIL(I-1)
        E3R(I)=ALPHA3*DTIME/DRSOIL(I-1)*(2.0D0/DRSOIL(I-1)-1.0D0/R)
        E1R(I)=1.0D0-E2R(I)-E3R(I)
71      CONTINUE
789     FORMAT(1X,6E18.11)
C
C   CALCULATE WATER TEMPERATURE
C
        KK=DTIME/PDTIME+.1D0
        IF(R3R2 .GT. EPS) GO TO 1160
        DO 1100 K=1,KK
        IF(V1 .LT. 1.0D-1) GO TO 1104
      IF(J .EQ. 1)U(1,ITHEN)=BETA1*U(1,INOW)+BETA2*TH2O+
     &            BETA3*T(1,1,INOW)
      IF(J .NE. 1)U(J,ITHEN)=BETA1*U(J,INOW)+BETA2*U(J-1,INOW)+
     &            BETA3*T(1,J,INOW)
C
C        CALCULATE PIPE WALL TEMPERATURE WHEN FLUID FLOW IS "ON"
C
        T(1,J,ITHEN)=GAMMA1*T(1,J,INOW)+GAMMA2*T(2,J,INOW)+
     &               GAMMA3*U(J,INOW)
        GO TO 1109
1104    U(J,ITHEN)=2.0D0*RK1*R1*(T(2,J,INOW)-
     &    T(1,J,INOW))*PDTIME/(RHOF*CPF*R1**2)/DRPIPE+U(J,INOW)
C
C   CALCULATE PIPE WALL TEMPERATURE
C
C       NEXT LINE IS ADDED TO INPOSE THE B.C. ON THE WALL
C       WHEN THE FLUID IS STOPED
C
        T(1,J,ITHEN)=U(J,ITHEN)
        GO TO 1108
1109    IF (J .EQ. 1)HFLUX=HFLUX+PI*R1*PDTIME*DZ*H1*
     &  (T(1,J,INOW)*3.0D0-T(1,J+1,INOW)-U(1,INOW)-TH2O)*AFRACT
        IF (J .NE. 1) HFLUX=HFLUX+PI*R1*PDTIME*DZ*H1*
     &  (T(1,J,INOW)+T(1,J-1,INOW)-U(J,INOW)-U(J-1,INOW))*AFRACT
1108  IF(NPM1 .LT. 2) GO TO 1120
      DO 1110 I=2,NPM1
      T(I,J,ITHEN)=C1R(I)*T(I,J,INOW)+
     &    C2R(I)*T(I+1,J,INOW)+C3R(I)*T(I-1,J,INOW)
 1110 CONTINUE
 1120 CONTINUE
C
```

```
      T(NPIPE,J,ITHEN)=MU1*S(2,J,INOW)+MU2*T(NPIPE,J,INOW)+
     &                 MU3*T(NPM1,J,INOW)
        DO 1102 I=1,NPIPE
   T(I,J,INOW)=T(I,J,ITHEN)
1102    CONTINUE
        U(J,INOW)=U(J,ITHEN)
1100    CONTINUE
      IF(T(NPIPE,J,ITHEN) .LE. TFREEZ) GO TO 1150
      DO 1130 I=1,NFREEZ
 1130 F(I,J,ITHEN)=T(NPIPE,J,ITHEN)
      S(1,J,ITHEN)=T(NPIPE,J,ITHEN)
      GO TO 1190
 1150 F(1,J,ITHEN)=T(NPIPE,J,ITHEN)
      IF(NFZM1 .LT. 2)GO TO 1141
      DO 1140 I=2,NFZM1
      RF(I)=(R2+DRFZ(J)*(.5D0+(I-2)))
     &    /(R2+DRFZ(J)*(.5D0+(I-1)))
      F(I,J,ITHEN)=(F(I+1,J,INOW)+RF(I)*F(I-1,J,INOW))/(1.0D0+RF(I))
 1140 CONTINUE
1141  F(NFREEZ,J,ITHEN)=TFREEZ
      S(1,J,ITHEN)=TFREEZ
      GO TO 1190
1160    DO 1155 K=1,KK
        IF(V1 .LT. 1.0D-1) GO TO 1164
        IF(J.EQ.1)U(J,ITHEN)=BETA1*U(J,INOW)+BETA2*TH2O+
     &                       BETA3*T(1,J,INOW)
        IF(J.NE.1)U(J,ITHEN)=BETA1*U(J,INOW)+BETA2*U(J-1,INOW)
     &                      +BETA3*T(1,J,INOW)
C
C       CALCULATED WALL TEMPERATURE WHEN ICE IS MORE THAN EPS
C
        T(1,J,ITHEN)=GAMMA1*T(1,J,INOW)+GAMMA2*T(2,J,INOW)+
     &               GAMMA3*U(J,INOW)
        GO TO 1165
1164    U(J,ITHEN)=2.0D0*RK1*R1*(T(2,J,INOW)-T(1,J,INOW))*
     &             PDTIME/(RHOF*CPF*R1**2)/DRPIPE+U(J,INOW)
C
C       CALCULATE PIPE WALL TEMPERATURE WHEN FLOW STOPPED
C
        T(1,J,ITHEN)=U(J,ITHEN)
1165    IF(NPM1 .LT. 2)GO TO 1166
        DO 1161 I=2,NPM1
   T(I,J,ITHEN)=C1R(I)*T(I,J,INOW)+
     &    C2R(I)*T(I+1,J,INOW)+C3R(I)*T(I-1,J,INOW)
1161       CONTINUE
1166       IF(V1.LT.1.0D-1)GO TO 1162
   IF (J .EQ. 1)HFLUX=HFLUX+PI*R1*PDTIME*DZ*H1*
     &  (T(1,J,INOW)*3.D0-T(1,J+1,INOW)-U(1,ITHEN)-TH2O)*AFRACT
   IF (J .NE. 1)HFLUX=HFLUX+PI*R1*PDTIME*DZ*H1*
     &  (T(1,J,INOW)+T(1,J-1,ITHEN)-U(J,ITHEN)-U(J-1,INOW))*AFRACT
1162  T(NPIPE,J,ITHEN)=MU1*F(2,J,INOW)+MU2*T(NPIPE,J,INOW)+
     &                 MU3*T(NPM1,J,INOW)
        DO 1163 I=1,NPIPE
   T(I,J,INOW)=T(I,J,ITHEN)
```

```
1163    CONTINUE
      F(1,J,ITHEN)=T(NPIPE,J,ITHEN)
      DO 1340 I=2,NFZM1
      F(I,J,ITHEN)=D1R(I)*F(I,J,INOW)+
     &    D2R(I)*F(I+1,J,INOW)+D3R(I)*F(I-1,J,INOW)
 1340 CONTINUE
        DO 1341 I=2,NFZM1
        F(I,J,INOW)=F(I,J,ITHEN)
1341    CONTINUE
        U(J,INOW)=U(J,ITHEN)
1155    CONTINUE
      F(NFREEZ,J,ITHEN)=TFREEZ
C
C   CALCULATE TEMPERATURE IN SOIL ZONE
C
 1190 CONTINUE
C       NEXT LINESARE FOR VARIABLE FARFIELD TEMPERATURE
        IF(DMOD(TIME,60.D0) .GT. .001D0)GO TO 1345
C       3652.5=8766.0*60.0/144.0 --- DUE TO UNIT CONVERSION
   Z=DPTH*DSQRT(PI/(RK3/(RHO3*CP3)*3652.5D0))
   S(NSOIL,J,ITHEN)=TE-DTE*DEXP(-Z)*DCOS(
     &    PI*(TYEAR+TIME/60.D0)/4383.D0-Z-PHASE)
1345  DO 1350 I=2,NSOIL1
      S(I,J,ITHEN)=E1R(I)*S(I,J,INOW)+
     &    E2R(I)*S(I+1,J,INOW)+E3R(I)*S(I-1,J,INOW)
        IF(S(I,J,ITHEN) .GT. S(NSOIL,J,ITHEN))
     &  S(I,J,ITHEN)=S(NSOIL,J,ITHEN)
 1350 CONTINUE
      DELTAR(J)=0.0D0
      IF(T(NPIPE,J,ITHEN).GE.TFREEZ)R3(J)=R2
      IF(T(NPIPE,J,ITHEN).GE.TFREEZ)GO TO 1355
        IF(R3R2 .GT. EPS)
     &  DELTAR(J)=(RK2*(F(NFREEZ-1,J,INOW)-F(NFZM1-1,J,INOW))
     &    /DRFZ(J)-
     &    RK3*(S(2,J,INOW)-
     &    S(1,J,INOW))/DRSOIL(1))*DTIME/(LATENT*MOIST*RHO3)
        IF(R3R2 .GT. EPS)GO TO 1355
        DELTAR(J)=(RK1*(T(NPIPE,J,INOW)-T(NPM1,J,INOW))
     &     /DRPIPE*R2/R3(J)-
     &      RK3*(S(2,J,INOW)-
     &     S(1,J,INOW))/DRSOIL(1))*DTIME/(LATENT*MOIST*RHO3)
1355  IF(V1 .LT. 1.0D-1) GO TO 1477
      FUSION=FUSION+RHO3*LATENT*MOIST*DELTAR(J)*2.0D0*PI*DZ*R3(J)
        IF(J .EQ. 1)BTUSY=BTUSY+PI*RK3*DZ*DTIME*R3(J)*
     &    (3.0D0*S(2,1,INOW)-S(2,2,INOW)-3.0D0*S(1,1,INOW)
     &    +S(1,2,INOW))/DRSOIL(1)*AFRACT
      IF(J .NE. 1)BTUSY=BTUSY+PI*RK3*DZ*DTIME*R3(J)*
     &(S(2,J,INOW)+S(2,J-1,INOW)-S(1,J,INOW)-S(1,J-1,INOW))
     &  /DRSOIL(1)*AFRACT
1477  R3(J)=R3(J)+DELTAR(J)
 1300 CONTINUE
        ERROR=(BTUSY+FUSION-HFLUX)/HFLUX*100.0D0
888   FORMAT(1X,10F8.4)
      IF(STOP) GO TO 190
```

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C
C   ROUND TIME TO THE NEXT HIGHEST HOUR:MINUTE:SECOND
C
        IF(DMOD(TIME,60.0D0) .GT. DTIME/2.0D0)GO TO 2101
  190 TIME2=TIME+.5/60.
      HOURS=TIME2/60.
      DAYS=HOURS/24
      HOURS=HOURS-24*DAYS
      MINUTE=TIME2-60.*(HOURS+24.0D0*DAYS)
      SECOND=60.*(TIME2-60.*(HOURS+24.0D0*DAYS)-MINUTE)
C
      WRITE(IOUT,490)DAYS,HOURS,MINUTE,SECOND
        IF(ITIME .LT. NPRINT) GO TO 2100
        ITIME=0
      WRITE(IOUT,1901)
  490 FORMAT(/1H0,'TIME = ',I3,' DAYS ',I3,' HOURS ',I3,
     &       ' MINUTES ',I3,' SECONDS')
      DO 499 J=1,NZ
      WRITE(IOUT,1902)DEPTH(J),R3(J),U(J,ITHEN),T(1,J,ITHEN),
     &  T(2,J,ITHEN),
     &  F(NFREEZ,J,ITHEN),
     &                (S(I+1,J,ITHEN),I=1,NSOIL1)
  499 CONTINUE
 2100 WRITE(IOUT,997)BTUSY,
     &               FUSION,HFLUX,
     &               ERROR,BTH2O,DELTAR(1)
  997 FORMAT('0',
     &           'SENSIBLE ENERGY          ',F11.2,/,
     &       ' ','LATENT ENERGY            ',F10.2,/,
     &        1X,'HEAT FROM PIPE TO FLUID  ',F11.2,/,
     &        1X,'ERROR                    ',E11.4,/,
     &        1X,'FLUID INLET TEMP "ON"    ',F10.2,/,
     &        1X,'ICE AROUND COIL AT INLET ',F10.4)
        WRITE(IOUT,996)ON,AFRACT
996     FORMAT(  ' ON TIME: MIN/HR         ',F10.3,'          FRACTION OF
     & ON TIME',F10.3)
  998 FORMAT(1X,10F5.1)
C        IF(TIME .LT. (TIMMAX-DTIME)) GO TO 2100
C      REWIND 20
C      WRITE(20,2001)TIME,BTUSY,FUSION,HFLUX,R3,T,
C     &    F,S,U
 2101 IF(STOP)GO TO 2200
        GO TO 1000
 2200 STOP
      END
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C
C       THIS SUBROUTINE IS CALLED FLUID1.TEM.  IT IS USED TO INPUT
C       FLUID INLET TEMPERATURE TO GROUND COIL.  THE LIST BELOW IS
C       THE FLUID INLET TEMPERATURE FROM THE BROOKHAVEN NATIONAL LAB.
C       FIELD EXPERIMENTAL RESULTS
C
        SUBROUTINE FLUID1(TIME,TH2O)
        IMPLICIT REAL*8(A-H,O-Z)
        IF(TIME .LE. 720.0D0)TH2O=42.0D0
        IF(TIME .GT. 720.0 .AND. TIME .LE. 2160.0D0)
     &  TH2O=-(TIME-2160.0D0)/720.0D0+40.0D0
        IF(TIME.GT.2160.0D0 .AND. TIME.LE.3600.0D0)
     &  TH2O=(TIME-2160.0D0)/1440.0D0+40.0D0
        IF(TIME.GT.3600.0D0 .AND. TIME .LE. 6480.0D0)
     &  TH2O=-(TIME-6480.0D0)/1440.0D0+39.0D0
        IF(TIME.GT.6480.0D0 .AND. TIME .LE. 7920.0D0)
     &  TH2O=-(TIME-7920.0D0)/360.0D0+35.0D0
        IF(TIME.GT.7920.0D0 .AND. TIME .LE. 9360.0D0)
     &  TH2O=.8D0*(TIME-7920.0D0)/1440/.0D0+35.0D0
        IF(TIME .GT. 9360.0D0 .AND. TIME .LE. 12240.0D0)
     &  TH2O=5.3D0*(TIME-9360.0D0)/2880.0D0+35.8D0
        IF(TIME .GT. 12240.0D0 .AND. TIME .LE. 13680.0D0)
     &  TH2O=-3.1D0*(TIME-13680.0D0)/1440.0D0+38.0D0
        IF(TIME .GT. 13680.0D0 .AND. TIME .LE. 15120.0D0)
     &  TH2O=-1.2D0*(TIME-15120.0D0)/1440.0D0+36.8D0
        IF(TIME .GT. 15120.0D0 .AND. TIME .LE. 16560.0D0)
     &  TH2O=-3.3D0*(TIME-16560.0D0)/1440.0D0+33.5D0
        IF(TIME .GT. 16560.0D0 .AND. TIME .LE. 18000.0D0)
     &  TH2O=1.6D0*(TIME-16560.0D0)/1440.0D0+33.5D0
        IF(TIME .GT. 18000.D0 .AND. TIME .LE. 19440.D0)
     &  TH2O=.8D0*(TIME-18000.D0)/1440.D0+35.1D0
        IF(TIME .GT. 19440.D0 .AND. TIME .LE. 20880.D0)
     &  TH2O=-2.6D0*(TIME-20880.D0)/1440.D0+33.3D0
        IF(TIME .GT. 20880.D0 .AND. TIME .LE. 22320.D0)
     &  TH2O=-.9D0*(TIME-22320.D0)/1440.D0+32.4D0
        IF(TIME .GT. 22320.D0 .AND. TIME .LE. 23760.D0)
     &  TH2O=-.5D0*(TIME-23760.D0)/1440.D0+31.9D0
        IF(TIME .GT. 23760.D0 .AND. TIME .LE. 25200.D0)
     &  TH2O=(TIME-23760.D0)/1440.D0+31.9D0
        IF(TIME .GT. 25200.D0 .AND. TIME .LE. 26640.D0)
     &  TH2O=32.9D0
        IF(TIME .GT. 26640.D0 .AND. TIME .LE. 28080.D0)
     &  TH2O=-.7D0*(TIME-28080.D0)/1440.D0+32.2D0
        IF(TIME .GT. 28080 .AND. TIME .LE. 29520.D0)
     &  TH2O=.4D0*(TIME-28080.D0)/1440.D0+32.2D0
        IF(TIME .GT. 29520.D0 .AND. TIME .LE. 30960.D0)
     &  TH2O=2.4D0*(TIME-29520.D0)/1440.D0+32.6D0
        IF(TIME .GT. 30960.D0 .AND. TIME .LE. 32400.D0)
     &  TH2O=-3.2D0*(TIME-32400.D0)/1440.D0+31.8D0
        IF(TIME .GT. 32400.D0 .AND. TIME .LE. 33840.D0)
     &  TH2O=-.13D0*(TIME-33840.D0)/1440.D0+31.7
        IF(TIME .GT. 33840.D0 .AND. TIME .LE. 35280.D0)
     &  TH2O=-1.8D0*(TIME-35280.D0)/1440.D0+29.9D0
        IF(TIME .GT. 35280.D0 .AND. TIME .LE. 36720.D0)
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     &  TH2O=-.9D0*(TIME-36720.D0)/1440.D0+29.0D0
        IF(TIME .GT. 36720.D0 .AND. TIME .LE. 38160.D0)
     &  TH2O=-.2D0*(TIME-38160.D0)/1440.D0+28.8D0
        IF(TIME .GT. 38160.D0 .AND. TIME .LE. 41040.D0)
     &  TH2O=2.6D0*(TIME-38160.D0)/2880.D0+28.8D0
        IF(TIME .GT. 41040.D0 .AND. TIME .LE. 43920.D0)
     &  TH2O=-.4D0*(TIME-43920.D0)/2880.D0+30.6D0
        IF(TIME .GT. 43920.D0 .AND. TIME .LE. 45360.D0)
     &  TH2O=-1.2D0*(TIME-45360.D0)/1440.D0+29.4D0
        IF(TIME .GT. 45360.D0 .AND. TIME .LE. 46800.D0)
     &  TH2O=1.2D0*(TIME-45360.D0)/1440.D0+29.4D0
        IF(TIME .GT. 46800.D0 .AND. TIME .LE. 49680.D0)
     &  TH2O=.5D0*(TIME-46800.D0)/2880.D0+30.6D0
        IF(TIME .GT. 49680.D0 .AND. TIME .LE. 52560.D0)
     &  TH2O=-2.1D0*(TIME-52560.D0)/2880.D0+29.0D0
        IF(TIME .GT. 52560.D0 .AND. TIME .LE. 54000.D0)
     &  TH2O=1.5D0*(TIME-52560.D0)/1440.D0+29.0D0
        IF(TIME .GT. 54000.D0 .AND. TIME .LE. 56880.D0)
     &  TH2O=-1.6D0*(TIME-56880.D0)/2880.D0+28.9D0
        IF(TIME .GT. 56880.D0 .AND. TIME .LE. 58320.D0)
     &  TH2O=1.8D0*(TIME-56880.D0)/1440.D0+28.9D0
        IF(TIME .GT. 58320.D0 .AND. TIME .LE. 59760.D0)
     &  TH2O=-.1D0*(TIME-59760.D0)/1440.D0+30.6D0
        IF(TIME .GT. 59760.D0 .AND. TIME .LE. 61200.D0)
     &  TH2O=-.8D0*(TIME-61200.D0)/1440.D0+29.8D0
        IF(TIME .GT. 61200.D0 .AND. TIME .LE. 62640.D0)
     &  TH2O=1.1D0*(TIME-61200.D0)/1440.D0+29.8D0
        IF(TIME .GT. 62640.D0 .AND. TIME .LE. 64080.D0)
     &  TH2O=-3.9D0*(TIME-64080.D0)/1440.D0+27.0D0
        IF(TIME .GT. 64080.D0 .AND. TIME .LE. 68400.D0)
     &  TH2O=27.0D0
        IF(TIME .GT. 68400.D0 .AND. TIME .LE. 69840.D0)
     &  TH2O=-1.4D0*(TIME-69840.D0)/1440.D0+25.6D0
        IF(TIME .GT. 69840.D0 .AND. TIME .LE. 72720.D0)
     &  TH2O=1.1D0*(TIME-69840.D0)/2880.D0+25.6D0
        IF(TIME .GT. 72720.D0 .AND. TIME .LE. 75600.D0)
     &  TH2O=26.75D0
        IF(TIME .GT. 75600.D0 .AND. TIME .LE. 77040.D0)
     &  TH2O=-1.2D0*(TIME-77040.D0)/1440.D0+25.5D0
        IF(TIME .GT. 77040.D0 .AND. TIME .LE. 78480.D0)
     &  TH2O=-.5D0*(TIME-78480.D0)/1440.D0+25.0D0
        IF(TIME .GT. 78480.D0)
     &  TH2O=.8D0*(TIME-78480.D0)/1440.D0+25.0D0
        TH2O=26.0D0
        RETURN
    END
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C       THIS SUBROUTINE IS CALLED BCYCLE.F4.  IT IS USED TO
C       SPECIFY THE HEAT PUMP ON/OFF CYCLING SCHEDULE. THIS
C       PARTICULAR PRINT OUT IS FROM THE BROOKHAVEN NATIONAL
C       LABORATORY FIELD EXPERIMENTAL RESULTS
C
        SUBROUTINE BCYCLE(TIME,VINNER,V1,ON)
C
   IMPLICIT REAL*8(A-H,O-Z)
   INTEGER HOUR,HOURS
   REAL*8 MIN
C
C  THE HEAT PUMP RUNS THE FIRST "ON" MINUTES OF THE HOUR
C
        DATA IFIRST / 0 /
C
C
   IF (IFIRST .EQ. 0) GO TO 400
1  HOUR = TIME/60.
   MIN  = TIME - 60*HOUR
   HOUR = MOD(HOUR,24)
150     V1=0.D0
        IF(TIME .LE. 12960.01D0)ON=14.0D0
        IF(TIME .GT. 12960.01D0 .AND. TIME .LE. 14400.01D0)
     &  ON=18.0D0
        IF(TIME .GT. 14400.01D0 .AND. TIME .LE. 15840.01D0)
     &  ON=22.0D0
   IF(TIME .GT. 15840.01D0 .AND. TIME .LE. 17280.01D0)
     &  ON=35.6D0
        IF(TIME .GT. 17280.01D0 .AND. TIME .LE. 18720.01D0)
     &  ON=22.0D0
   IF(TIME .GT. 18720.01D0 .AND. TIME .LE. 20160.01D0)
     &  ON=19.0D0
   IF(TIME .GT. 20160.01D0 .AND. TIME .LE. 21600.01D0)
     &  ON=31.5D0
   IF(TIME .GT. 21600.01D0 .AND. TIME .LE. 23040.01D0)
     &  ON=32.0D0
   IF(TIME .GT. 23040.01D0 .AND. TIME .LE. 24480.01D0)
     &  ON=32.0D0
        IF(TIME .GT. 24480.01D0 .AND. TIME .LE. 25920.01D0)
     &  ON=25.0D0
   IF(TIME .GT. 25920.01D0 .AND. TIME .LE. 27360.01D0)
     &  ON=21.5D0
   IF(TIME .GT. 27360.01D0 .AND. TIME .LE. 28800.01D0)
     &  ON=26.0D0
   IF(TIME .GT. 28800.01D0 .AND. TIME .LE. 30240.01D0)
     &  ON=22.0D0
   IF(TIME .GT. 30240.01D0 .AND. TIME .LE. 31680.01D0)
     &  ON=25.5D0
   IF(TIME .GT. 31680.01D0 .AND. TIME .LE. 33120.01D0)
     &  ON=26.0D0
   IF(TIME .GT. 33120.01D0 .AND. TIME .LE. 34560.01D0)
     &  ON=25.5D0
        IF(TIME .GT. 34560.01D0 .AND. TIME .LE. 36000.01D0)
     &  ON=32.0D0
```

```
      IF(TIME .GT. 36000.01D0 .AND. TIME .LE. 37440.01D0)
     &  ON=34.0D0
         IF(TIME .GT. 37440.01D0 .AND. TIME .LE. 38880.01D0)
     &  ON=33.0D0
      IF(TIME .GT. 38880.01D0 .AND. TIME .LE. 40320.01D0)
     &  ON=26.5D0
      IF(TIME .GT. 40320.01D0 .AND. TIME .LE. 41760.01D0)
     &  ON=16.5D0
      IF(TIME .GT. 41760.01D0 .AND. TIME .LE. 43200.01D0)
     &  ON=19.5D0
         IF(TIME .GT. 43200.D0 .AND. TIME .LE. 44640.D0)
     &    ON=23.D0
      IF(TIME .GT. 44640.D0 .AND. TIME .LE. 46080.D0)
     &  ON=26.0D0
      IF(TIME .GT. 46080.D0 .AND. TIME .LE. 47520.D0)
     &  ON=21.5D0
      IF(TIME .GT. 47520.D0 .AND. TIME .LE. 48960.D0)
     &  ON=15.5D0
      IF(TIME .GT. 48960.D0 .AND. TIME .LE. 50400.D0)
     &  ON=19.0D0
      IF( TIME .GT. 50400.D0 .AND. TIME .LE. 51840.D0)
     &  ON=25.0D0
      IF(TIME .GT. 51840.D0 .AND. TIME .LE. 53280.D0)
     &  ON=28.5D0
      IF(TIME .GT. 53280.D0 .AND. TIME .LE. 54720.D0)
     &  ON=21.5D0
      IF(TIME .GT. 54720.D0 .AND. TIME .LE. 56160.D0)
     &  ON=26.5D0
      IF(TIME .GT. 56160.D0 .AND. TIME.LE. 57600.D0)
     &  ON=29.0D0
         IF(TIME .GT. 57600.D0 .AND. TIME .LE. 59040.D0)
     &  ON=17.5D0
         IF(TIME .GT. 59040.D0 .AND. TIME .LE. 60480.D0)
     &  ON=21.0D0
         IF(TIME .GT. 60480.D0 .AND. TIME .LE. 61920.D0)
     &  ON=25.0D0
         IF(TIME .GT. 61920.D0 .AND. TIME .LE. 63360.D0)
     &  ON=19.0D0
      IF(TIME .GT. 63360.D0 .AND. TIME .LE. 69120.D0)
     &  ON=44.0D0
         IF(MIN .GT. ON) RETURN
C
      V1 = VINNER
      RETURN
400      IFIRST = 1
      GO TO 1
      END
```

B.2. Sample Calculation

```
GROUND COIL WITH SOIL FREEZING

GEOMETRIC DATA :
     R1      - INTERNAL RADIUS OF PIPE          0.805 INCHES
     R2      - EXTERNAL RADIUS OF PIPE          0.912 INCHES
     R3      - RADIUS OF FROZEN REGION          0.912  0.912  0.912  0.912  0.912  0.912  0.912  0.912  0.912  0.912
INCHES
     R4      = DISTANCE FROM PIPE TO
               UNDISTURBED SOIL               120.000 INCHES
     ZMAX    - DEPTH OF WELL                  500.000 FEET

GEOMETRIC GRID :
     NPIPE   - NUMBER OF MESH POINTS IN PIPE     2
     DRPIPE  - RADIAL SPACING OF MESH POINTS
               IN PIPE                          0.107 INCHES
     NFREEZ  - NUMBER OF MESH POINTS IN
               FROZEN ZONE                      2
     DRFZ    - RADIAL SPACING OF POINTS IN
               FROZEN ZONE                       0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
                                                 0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000 INCHES
     NSOIL   - NUMBER OF POINTS IN OUTER SOIL     6
     DRSOIL  - RADIAL SPACING OF POINTS IN
               OUTER SOIL                        2.000  5.000 10.000 12.000 18.000 INCHES
     NZ      - NUMBER OF VERTICAL MESH POINTS    10
     DZ      - VERTICAL SPACING OF POINTS        600.00

TIME PARAMETERS:
     TIMMAX - LENGTH OF SIMULATION               6.00 HOURS
     TIMPRT - TIMING OF PRINTED INFORMATION      6.0000 HOURS
     DTIME = TIME STEP                          2.00000 MINUTES
     PDTIME = SMALL TIME STEP                    0.05000 MINUTES

PUMPING DATA:
     GPM     - PUMPING RATE                      3.883 GALLONS/MINUTE
     BINNER - VELOCITY OF FLUID                 36.721 FEET/MINUTE

TEMPERATURE DATA:
     TINFIN - AMBIENT SOIL TEMPERATURE          0.000 F

MATERIAL PROPERTIES:

PIPE:
     CONDUCTIVITY                                0.266 BTU/HR-FT-F
     HEAT TRANSFER RATE                        125.000 BTU/HR-FT2-F
     DENSITY                                    58.660 LBM/FT3
     SPECIFIC HEAT                               0.520 BTU/LBM-F
     ALPHA                                     0.00872 FT2/HR

FROZEN AREA:
     CONDUCTIVITY                                1.000 BTU/HR-FT-F
     HEAT TRANSFER RATE                          0.000 BTU/HR-FT2-F
     DENSITY                                   113.120 LBM/FT3
     SPECIFIC HEAT                               0.235 BTU/LBM-F
     ALPHA                                     0.03768 FT2/HR
```

```
SOIL:
     CONDUCTIVITY                                  1.000 BTU/HR-FT-F
     HEAT TRANSFER RATE                            0.000 BTU/HR-FT2-F
     DENSITY                                     113.120 LBM/FT3
     SPECIFIC HEAT                                 0.235 BTU/LBM-F
     ALPHA                                      0.03768 FT2/HR

WORKING FLUID:
     RHOF   -DENSITY                              64.600 LBM/FT3
    CPF     - SPECIFIC HEAT                        0.925 BTU/LBM-F

 DEPTH   ICE     H2O        PIPE                     FROZEN REGION       SOIL
  FT.  RADIUS          ------------------------- ------------------ --------
 50.0  0.9120   47.51 I 47.51 47.51 I 47.51 I 47.51 47.51 47.51 47.51 47.51
100.0  0.9120   47.51 I 47.51 47.51 I 47.51 I 47.51 47.51 47.51 47.51 47.51
150.0  0.9120   47.51 I 47.51 47.51 I 47.51 I 47.51 47.51 47.51 47.51 47.51
200.0  0.9120   47.51 I 47.51 47.51 I 47.51 I 47.51 47.51 47.51 47.51 47.51
250.0  0.9120   47.51 I 47.51 47.51 I 47.51 I 47.51 47.51 47.51 47.51 47.51
300.0  0.9120   47.51 I 47.51 47.51 I 47.51 I 47.51 47.51 47.51 47.51 47.51
350.0  0.9120   47.51 I 47.51 47.51 I 47.51 I 47.51 47.51 47.51 47.51 47.51
400.0  0.9120   47.51 I 47.51 47.51 I 47.51 I 47.51 47.51 47.51 47.51 47.51
450.0  0.9120   47.51 I 47.51 47.51 I 47.51 I 47.51 47.51 47.51 47.51 47.51
500.0  0.9120   47.51 I 47.51 47.51 I 47.51 I 47.51 47.51 47.51 47.51 47.51


TIME =   0 DAYS   1 HOURS   0 MINUTES   0 SECONDS

SENSIBLE ENERGY                2558.04
LATENT ENERGY                   64.10
HEAT FROM PIPE TO FLUID        4050.61
ERROR                       -0.3527E+02
FLUID INLET TEMP "ON"           26.00
ICE AROUND COIL AT INLET       0.0000
ON TIME: MIN/HR               14.000         FRACTION OF ON TIME     1.000


TIME =   0 DAYS   2 HOURS   0 MINUTES   0 SECONDS

SENSIBLE ENERGY                5030.03
LATENT ENERGY                   322.15
HEAT FROM PIPE TO FLUID        7340.43
ERROR                       -0.2709E+02
FLUID INLET TEMP "ON"           26.00
ICE AROUND COIL AT INLET       0.0212
ON TIME: MIN/HR               14.000         FRACTION OF ON TIME     1.000


TIME =   0 DAYS   3 HOURS   0 MINUTES   0 SECONDS

SENSIBLE ENERGY                7172.91
LATENT ENERGY                   669.07
HEAT FROM PIPE TO FLUID       10268.62
```

```
ERROR                      -0.2363E+02
FLUID INLET TEMP "ON"        26.00
ICE AROUND COIL AT INLET     0.0195
ON TIME: MIN/HR             14.000        FRACTION OF ON TIME     1.000


TIME =   0 DAYS   4 HOURS   0 MINUTES   0 SECONDS

SENSIBLE ENERGY              9108.30
LATENT ENERGY               1069.65
HEAT FROM PIPE TO FLUID     12990.84
ERROR                      -0.2165E+02
FLUID INLET TEMP "ON"        26.00
ICE AROUND COIL AT INLET     0.0185
ON TIME: MIN/HR             14.000        FRACTION OF ON TIME     1.000


TIME =   0 DAYS   5 HOURS   0 MINUTES   0 SECONDS

SENSIBLE ENERGY             10892.79
LATENT ENERGY               1520.46
HEAT FROM PIPE TO FLUID     15570.22
ERROR                      -0.2028E+02
FLUID INLET TEMP "ON"        26.00
ICE AROUND COIL AT INLET     0.0177
ON TIME: MIN/HR             14.000        FRACTION OF ON TIME     1.000


TIME =   0 DAYS   6 HOURS   0 MINUTES   0 SECONDS

 DEPTH   ICE     H2O        PIPE                    FROZEN REGION       SOIL
  FT.  RADIUS          ------------------------- ------------------ --------
 50.0  0.9292   28.53 I 29.04 30.69 I 32.00 I 36.63 41.33 46.27 47.35 47.45
100.0  0.9120   30.40 I 30.79 32.07 I 32.07 I 36.79 41.43 46.30 47.36 47.45
150.0  0.9120   31.80 I 32.10 33.12 I 33.12 I 36.96 41.55 46.33 47.36 47.45
200.0  0.9120   32.86 I 33.11 33.94 I 33.94 I 37.16 41.68 46.37 47.37 47.45
250.0  0.9120   33.70 I 33.90 34.60 I 34.60 I 37.37 41.83 46.41 47.37 47.45
300.0  0.9120   34.37 I 34.55 35.15 I 35.15 I 37.62 42.00 46.46 47.38 47.45
350.0  0.9120   34.95 I 35.10 35.65 I 35.65 I 37.90 42.20 46.51 47.39 47.45
400.0  0.9120   35.46 I 35.61 36.11 I 36.11 I 38.23 42.42 46.56 47.39 47.45
450.0  0.9120   35.94 I 36.08 36.56 I 36.56 I 38.58 42.65 46.61 47.40 47.45
500.0  0.9120   36.40 I 36.53 36.99 I 36.99 I 38.93 42.87 46.66 47.40 47.45

SENSIBLE ENERGY             12559.65
LATENT ENERGY               1998.02
HEAT FROM PIPE TO FLUID     18041.77
ERROR                      -0.1931E+02
FLUID INLET TEMP "ON"        26.00
ICE AROUND COIL AT INLET     0.0172
ON TIME: MIN/HR             14.000        FRACTION OF ON TIME     1.000
```

Appendix C

GROUND-COIL MODEL WITH SEASONAL GROUND TEMPERATURE VARIATION AT DEPTHS

C.1. Computer Code Listing

```
C
C       THIS CODE IS NAMED ECHX1.ONE
C       THIS CODE IS FOR HORIZONTAL COIL WITH GROUND SEASONAL
C       TEMP. VARIATION AND SAND BACKFILLING CHOICE.
C       IF THERE IS NO SPECIAL BACKFILLED MATERIAL, SET R3=R2
C       IN THE DATA STATEMENT.
C       THE COIL OUTSIDE EGDE TEMP. IS THE BACKFLLED MATERIAL
G       INSIDE EDGE TEMP. THE INSIDE EDGE OF SOIL TEMP. IS THE
C       BACKFILLED MATERIAL OUTSIDE EDGE TEMP.
C
      IMPLICIT REAL*8(A-H,O-Z)
      DOUBLE PRECISION MU1,MU2,MU3,LATENT,MOIST
      INTEGER DAYS,HOURS,MINUTE,SECOND
      LOGICAL OLDATA,STOP
      DIMENSION TITLE(20),U(20,2),T(10,20,2),F(10,20,20,2),
     &          S(10,20,20,2),SUM(20),SOILT(20)
      DIMENSION DEPTH(20),D1R(10),D2R(10),D3R(10),
     &          E1R(10),E2R(10),E3R(10),E4R(10),DRSOIL(8),
     &          ETA1(10),ETA2(10),
     &          C1R(10),C2R(10),C3R(10),C4R(10)
C
C
      DATA PI /3.141592654D0/
C
C
C
C  RHOF=DENSITY OF FLUID: PB/FT3
C  CPF=SPECIFIC HEAT OF FLUID: BTU PER PB PER F
C  RK1 = THERMAL CONDUCTIVITY OF COIL WALL: BTU/HR/FT/F
C  RK2 = THERMAL CONDUCTIVITY OF BACKFILLED REGION: BTU/HR/FT/F
C  RK3 = THERMAL CONDUCTIVITY OF SOIL  REGION: BTU/HR/FT/F
C  RHO1 = DENSITY OF COIL MATERIAL: PB/FT3
C  RHO2 = DENSITY OF BACKFILL REGION: PB/FT3
C  RHO3 = DENSITY OF SOIL  REGION: PB/FT3
C  CP1 = SPECIFIC HEAT OF COIL MATERIAL: BTU/PB/F
C  CP2 = SPECIFIC HEAT OF BACKFILLED MATERIAL: BTU/PB/F
C  CP3 = SPECIFIC HEAT OF SOIL: BTU/PB/F
C  H1 = CONVECTIVE HEAT TRANSFER COEFFICIENT BETWEEN FLUID AND COIL WALL
C        BTU PER HR PER FT2 PER F
C  TIMMAX = MAXIMUM PROGRAM RUNNING TIME, HOUR
C  TIMPRT = TIME INTERVAL BETWEEN DATA PRINT OUT, HOUR
C  GPM = FLUID FLOW RATE; GAL PER MIN
C  R1 = COIL INSIDE RADIUS: INCH
C  R2 = COIL OUTSIDE RADIUS: INCH
C  R3 = BOUNDARY OF BACKFILLED MATERIAL AND SOIL REGIONS: INCH
C  R4 = FARFIELD RADIUS: INCH
C  DTIME = TIME STEP FOR FLUID AND SOIL NON-FROZEN REGION: MIN
C  PDTIME = TIME STEP FOR COIL WALL AND SOIL FROZEN REGION: MIN
C  ZMAX = LENGTH OF THE GROUND COIL: FT
C  TH2O = FLUID INLET TEMPERATURE: NOT NECESSARILY CONSTANT: F
C        TH2O ACTUALLY REPRESENTS THE HEAT PUMP MODEL
C  NZ = NO. OF NODAL POINTS IN VERTICAL DIRECTION: FT
C  NPIPE = NO. OF NODAL POINTS OF COIL WALL
C  NFREEZ = NO. OF NODAL POINTS OF BACKFILLED REGION
```

```
C  NSOIL = NO. OF NODAL POINTS IN SOIL REGION
C  DRSOIL = DISTANCE BETWEEN NODAL POINTS IN SOIL
C            REGION: DOES NOT NECESSARILY BE CONSTANT: INCH
C         DANGLE = ANGULAR KNODAL DISTANCE: RAD
C         DPTH = COIL BURIAL DEPTH: INCH
C         TE = ANNUAL AVERAGE AMBIENT AIR TEMPERATURE: F
C         DTE = AMPLITUDE OF ANNUAL AMBIENT AIR TEMP VARIATION: F
C         PHASE = PHASE ANGLE USED IN KUSUDA'S CORRELATION: RAD
      DATA RKF, RHOF, CPF /.26D0, 60.4D0, 1.D0/
      DATA RK1, RHO1, CP1, H1/.125D0,58.6D0, .52D0, 92.910D0/
      DATA RK2, RHO2, CP2/1.26D0, 113.12D0, .296D0/
      DATA RK3, RHO3, CP3/1.26D0, 113.12D0, .296D0/
      DATA IOUT/7/, OLDATA/.FALSE./, STOP/.FALSE./
      DATA TIMMAX, TIMPRT /6.0D0, 6.0D0/
      DATA GPM/6.67D0/
      DATA R1,R2,R3,R4/.805D0, .95D0, .95D0,120.0D0/
      DATA DTIME/20.0D-1/,PDTIME/10.0D-2/
      DATA ZMAX/760.0D0/
      DATA NZ/10/, NPIPE/2/, NFREEZ/2/, NSOIL/9/, NRAD/17/
      DATA DRSOIL/3.D0,6.D0,6.D0,6.D0,6.D0,9.D0,12.D0,12.0D0/
      DATA TE,DTE,PHASE,TYEAR /60.D0,20.D0,.44D0,4350.0D0/
        DATA DPTH,RFAR,EPS/60.D0,60.D0,.05D0/
C
      NSOIL1=NSOIL-1
      NPM1=NPIPE-1
      NFZM1=NFREEZ-1
      NZM1=NZ-1
        NRAD1=NRAD-1
C
      TIME=0.
      BTUSY=0.0D0
      DZ=ZMAX/DBLE(NZ)
      HFLUX=0.
        AQGR=0.0D0
        DANGLE = PI/DBLE(NRAD-1)
        DRPIPE=(R2-R1)/DBLE(NPM1)
C
C       FORT9 FILE IS FOR MEASURED GROUND TEMP. AT 2,3,4 AND 10 FT
C
        READ(9,3002)TG2,TG3,TG4,TG10
3002    FORMAT(4F10.4)
        TG2=TG2*1.8D0+32.0D0
        TG3=TG3*1.8D0+32.0D0
        TG4=TG4*1.8D0+32.0D0
        TG10=TG10*1.8D0+32.0D0
C
C       USE KUSUDA AND ACHENBACH'S CORRELATION TO CALCULATE
C       GROUND FARFIELD TEMPERATURE, OR INPUT KNOWN GROUND
C       TEMPERATURES AT DEPTHS. IN THIS PROGRAM, THE MEASURED
C       GROUND TEMP. ARE USED
C
      R3R2=R3-R2
      DO 40 K=1,2
        DO 11 J=1,NZ
```

```
      DO 12 I=1,NSOIL
      IF(I .EQ. 1)R=R3
   IF(I .NE. 1)R=R+DRSOIL(I-1)
      DO 14 M=1,NRAD
      Z=(DPTH-R*DSIN(PI/2.0D0-(M-1)*DANGLE))/12.D0
C     &      *DSQRT(PI/(RK3/(RHO3*CP3)*8766.D0))
C  S(I,J,M,K)=TE-(DTE*DEXP(-Z)+15.0D0)*DCOS(PI*TYEAR/4383.D0-Z-
C     &                    PHASE)
      IF(Z .LE. 3.0D0)S(I,J,M,K)=(TG3-TG2)*(Z-2.0D0)+TG2
      IF(Z .GT. 3.0D0 .AND. Z .LE. 4.0D0)S(I,J,M,K)=
     &   (TG4-TG3)*(Z-3.0D0)+TG3
      IF(Z .GT. 4.0D0)S(I,J,M,K)=
     &   (TG10-TG4)*(Z-4.0D0)/6.0D0+TG4
      SOILT(M)=S(NSOIL,1,M,K)
14    CONTINUE
12    CONTINUE
      DO 15 I=1,NPIPE
15 T(I,J,K)=S(1,J,(NRAD+1)/2,K)
   DO 16 M=1,NRAD
   DO 17 I=1,NFZM1
   F(1,J,M,K)=T(NPIPE,J,K)
17 F(I+1,J,M,K)=S(1,J,M,K)
16 CONTINUE
      U(J,K)=T(1,J,K)
11    CONTINUE
   40 CONTINUE
C     IF(OLDATA)READ(19,2001,END=41)TIME,BTUSY,HFLUX,R3,
C     &    T,F,S,U
C   41 CONTINUE
 2001 FORMAT(7(1PE11.4))
      DZ=12.0D0*ZMAX/DBLE(NZ)
      DRFZ=(R3R2)/DBLE(NFZM1)
C
C  SET VELOCITY OF FLUID
C
      VINNER=1728.0D0*(GPM*.1337D0)/(PI*R1*R1)
      DO 60 IZ=1,NZ
      DEPTH(IZ)=DBLE(IZ)*DZ/12.0D0
   60 CONTINUE
C
C   PRINT DATA
C
      WRITE(IOUT,1001)R1,R2,R3,R4,ZMAX
 1001 FORMAT('0GEOMETRIC DATA :',/,
     &    5X,' R1      - INTERNAL RADIUS OF PIPE    ',5X,F7.3,
     &                                               ' INCHES',/,
     &    5X,' R2      - EXTERNAL RADIUS OF PIPE    ',5X,F7.3,
     &                                               ' INCHES',/,
     &    5X,' R3      - RADIUS OF BACKFILL REGION  ',5X,F7.3,/,
     &                                               ' INCHES',/,
     &    5X,' R4      = DISTANCE FROM PIPE TO      ',/,
     &    5X,'           UNDISTURBED SOIL           ',5X,F7.3,
     &                                               ' INCHES',/,
     &    5X,' ZMAX    - LENTH OF COIL              ',5X,F7.3,
```

```
     &                                                  ' FEET')
      R4=R2 + 12.0D0*R4
      WRITE(IOUT,1002)NPIPE,DRPIPE,NFREEZ,DRFZ,NSOIL,DRSOIL,
     &                NZ,DZ
 1002 FORMAT('0GEOMETRIC GRID :',/,
     &    5X,' NPIPE  - NUMBER OF MESH POINTS IN PIPE   ',I3,/,
     &    5X,' DRPIPE - RADIAL SPACING OF MESH POINTS    ',/,
     &    5X,'          IN PIPE                         ',F7.3,
     &                                                   ' INCHES',/,
     &    5X,' NFREEZ - NUMBER OF MESH POINTS IN        ',/,
     &    5X,'          BACKFILL ZONE                   ',I3,/,
     &    5X,' DRFZ   - RADIAL SPACING OF POINTS IN      ',/,
     &    5X,'          BACKFILL ZONE                    ',F7.3,
     &                                                   ' INCHES',/,
     &    5X,' NSOIL  - NUMBER OF POINTS IN OUTER SOIL   ',I3,/,
     &    5X,' DRSOIL - RADIAL SPACING OF POINTS IN      ',/,
     &    5X,'          OUTER SOIL                       ',8F7.3,/,
     &    5X,' NZ     - NUMBER OF VERTICAL MESH POINTS   ',I3,/,
     &    5X,' DZ     - VERTICAL SPACING OF POINTS       ',F7.2,/,
     &                                                   ' INCHES')
C
      WRITE(IOUT,1003)TIMMAX,TIMPRT,DTIME
 1003 FORMAT('0TIME PARAMETERS:',/,
     &    5X,' TIMMAX - LENGTH OF SIMULATION            ',F7.2,
     &                                                   ' HOURS',/,
     &    5X,' TIMPRT - TIMING OF PRINTED INFORMATION     ',F7.4,
     &                                                   ' HOURS',/,
     &    5X,' DTIME  = TIME STEP                         ',F7.5,
     &                                                   ' MINUTES')
      V1FT=VINNER/12.0D0
      WRITE(IOUT,1004)GPM,V1FT
 1004 FORMAT('0PUMPING DATA:',/,
     &    5X,' GPM    - PUMPING RATE                    ',F7.3,
     &                                         ' GALLONS/MINUTE',/,
     &    5X,' BINNER - VELOCITY OF FLUID                ',F7.3,
     &                                         ' FEET/MINUTE')
C
      ALPHA1 = RK1/(RHO1*CP1)
      ALPHA2 = RK2/(RHO2*CP2)
      ALPHA3 = RK3/(RHO3*CP3)
C
      WRITE(IOUT,1006)
 1006 FORMAT('0MATERIAL PROPERTIES:')
      WRITE(IOUT,1007)
 1007 FORMAT('0PIPE:')
      WRITE(IOUT,1008)RK1,H1,RHO1,CP1,ALPHA1
 1008 FORMAT(
     &    5X,' CONDUCTIVITY                             ',F7.3,
     &                                 ' BTU/HR-FT-F',/,
     &    5X,' HEAT TRANSFER RATE                       ',F7.3,
     &                                 ' BTU/HR-FT2-F',/,
     &    5X,' DENSITY                                  ',F7.3,
     &                                 ' LBM/FT3',/,
     &    5X,' SPECIFIC HEAT                            ',F7.3,
```

```
     &                                    ' BTU/LBM-F',/,
     &    5X,' ALPHA                                      ',F7.5,
     &                                    ' FT2/HR')
C
      WRITE(IOUT,1009)
 1009 FORMAT('0BACKFILL AREA:')
      WRITE(IOUT,1008)RK2,H2,RHO2,CP2,ALPHA2
      WRITE(IOUT,1010)
 1010 FORMAT('0SOIL:')
      WRITE(IOUT,1008)RK3,H3,RHO3,CP3,ALPHA3
C
      WRITE(IOUT,1011)RHOF,CPF
 1011 FORMAT('0WORKING FLUID:',/,
     &    5X,' RHOF   -DENSITY                            ',F7.3,
     &                                        ' LBM/FT3',/,
     &    5X,'CPF     - SPECIFIC HEAT                     ',F7.3,
     &                                        ' BTU/LBM-F')
C
C   CHANGE UNITS TO MINUTES AND INCHES
C
      TIMMAX=60.0D0*TIMMAX+TIME
      NPRINT=(60.0D0*TIMPRT+DTIME/2.0D0)/DTIME
      ZMAX=12.0D0*ZMAX
        RKF=RKF/(60.D0*12.D0)
      RK1=RK1/(60.0D0*12.0D0)
      RK2=RK2/(60.0D0*12.0D0)
      RK3=RK3/(60.0D0*12.0D0)
C
      H1=H1/(60.0D0*144.0D0)
      H2=H2/(60.0D0*144.0D0)
      H3=H3/(60.0D0*144.0D0)
C
      RHOF=RHOF/1728.0D0
      RHO1=RHO1/1728.0D0
      RHO2=RHO2/1728.0D0
      RHO3=RHO3/1728.0D0
C
      ALPHA1=RK1/(RHO1*CP1)
      ALPHA2=RK2/(RHO2*CP2)
      ALPHA3=RK3/(RHO3*CP3)
C
C   SET CONSTANTS USED IN THE CALCULATIONS
C
      DTDZ=PDTIME/DZ
      BETA2=VINNER*DTDZ
      BETA3=2.0D0*H1*PDTIME/(RHOF*CPF*R1)
        BETA1=1.0D0-BETA2-BETA3
      A1DTDR=ALPHA1*PDTIME/DRPIPE
        A2DTDR=ALPHA2*DTIME/DRFZ
      GAMMA2=A1DTDR*(2.0D0/DRPIPE+1.0D0/R1)
      GAMMA3=2.0D0*A1DTDR*H1/RK1
      GAMMA1=1.0D0-GAMMA2-GAMMA3
        A3DTDR=ALPHA3*DTIME/DRSOIL(1)
   SAND1=RK3/RK2*2.0D0*A2DTDR/DRSOIL(1)
```

```
   SAND2=2.0D0*A2DTDR*(1.0D0/DRFZ-1.0D0/2.0D0/R3)
   SAND3=DRFZ*A2DTDR/(R3*DANGLE)**2
   SAND4=1.0D0-SAND1-SAND2-2.0D0*SAND3
      DO 70 I=1,NPIPE
      R=R1+(DBLE(I)-1.0D0)*DRPIPE
      C2R(I)=A1DTDR*(1.0D0/DRPIPE+1.0D0/R)
      C3R(I)=A1DTDR/DRPIPE
      C1R(I)=1.0D0-C2R(I)-C3R(I)
   70 CONTINUE
C
C
      ITIME=0
C      WRITE(IOUT,2)TITLE
      HOURS=(TIME+.5/60.)/60.
      DAYS=HOURS/24
      HOURS=HOURS-24*DAYS
      MINUTE=TIME-60*(HOURS+24.0D0*DAYS)
      SECOND=60.*(TIME-60*(HOURS+24.0D0*DAYS)-MINUTE)
        WRITE(IOUT,1909)
1909    FORMAT(/,'  INITIAL FLUID, COIL, AND GROUND TEMPERATURE')
      WRITE(IOUT,1901)
 1901 FORMAT('0 LENGTH  H2O        PIPE',10X,'SOIL',/,'   FT.',
     &        25X,102('-'))
C
      DO 99 J=1,NZ
      WRITE(IOUT,1902)DEPTH(J),U(J,1),T(1,J,1),T(2,J,1),
     &              ((S(I,J,M,1),I=2,NSOIL),M=1,NRAD,4)
 1902 FORMAT(' ',F5.1,2X,F6.2,' I',2F6.2,' I',8F6.2,
     &    /,30X,8F6.2,/,30X,8F6.2,/,30X,8F6.2,/,30X,8F6.2)
   99 CONTINUE
      WRITE(IOUT,1902)
C
C   BEGIN TRANSIENT CALCULATIONS
C
 1000 INOW=MOD(ITIME,2)+1
      ITHEN=MOD(ITIME+1,2)+1
      ITIME=ITIME+1
        IF(DMOD(TIME,60.0D0) .GE. DTIME)GO TO 103
C
C       SUBROUTINE FLUID IS TO DETERMINE THE COIL FLUID INLET
C       TEMPERATURE.  SUBROUTINE CYCLE IS TO DETERMINE THE
C       GROUND COIL FLUID PUMP CYCLIC OPERATION.  IN THIS PROGRAM,
C       THE MEASURED FLUID TEMP. IS INPUT AS READ FROM FORT10 FILE,
C       ITEM ATH2O. CYCLE OF "ON" AND "OFF" IS DETERMINED BY MEASURED
C       HEAT PUMP POWER CONSUMPTION DIVIDED BY THAT AT STEADY STATE
C
C        CALL FLUID(TIME,TH2O)
C        CALL CYCLE(TIME,VINNER,V1,ON)
C       NEXT 7LINES ARE ADDED TO READ DATA FROM DATA FILE
C
        READ(10,3003)QGR,HPP,ATH2O,THOUT,AMB
        READ(9,3002)TG2,TG3,TG4,TG10
        TG2=TG2*1.8D0+32.0D0
        TG3=TG3*1.8D0+32.0D0
```

```
        TG4=TG4*1.8D0+32.0D0
        TG10=TG10*1.8D0+32.0D0
        THOUT=THOUT*1.8D0+32.0D0
        ATH2O=ATH2O*1.8D0+32.0D0
        AMB=AMB*1.8D0+32.0D0
3003    FORMAT(5F10.4)
        QGR=QGR*3.413D0
        AQGR=AQGR+QGR
        IF(HPP .LT. 2320.0D0)ONT=HPP/2320.0D0*60.0D0
        IF(HPP .GE. 2320.0D0)ONT=60.0D0
        LT=ONT/DTIME
        FRACT=ONT-DTIME*(DBLE(LT))
        IF(LT.EQ.0)GO TO 102
        AFRACT=1.0D0+FRACT/DTIME/DBLE(LT)
102     IF(LT.EQ.0)AFRACT=1.0D0+ONT/DTIME
103     V1=VINNER
      TIME=TIME+DTIME
        IF(DMOD(TIME,60.0D0) .GT. ONT)V1=0.0D0
        TH2O=ATH2O
      IF(TIME .GT. TIMMAX)STOP=.TRUE.
        IF(TIME .GT. TIMMAX)GO TO 2200
        IF(TH2O .LE. U(1,INOW))GO TO 1401
        IF(ONT .LT. 0.01D0)V1=0.0D0
        TH2O=U(NZ,INOW)-QGR/ONT/(GPM*.1337D0*RHOF*CPF)/1728.0D0
        IF(TH2O .GT. ATH2O)TH2O=ATH2O
        IF(V1.LT.0.1D-1)TH2O=U(1,INOW)
C
1401  DO 1300 J=1,NZ
      IF(R3R2 .GT. EPS)GO TO 1050
      MU2=2.0D0*RK3/RK1*A1DTDR/DRSOIL(1)
      MU3=A1DTDR*(2.0D0/DRPIPE-1.0D0/R2)
      MU1=1.0D0-MU2-MU3
      GO TO 1020
C
1050  MU2=2.0D0*RK2/RK1*A1DTDR/DRFZ
      MU3=A1DTDR*(2.0D0/DRPIPE-1.0D0/R2)
      MU1=1.0D0-MU2-MU3
        IF(NFZM1 .LT. 2)GO TO 1020
      DO 1200 I=2,NFZM1
      R=R2+(DBLE(I)-1.0D0)*DRFZ
      D2R(I)=A2DTDR*(1.0D0/DRFZ+1.0D0/R)
      D3R(I)=A2DTDR/DRFZ
      D1R(I)=1.0D0-D2R(I)-D3R(I)
 1200 CONTINUE
 1020 CONTINUE
      R=R3
      DO 71 I=2,NSOIL1
  R=R+DRSOIL(I-1)
  DRAVG=(DRSOIL(I)+DRSOIL(I-1))*.5D0
        E2R(I)=2.0D0*ALPHA3*DTIME/DRSOIL(I)/DRSOIL(I-1)
        E3R(I)=ALPHA3*DTIME/DRSOIL(I-1)*(2.0D0/DRSOIL(I-1)-1.0D0/R)
        E4R(I)=ALPHA3*DTIME/((R*DANGLE)**2)
        E1R(I)=1.0D0-E2R(I)-E3R(I)-2.0D0*E4R(I)
71      CONTINUE
```

```
C
C   CALCULATE FLUID TEMPERATURE
C
        KK=DTIME/PDTIME+.1
        SUM(J)=0.0D0
        DO 1125 M=2,NRAD1
1125    SUM(J)=SUM(J)+S(2,J,M,INOW)
   SUM(J)=SUM(J)+(S(2,J,1,INOW)+S(2,J,NRAD,INOW))*.5D0
   SUM(J)=SUM(J)/DBLE(NRAD1)
        IF(R3R2 .GT. EPS)GO TO 1160
        DO 801 K=1,KK
        IF(V1 .LT. 1.0D-1) GO TO 1104
      IF(J .EQ. 1)U(1,ITHEN)=BETA1*U(1,INOW)+BETA2*TH2O+
     &            BETA3*T(1,1,INOW)
      IF(J .NE. 1)U(J,ITHEN)=BETA1*U(J,INOW)+BETA2*U(J-1,INOW)+
     &            BETA3*T(1,J,INOW)
        T(1,J,ITHEN)=GAMMA1*T(1,J,INOW)+GAMMA2*T(2,J,INOW)
     &    +GAMMA3*U(J,INOW)
        IF(J.EQ.1)HFLUX=HFLUX+PI*R1*PDTIME*DZ*H1*
     &  (T(1,J,INOW)*3.0D0-T(1,J+1,INOW)-U(1,INOW)-TH2O)*AFRACT
        IF(J.NE.1)HFLUX=HFLUX+PI*R1*PDTIME*DZ*H1*
     &  (T(1,J,INOW)+T(1,J-1,INOW)-U(J,INOW)-U(J-1,INOW))*AFRACT
        GO TO 1108
C
C   CALCULATE PIPE WALL TEMPERATURE
C
1104    U(J,ITHEN)=2.0D0*R1*RK1*(T(2,J,INOW)-T(1,J,INOW))*PDTIME/
     &    (RHOF*CPF*R1**2)/DRPIPE+U(J,INOW)
C
C       NEXT LINE IS ADDED TEMPORARY TO CHECK THE B.C.
C       IMPOSED ON THE WALL WHEN THE FLUID FLOW STOPPED.
C
        T(1,J,ITHEN)=U(J,ITHEN)
1108  IF(NPM1 .LT. 2) GO TO 1120
      DO 1110 I=2,NPM1
      T(I,J,ITHEN)=C1R(I)*T(I,J,INOW)+
     &    C2R(I)*T(I+1,J,INOW)+C3R(I)*T(I-1,J,INOW)
 1110 CONTINUE
C
1120  T(NPIPE,J,ITHEN)=MU1*T(NPIPE,J,INOW)+MU2*SUM(J)+
     &                 MU3*T(NPM1,J,INOW)
      U(J,INOW)=U(J,ITHEN)
        DO 1102 I=1,NPIPE
   T(I,J,INOW)=T(I,J,ITHEN)
1102    CONTINUE
 801    CONTINUE
        GO TO 1191
1160    SUM(J)=0.0D0
        DO 1159 M=2,NRAD1
1159    SUM(J)=SUM(J)+F(2,J,M,INOW)
        SUM(J)=SUM(J)+(F(2,J,1,INOW)+F(2,J,NRAD,INOW))*.5D0
        SUM(J)=SUM(J)/DBLE(NRAD1)
        DO 1155 K=1,KK
        IF(V1 .LT. 1.0D-1)GO TO 1167
```

```
   IF(J .EQ. 1)U(1,ITHEN)=BETA1*U(1,INOW)+BETA2*TH2O+
     &  BETA3*T(1,1,INOW)
   IF(J .NE. 1)U(J,ITHEN)=BETA1*U(J,INOW)+BETA2*U(J-1,INOW)
     &       +BETA3*T(1,J,INOW)
        T(1,J,ITHEN)=GAMMA1*T(1,J,INOW)+GAMMA2*T(2,J,INOW)+
     &    GAMMA3*U(J,INOW)
        IF(J.EQ.1)HFLUX=HFLUX+PI*R1*PDTIME*DZ*H1*
     &  (T(1,J,INOW)*3.0D0-T(1,J+1,INOW)-U(1,INOW)-TH2O)*AFRACT
        IF(J.NE.1)HFLUX=HFLUX+PI*R1*PDTIME*DZ*H1*
     &  (T(1,J,INOW)+T(1,J-1,INOW)-U(J,INOW)-U(J-1,INOW))*AFRACT
        GO TO 1164
1167    U(J,ITHEN)=2.0D0*RK1*(T(2,J,INOW)-T(1,J,INOW))*PDTIME
     &    /(RHOF*CPF*R1**2)/DLOG(1.D0+DRPIPE/R1)
     &    +U(J,INOW)
        T(1,J,ITHEN)=U(J,ITHEN)
1164    IF(NPM1 .LT. 2)GO TO 1162
        DO 1161 I=2,NPM1
   T(I,J,ITHEN)=C1R(I)*T(I,J,INOW)+
     &    C2R(I)*T(I+1,J,INOW)+C3R(I)*T(I-1,J,INOW)
1161      CONTINUE
1162  T(NPIPE,J,ITHEN)=MU1*T(NPIPE,J,INOW)+MU2*SUM(J)+
     &                 MU3*T(NPM1,J,INOW)
        U(J,INOW)=U(J,ITHEN)
        DO 1163 I=1,NPIPE
   T(I,J,INOW)=T(I,J,ITHEN)
1163    CONTINUE
1155    CONTINUE
        DO 1170 M=1,NRAD
      F(1,J,M,ITHEN)=T(NPIPE,J,ITHEN)
1170    CONTINUE
        IF(NFZM1 .LT. 2)GO TO 1190
        DO 1342 M=1,NRAD
      DO 1340 I=2,NFZM1
      F(I,J,M,ITHEN)=D1R(I)*F(I,J,M,INOW)+
     &    D2R(I)*F(I+1,J,M,INOW)+D3R(I)*F(I-1,J,M,INOW)
 1340 CONTINUE
1342    CONTINUE
1190    DO 1157 M=1,NRAD
        IF(M .EQ. 1)BF=2.0D0*F(NFREEZ,J,M+1,INOW)
   IF(M .EQ. NRAD)BF=2.0D0*F(NFREEZ,J,M-1,INOW)
   IF(M .NE. 1 .AND. M .NE. NRAD)
     &      BF=F(NFREEZ,J,M+1,INOW)+F(NFREEZ,J,M-1,INOW)
        F(NFREEZ,J,M,ITHEN)=SAND1*S(2,J,M,INOW)+SAND2*
     &    F(NFZM1,J,M,INOW)+SAND3*BF+SAND4*F(NFREEZ,J,M,INOW)
1157    CONTINUE
C
C   CALCULATE TEMPERATURE IN SOIL ZONE
C
1191    CONTINUE
C
C       NEXT LINESARE FOR UPDATING VARIABLE FARFIELD TEMPERATURE WITH
C       KUSUDA AND ACHENBACH'S CORRELATION
C
        IF(DMOD(TIME,60.0D0) .GT. .001D0)GO TO 3125
```

```
        R=RFAR
        DO 3050 M=1,NRAD
   ZZ=(DPTH-R*DSIN(PI/2.D0-(M-1)*DANGLE))/12.D0
C       3652.5=60*8766/144
C        Z=ZZ*DSQRT(PI/ALPHA3/3652.5D0)
C        SOILT(I,J,M)=TE-(DTE*DEXP(-Z)+15.0D0)*DCOS(PI*(TYEAR+TIME
C     &    /60.D0)/4383.D0-Z-PHASE)
        IF(ZZ.LE.3.0D0)SOILT(M)=(TG3-TG2)*(ZZ-2.0D0)+TG2
        IF(ZZ.GT.3.0D0 .AND. ZZ.LE.4.0D0)SOILT(M)=
     &    (TG4-TG3)*(ZZ-3.0D0)+TG3
        IF(ZZ.GT.4.0D0)SOILT(M)=(TG10-TG4)*(ZZ-4.0D0)/6.0D0+TG4
3050    CONTINUE
3125    DO 3100 M=1,NRAD
        S(NSOIL,J,M,ITHEN)=SOILT(M)
        IF(R3R2.GE.EPS)GO TO 3124
        S(1,J,M,ITHEN)=T(NPIPE,J,ITHEN)
        S(1,J,M,INOW)=T(NPIPE,J,INOW)
        GO TO 3126
3124    S(1,J,M,ITHEN)=F(NFREEZ,J,M,ITHEN)
        S(1,J,M,INOW)=F(NFREEZ,J,M,INOW)
3126    DO 3150 I=2,NSOIL1
   S(I,J,M,ITHEN)=E1R(I)*S(I,J,M,INOW)
     &    +E2R(I)*S(I+1,J,M,INOW)+E3R(I)*S(I-1,J,M,INOW)
        IF(M .EQ. 1)S(I,J,M,ITHEN)=S(I,J,M,ITHEN)+E4R(I)*2.D0*
     &    S(I,J,M+1,INOW)
   IF(M .NE. 1 .AND. M .NE. NRAD)S(I,J,M,ITHEN)=S(I,J,M,ITHEN)+
     &    E4R(I)*(S(I,J,M+1,INOW)+S(I,J,M-1,INOW))
   IF(M .EQ. NRAD)S(I,J,M,ITHEN)=S(I,J,M,ITHEN)+E4R(I)*
     &    S(I,J,M-1,INOW)*2.D0
3150    CONTINUE
3100    CONTINUE
1355  IF(V1 .LT. 1.0D-1) GO TO 1477
        IF(J .EQ.1)
     &  BTUSY=BTUSY+PI*RK3*DZ*DTIME*R2*(3.D0*SUM(J)-
     &  SUM(J+1)-3.D0*T(NPIPE,J,INOW)+T(NPIPE,J+1,INOW))/
     &  DRSOIL(1)*AFRACT
        IF(J .NE. 1)
     &  BTUSY=BTUSY+PI*RK3*DZ*DTIME*R2*(SUM(J)+SUM(J-1)
     &  -T(NPIPE,J,INOW)-T(NPIPE,J-1,INOW))/
     &  DRSOIL(1)*AFRACT
1477    CONTINUE
 1300 CONTINUE
        ERROR=(BTUSY-HFLUX)/HFLUX*100.0D0
888   FORMAT(1X,10F8.4)
      IF(STOP) GO TO 190
C
C   ROUND TIME TO THE NEXT HIGHEST HOUR:MINUTE:SECOND
C
        IF(DMOD(TIME,60.0D0) .GT. DTIME/2.0D0)GO TO 2101
  190 TIME2=TIME+.5/60.
      HOURS=TIME2/60.
      DAYS=HOURS/24
      HOURS=HOURS-24*DAYS
      MINUTE=TIME2-60.*(HOURS+24.0D0*DAYS)
```

```
      SECOND=60.*(TIME2-60.*(HOURS+24.0D0*DAYS)-MINUTE)
C
      WRITE(IOUT,490)DAYS,HOURS,MINUTE,SECOND
      WRITE(6,490)DAYS,HOURS,MINUTE,SECOND
        IF(ITIME .LT. NPRINT)GO TO 2100
        ITIME=0
      WRITE(IOUT,1901)
  490 FORMAT(/1H0,'TIME = ',I3,' DAYS ',I3,' HOURS ',I3,
     &       ' MINUTES ',I3,' SECONDS')
      DO 499 J=1,NZ
      WRITE(IOUT,1902)DEPTH(J),U(J,ITHEN),T(1,J,ITHEN),
     &  T(2,J,ITHEN),
     &            ((S(I,J,M,ITHEN),I=2,NSOIL),M=1,NRAD,4)
      WRITE(6,1902)DEPTH(J),U(J,ITHEN),T(1,J,ITHEN),
     &  T(2,J,ITHEN),
     &            ((S(I,J,M,ITHEN),I=2,NSOIL),M=1,NRAD,4)
  499 CONTINUE
2100    WRITE(IOUT,997)BTUSY,HFLUX,ERROR,TH2O,ATH2O,AMB
        WRITE(6,997)BTUSY,HFLUX,ERROR,TH2O,ATH2O,AMB
  997 FORMAT('0',
     &           'SENSIBLE ENERGY                ',F15.2,/,1X,
     &           'HEAT FROM PIPE TO FLUID        ',F15.2,/,1X,
     &           '% OF ERROR                     ',F15.4,/,1X,
     &           'INLET FLUID TEMP               ',F15.2,/,1X,
     &           'MEASURED INLET FLUID TEMP      ',F15.2,/,1X,
     &           'AMBIENT AIR TEMP               ',F15.2)
        WRITE(IOUT,996)ONT,AFRACT
        WRITE(6,996)ONT,AFRACT
996     FORMAT(  ' ON TIME: MIN/HR     ',F10.3,5X,'FRACTION OF
     & ON TIME',F10.4)
  998 FORMAT(1X,10F5.1)
C
C       NEXT COMMENTED LINES ARE FOR PRINT OUT OF DETAILED GROUND
C       TEMPERATURE DISTRIBUTION
C
C        IF(TIME .LT. (TIMMAX-DTIME)) GO TO 2101
C        DO 5000 J=1,NZ
C        WRITE(IOUT,5001)DEPTH(J),((S(I,J,M,ITHEN),I=1,NSOIL),
C     &    M=1,NRAD)
C5000    CONTINUE
C5001    FORMAT(3X,F6.2,5X,8F8.2/(14X,8F8.2))
C      REWIND 21
C      WRITE(21,2001)TIME,BTUSY,HFLUX,R3,T,
C     &    F,S,U
 2101   IF(STOP)GO TO 2200
        GO TO 1000
 2200 STOP
      END
```

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C       THIS FILE IS FORT9.  IT IS FOR GROUND FARFIELD TEMPERATURE (C)
C       MEASUREMENT AT 2,3,4, AND 10 FEET BELOW SURFACE AT UNIV. OF
C       TENNESSEE TECH HOUSE GROUND COIL HEAT PUMP PROJECT.  ONLY
C       FOUR DAY DATA ARE SHOWN. FOR FULL FILE, CONTACT V.C. MEI OF
C       ORNL, OR CALL (615) 576-4945
C
   11.0200   12.0700   13.2400   17.2000
   11.0000   12.0500   13.2300   17.2000
   10.9800   12.0400   13.2300   17.2000
   10.9500   12.0100   13.2200   17.1900
   10.9300   12.0000   13.2000   17.1900
   10.9100   11.9800   13.2000   17.1800
   10.8900   11.9600   13.1800   17.1800
   10.8800   11.9500   13.1800   17.1800
   10.8700   11.9400   13.1700   17.1900
   10.8400   11.9100   13.1600   17.1800
   10.8300   11.9000   13.1500   17.1800
   10.8100   11.8800   13.1500   17.1700
   10.7900   11.8600   13.1200   17.1600
   10.7700   11.8500   13.1200   17.1600
   10.7500   11.8300   13.1100   17.1600
   10.7300   11.8100   13.0900   17.1500
   10.7100   11.7900   13.0900   17.1500
   10.7000   11.7900   13.0800   17.1600
   10.6800   11.7700   13.0800   17.1600
   10.6700   11.7600   13.0600   17.1600
   10.6400   11.7300   13.0600   17.1400
   10.6200   11.7100   13.0400   17.1400
   10.6200   11.7200   13.0400   17.1600
   10.6000   11.6900   13.0300   17.1400
   10.5900   11.6900   13.0200   17.1500
   10.5700   11.6600   13.0100   17.1400
   10.5700   11.6500   13.0000   17.1500
   10.5500   11.6400   13.0000   17.1500
   10.5400   11.6200   12.9800   17.1400
   10.5200   11.6000   12.9700   17.1200
   10.5100   11.5900   12.9600   17.1300
   10.5100   11.5800   12.9500   17.1300
   10.4900   11.5600   12.9400   17.1200
   10.4800   11.5500   12.9300   17.1200
   10.4800   11.5500   12.9200   17.1300
   10.4600   11.5200   12.9100   17.1200
   10.4400   11.5000   12.8900   17.1000
   10.4500   11.5000   12.9000   17.1100
   10.4300   11.4900   12.8900   17.1100
   10.4200   11.4800   12.8800   17.1200
   10.4100   11.4600   12.8700   17.1100
   10.4000   11.4600   12.8600   17.1100
   10.3800   11.4400   12.8500   17.1100
   10.3600   11.4200   12.8300   17.1000
   10.3600   11.4200   12.8300   17.1000
   10.3300   11.3900   12.8100   17.0900
   10.3300   11.3900   12.8100   17.0900
   10.3200   11.3800   12.8000   17.0900
```

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C
C       THIS FILE IS FORT10. IT IS FOR HOURLY MEASUREMENT OF QGR (ENERGY
C       ABSORBED FROM GROUND, IN WATT), HPP (HEAT PUMP POWER CONSUMPTION
C       IN WATT), ATH2O (COIL FLUID INLET TEMP. IN C), THOUT (COIL FLUID
C       OUTLET TEMP. IN C), AND AMB (AMBIENT TEMP. IN C).  ONLY FOUR DAY
C       DATA ARE SHOWN. FOR FULL DATA FILE, CALL V.C. MEI OF ORNL AT
C       (615) 576-4945
C
 1506.7000  840.0000   10.3600   10.9200    3.5300
 2212.5000 1240.0000    7.4100   10.2500    3.1700
 2008.2000 1080.0000    9.5100   10.2300    3.1800
 2435.3999 1360.0000    6.9800    9.7600    2.8900
 2045.3999 1120.0000    9.4500   10.0200    2.3400
 2400.5999 1320.0000    6.8800    9.6700    1.8800
 2161.5000 1200.0000    8.7800    9.7300    3.5200
 2611.8999 1480.0000    6.6800    9.4500    3.7800
 2391.2998 1320.0000    8.2200    9.3300    3.9500
 2089.5000 1160.0000    6.9900    9.7900    4.3200
 2409.8999 1320.0000    8.2000    9.2900    5.5700
 2293.7998 1280.0000    6.7900    9.5900    6.3200
 2472.5999 1360.0000    8.2700    9.3200    9.1900
 1625.0999  920.0000    7.1600   10.0300    6.8600
 2077.8999 1160.0000    8.6500    9.7300    7.3100
 1571.7000  880.0000   10.7600   10.2800    6.8100
 2082.5000 1160.0000    8.6700    9.7000    5.9300
 1599.5999  880.0000   10.3800   10.2500    4.8000
 1123.7000  640.0000    9.5600   10.6100    4.0800
  675.6099  360.0000    9.9500   11.0200    3.6500
  982.0798  560.0000    7.9800   10.8700    3.5600
 1564.7998  880.0000    9.3100   10.3100    3.2500
 1367.3999  760.0000    9.1200   10.2500    3.0300
 1478.8999  840.0000   13.4700   12.0600    2.9200
 1439.3999  800.0000    7.7600   10.6500    2.7300
 1871.2000 1040.0000    8.9000   10.0400    2.4400
 1815.5000 1040.0000    7.3000   10.1300    2.3800
 2210.2000 1240.0000    8.6000    9.7000    2.4900
 2133.5999 1200.0000    6.9600    9.7700    1.8800
 2233.3999 1240.0000    8.4000    9.5100    1.2800
 2189.2998 1200.0000    6.8300    9.5900    0.8000
 2033.7998 1120.0000    8.6300    9.6500   -0.2400
 1360.5000  760.0000   10.5000   10.5000   -1.3400
 1163.0999  640.0000    9.8000   10.6300    1.4200
  742.9399  440.0000   15.0500   12.0300    2.6900
 1174.7000  640.0000   10.3100   11.0300    6.0500
  329.6799  200.0000   15.5100   13.1200    8.5500
    0.0000    0.0000   18.2300   17.5300    7.0700
    0.0000    0.0000   18.5700   19.4800    5.8800
    0.0000    0.0000   18.5900   20.3400    6.0800
    0.0000    0.0000   18.4600   20.8100    5.1100
    0.0000    0.0000   18.2700   21.0300    3.3200
    0.0000    0.0000   17.9700   21.0200    2.2900
  703.4800  400.0000   10.3300   11.6000    1.6200
  740.6199  400.0000   10.1400   11.4000    1.6300
  798.6599  440.0000   13.5000   11.8200    0.7700
 1297.7998  720.0000   12.6700   11.4400    0.1500
 1799.2998 1000.0000    7.4900   10.3500   -0.9400
```

C.2. Sample Calculation

```
GEOMETRIC DATA :
      R1     - INTERNAL RADIUS OF PIPE          0.805 INCHES
      R2     - EXTERNAL RADIUS OF PIPE          0.950 INCHES
      R3     - RADIUS OF BACKFILL REGION        0.950 INCHES
      R4     = DISTANCE FROM PIPE TO
               UNDISTURBED SOIL               120.000 INCHES
      ZMAX   - LENTH OF COIL                   760.000 FEET

GEOMETRIC GRID :
      NPIPE  - NUMBER OF MESH POINTS IN PIPE     2
      DRPIPE - RADIAL SPACING OF MESH POINTS
               IN PIPE                           0.145 INCHES
      NFREEZ - NUMBER OF MESH POINTS IN
               BACKFILL ZONE                     2
      DRFZ   - RADIAL SPACING OF POINTS IN
               BACKFILL ZONE                     0.000 INCHES
      NSOIL  - NUMBER OF POINTS IN OUTER SOIL    9
      DRSOIL - RADIAL SPACING OF POINTS IN
               OUTER SOIL                        3.000  6.000  6.000  6.000  6.000  9.000 12.000 12.000
      NZ     - NUMBER OF VERTICAL MESH POINTS   10
      DZ     - VERTICAL SPACING OF POINTS       912.00 INCHES

TIME PARAMETERS:
      TIMMAX - LENGTH OF SIMULATION              6.00 HOURS
      TIMPRT - TIMING OF PRINTED INFORMATION     6.0000 HOURS
      DTIME  = TIME STEP                         2.00000 MINUTES

PUMPING DATA:
      GPM    - PUMPING RATE                      6.670 GALLONS/MINUTE
      BINNER - VELOCITY OF FLUID                63.078 FEET/MINUTE

MATERIAL PROPERTIES:

PIPE:
      CONDUCTIVITY                              0.125 BTU/HR-FT-F
      HEAT TRANSFER RATE                       92.910 BTU/HR-FT2-F
      DENSITY                                  58.600 LBM/FT3
      SPECIFIC HEAT                             0.520 BTU/LBM-F
      ALPHA                                   0.00410 FT2/HR

BACKFILL AREA:
      CONDUCTIVITY                              1.260 BTU/HR-FT-F
      HEAT TRANSFER RATE                        0.000 BTU/HR-FT2-F
      DENSITY                                 113.120 LBM/FT3
      SPECIFIC HEAT                             0.296 BTU/LBM-F
      ALPHA                                   0.03763 FT2/HR

SOIL:
      CONDUCTIVITY                              1.260 BTU/HR-FT-F
      HEAT TRANSFER RATE                        0.000 BTU/HR-FT2-F
      DENSITY                                 113.120 LBM/FT3
      SPECIFIC HEAT                             0.296 BTU/LBM-F
      ALPHA                                   0.03763 FT2/HR
```

WORKING FLUID:

RHOF	- DENSITY	60.400 LBM/FT3
CPF	- SPECIFIC HEAT	1.000 BTU/LBM-F

INITIAL FLUID, COIL, AND GROUND TEMPERATURE

LENGTH FT.	H2O	PIPE	SOIL							
76.0	57.02 I	57.02 57.02 I	56.63	56.03	55.14	54.09	53.10	51.69	49.80	47.91
			56.74	56.32	55.90	55.21	54.47	53.39	52.05	50.72
			57.02	57.02	57.02	57.02	57.02	57.02	57.02	57.02
			57.30	57.72	58.14	58.56	58.98	59.61	60.45	61.29
			57.41	58.01	58.60	59.19	59.79	60.68	61.87	63.05
152.0	57.02 I	57.02 57.02 I	56.63	56.03	55.14	54.09	53.10	51.69	49.80	47.91
			56.74	56.32	55.90	55.21	54.47	53.39	52.05	50.72
			57.02	57.02	57.02	57.02	57.02	57.02	57.02	57.02
			57.30	57.72	58.14	58.56	58.98	59.61	60.45	61.29
			57.41	58.01	58.60	59.19	59.79	60.68	61.87	63.05
228.0	57.02 I	57.02 57.02 I	56.63	56.03	55.14	54.09	53.10	51.69	49.80	47.91
			56.74	56.32	55.90	55.21	54.47	53.39	52.05	50.72
			57.02	57.02	57.02	57.02	57.02	57.02	57.02	57.02
			57.30	57.72	58.14	58.56	58.98	59.61	60.45	61.29
			57.41	58.01	58.60	59.19	59.79	60.68	61.87	63.05
304.0	57.02 I	57.02 57.02 I	56.63	56.03	55.14	54.09	53.10	51.69	49.80	47.91
			56.74	56.32	55.90	55.21	54.47	53.39	52.05	50.72
			57.02	57.02	57.02	57.02	57.02	57.02	57.02	57.02
			57.30	57.72	58.14	58.56	58.98	59.61	60.45	61.29
			57.41	58.01	58.60	59.19	59.79	60.68	61.87	63.05
380.0	57.02 I	57.02 57.02 I	56.63	56.03	55.14	54.09	53.10	51.69	49.80	47.91
			56.74	56.32	55.90	55.21	54.47	53.39	52.05	50.72
			57.02	57.02	57.02	57.02	57.02	57.02	57.02	57.02
			57.30	57.72	58.14	58.56	58.98	59.61	60.45	61.29
			57.41	58.01	58.60	59.19	59.79	60.68	61.87	63.05
456.0	57.02 I	57.02 57.02 I	56.63	56.03	55.14	54.09	53.10	51.69	49.80	47.91
			56.74	56.32	55.90	55.21	54.47	53.39	52.05	50.72
			57.02	57.02	57.02	57.02	57.02	57.02	57.02	57.02
			57.30	57.72	58.14	58.56	58.98	59.61	60.45	61.29
			57.41	58.01	58.60	59.19	59.79	60.68	61.87	63.05
532.0	57.02 I	57.02 57.02 I	56.63	56.03	55.14	54.09	53.10	51.69	49.80	47.91
			56.74	56.32	55.90	55.21	54.47	53.39	52.05	50.72
			57.02	57.02	57.02	57.02	57.02	57.02	57.02	57.02
			57.30	57.72	58.14	58.56	58.98	59.61	60.45	61.29
			57.41	58.01	58.60	59.19	59.79	60.68	61.87	63.05
608.0	57.02 I	57.02 57.02 I	56.63	56.03	55.14	54.09	53.10	51.69	49.80	47.91
			56.74	56.32	55.90	55.21	54.47	53.39	52.05	50.72
			57.02	57.02	57.02	57.02	57.02	57.02	57.02	57.02
			57.30	57.72	58.14	58.56	58.98	59.61	60.45	61.29
			57.41	58.01	58.60	59.19	59.79	60.68	61.87	63.05
684.0	57.02 I	57.02 57.02 I	56.63	56.03	55.14	54.09	53.10	51.69	49.80	47.91
			56.74	56.32	55.90	55.21	54.47	53.39	52.05	50.72
			57.02	57.02	57.02	57.02	57.02	57.02	57.02	57.02
			57.30	57.72	58.14	58.56	58.98	59.61	60.45	61.29
			57.41	58.01	58.60	59.19	59.79	60.68	61.87	63.05

```
760.0   57.02 I 57.02 57.02 I 56.63 56.03 55.14 54.09 53.10 51.69 49.80 47.91
                              56.74 56.32 55.90 55.21 54.47 53.39 52.05 50.72
                              57.02 57.02 57.02 57.02 57.02 57.02 57.02 57.02
                              57.30 57.72 58.14 58.56 58.98 59.61 60.45 61.29
                              57.41 58.01 58.60 59.19 59.79 60.68 61.87 63.05


TIME =   0 DAYS   1 HOURS   0 MINUTES   0 SECONDS

SENSIBLE ENERGY                      2165.91
 HEAT FROM PIPE TO FLUID              2446.68
 % OF ERROR                          -11.4758
 INLET FLUID TEMP                       50.65
 MEASURED INLET FLUID TEMP              50.65
 AMBIENT AIR TEMP                       38.35
 ON TIME: MIN/HR         21.724     FRACTION OF          ON TIME    1.0862

TIME =   0 DAYS   2 HOURS   0 MINUTES   0 SECONDS

SENSIBLE ENERGY                      7277.17
 HEAT FROM PIPE TO FLUID              8083.82
 % OF ERROR                           -9.9786
 INLET FLUID TEMP                       45.34
 MEASURED INLET FLUID TEMP              45.34
 AMBIENT AIR TEMP                       37.71
 ON TIME: MIN/HR         32.069     FRACTION OF          ON TIME    1.0022

TIME =   0 DAYS   3 HOURS   0 MINUTES   0 SECONDS

SENSIBLE ENERGY                     11899.35
 HEAT FROM PIPE TO FLUID             13134.46
 % OF ERROR                           -9.4036
 INLET FLUID TEMP                       45.68
 MEASURED INLET FLUID TEMP              49.12
 AMBIENT AIR TEMP                       37.72
 ON TIME: MIN/HR         27.931     FRACTION OF          ON TIME    1.0743

TIME =   0 DAYS   4 HOURS   0 MINUTES   0 SECONDS

SENSIBLE ENERGY                     16568.02
 HEAT FROM PIPE TO FLUID             18043.29
 % OF ERROR                           -8.1763
 INLET FLUID TEMP                       44.56
 MEASURED INLET FLUID TEMP              44.56
 AMBIENT AIR TEMP                       37.20
 ON TIME: MIN/HR         35.172     FRACTION OF          ON TIME    1.0345

TIME =   0 DAYS   5 HOURS   0 MINUTES   0 SECONDS
```

```
SENSIBLE ENERGY                    21316.93
 HEAT FROM PIPE TO FLUID            23220.59
 % OF ERROR                          -8.1982
 INLET FLUID TEMP                      43.95
 MEASURED INLET FLUID TEMP             49.01
 AMBIENT AIR TEMP                      36.21
 ON TIME: MIN/HR          28.966    FRACTION OF          ON TIME    1.0345

TIME =   0 DAYS   6 HOURS   0 MINUTES   0 SECONDS

 LENGTH  H2O        PIPE          SOIL
   FT.                          ---------------------------------------------
  76.0   45.18 I 45.49 47.58 I 50.12 53.28 54.13 53.82 53.06 51.69 49.79 47.75
                               50.25 53.66 54.80 54.81 54.36 53.41 52.05 50.57
                               50.52 54.45 56.15 56.75 56.93 56.99 56.99 56.92
                               50.78 55.16 57.28 58.31 58.91 59.59 60.42 61.17
                               50.88 55.44 57.74 58.94 59.72 60.66 61.84 62.92
 152.0   45.83 I 46.10 47.96 I 50.28 53.35 54.16 53.83 53.06 51.69 49.79 47.75
                               50.40 53.73 54.83 54.82 54.36 53.41 52.05 50.57
                               50.68 54.52 56.17 56.76 56.93 56.99 56.99 56.92
                               50.93 55.23 57.31 58.32 58.91 59.59 60.42 61.17
                               51.04 55.51 57.77 58.95 59.72 60.66 61.84 62.92
 228.0   46.37 I 46.61 48.28 I 50.43 53.42 54.19 53.84 53.07 51.69 49.79 47.75
                               50.55 53.80 54.86 54.83 54.36 53.41 52.05 50.57
                               50.83 54.59 56.20 56.77 56.94 56.99 56.99 56.92
                               51.09 55.30 57.33 58.32 58.91 59.59 60.42 61.17
                               51.19 55.59 57.80 58.96 59.72 60.66 61.84 62.92
 304.0   46.83 I 47.04 48.57 I 50.58 53.49 54.21 53.85 53.07 51.69 49.79 47.75
                               50.70 53.87 54.88 54.84 54.36 53.41 52.05 50.57
                               50.98 54.66 56.22 56.77 56.94 56.99 56.99 56.92
                               51.23 55.37 57.36 58.33 58.92 59.59 60.42 61.17
                               51.34 55.66 57.82 58.97 59.73 60.67 61.84 62.92
 380.0   47.22 I 47.41 48.83 I 50.72 53.56 54.24 53.86 53.07 51.69 49.79 47.75
                               50.85 53.94 54.91 54.84 54.37 53.41 52.05 50.57
                               51.12 54.73 56.25 56.78 56.94 56.99 56.99 56.92
                               51.38 55.44 57.38 58.34 58.92 59.60 60.42 61.17
                               51.48 55.72 57.85 58.98 59.73 60.67 61.84 62.92
 456.0   47.56 I 47.74 49.07 I 50.87 53.63 54.26 53.86 53.07 51.69 49.79 47.75
                               50.99 54.00 54.93 54.85 54.37 53.41 52.05 50.57
                               51.27 54.80 56.27 56.79 56.94 56.99 56.99 56.92
                               51.52 55.50 57.41 58.35 58.92 59.60 60.42 61.17
                               51.63 55.79 57.87 58.98 59.73 60.67 61.84 62.92
 532.0   47.86 I 48.03 49.28 I 51.00 53.69 54.28 53.87 53.07 51.69 49.79 47.75
                               51.13 54.07 54.95 54.86 54.37 53.41 52.05 50.57
                               51.40 54.86 56.30 56.80 56.94 56.99 56.99 56.92
                               51.66 55.57 57.43 58.35 58.92 59.60 60.42 61.17
                               51.76 55.85 57.89 58.99 59.73 60.67 61.84 62.92
 608.0   48.13 I 48.29 49.48 I 51.14 53.76 54.31 53.88 53.08 51.69 49.79 47.75
                               51.26 54.13 54.98 54.87 54.37 53.41 52.05 50.57
                               51.54 54.93 56.32 56.80 56.95 56.99 56.99 56.92
                               51.80 55.63 57.46 58.36 58.92 59.60 60.42 61.17
                               51.90 55.92 57.92 59.00 59.73 60.67 61.84 62.92
```

684.0	48.38	I	48.53	49.67	I	51.27	53.82	54.33	53.89	53.08	51.69	49.79	47.75
						51.40	54.19	55.00	54.87	54.37	53.41	52.05	50.57
						51.67	54.99	56.34	56.81	56.95	56.99	56.99	56.92
						51.93	55.69	57.48	58.37	58.93	59.60	60.42	61.17
						52.03	55.98	57.94	59.00	59.74	60.67	61.84	62.92
760.0	48.60	I	48.75	49.85	I	51.40	53.88	54.35	53.89	53.08	51.69	49.79	47.75
						51.53	54.25	55.02	54.88	54.38	53.41	52.05	50.57
						51.80	55.05	56.36	56.82	56.95	56.99	56.99	56.92
						52.06	55.75	57.50	58.38	58.93	59.60	60.42	61.17
						52.16	56.04	57.96	59.01	59.74	60.67	61.84	62.92

SENSIBLE ENERGY	25247.20		
HEAT FROM PIPE TO FLUID	27274.77		
% OF ERROR	-7.4339		
INLET FLUID TEMP	44.38		
MEASURED INLET FLUID TEMP	44.38		
AMBIENT AIR TEMP	35.38		
ON TIME: MIN/HR 34.138	FRACTION OF	ON TIME	1.0041

Appendix D

GROUND-COIL MODEL WITH THERMAL INTERFERENCE

D.1. Computer Code Listing

```
C
C       THIS IS ECHX2.TWO, COPIED FROM SINGL2.PIP
C       THIS PROGRAM IS FOR GROUND COIL OPERATION WITH VARIABLE
C       FARFIELD BOUNDARY CONDITION AND SURFACE EFFECT, AND
C       THERMAL INTERFERENCE. THIS CODE HAS VARIABLE RADIAL AND
C       CIRCUMFRENTIAL KNODAL SPACINGS
C
      IMPLICIT REAL*8(A-H,O-Z)
      DOUBLE PRECISION MU1,MU2,MU3,LATENT,MOIST
      INTEGER DAYS,HOURS,MINUTE,SECOND
      LOGICAL OLDATA,STOP
      DIMENSION TITLE(20),U1(20,2),T1(20,20,2),U2(20,2),T2(20,20,2),
     &          S(20,20,20,2),SUM(20),SOILT(20),DRSOIL(10)
      DIMENSION DEPTH(20),E1R(20),E2R(20),E3R(20),SUM1(20),
     &          EATA1(20),EATA2(20),EATA3(20),SOIL(20),
     &          E1M(20,20),E2M(20,20),E3M(20,20),DANGLE(20)
C
      DATA PI /3.141592654D0/
C
C   DATA FOR NORTHWAY SILT LOAM
C
C
C  RHOF=DENSITY OF FLUID: PB/FT3
C  CPF=SPECIFIC HEAT OF FLUID: BTU PER PB PER F
C  RK1 = THERMAL CONDUCTIVITY OF COIL WALL: BTU/HR/FT/F
C  RK2 = THERMAL CONDUCTIVITY OF SOIL FROZEN REGION: BTU/HR/FT/F
C  RK3 = THERMAL CONDUCTIVITY OF SOIL NON-FROZEN REGION: BTU/HR/FT/F
C  RHO1 = DENSITY OF COIL MATERIAL: PB/FT3
C  RHO2 = DENSITY OF SOIL FROZEN REGION: PB/FT3
C  RHO3 = DENSITY OF SOIL NON-FROZEN REGION: PB/FT3
C  CP1 = SPECIFIC HEAT OF COIL MATERIAL: BTU/PB/F
C  CP2 = SPECIFIC HEAT OF FROZEN SOIL: BTU/PB/F
C  CP3 = SPECIFIC HEAT OF NON-FROZEN SOIL: BTU/PB/F
C  H1 = CONVECTIVE HEAT TRANSFER COEFFICIENT BETWEEN FLUID AND COIL WALL
C        BTU PER HR PER FT2 PER F
C  LATENT = LATENT HEAT OF THE SOIL MOISTURE: BTU/PB
C  MOIST = MOISTURE CONTENT IN THE SOIL; PERCENT OF SOIL TOTAL DENSITY
C  TIMMAX = MAXIMUM PROGRAM RUNNING TIME, HOUR
C  TIMPRT = TIME INTERVAL BETWEEN DATA PRINT OUT, HOUR
C  GPM = FLUID FLOW RATE; GAL PER MIN
C  R1 = COIL INSIDE RADIUS: INCH
C  R2 = COIL OUTSIDE RADIUS: INCH
C  R3 = BOUNDARY OF SOIL FROZEN  AND NON-FROZEN REGIONS: INCH
C  R4 = FARFIELD RADIUS: INCH
C  DTIME = TIME STEP FOR FLUID AND SOIL NON-FROZEN REGION: MIN
C  PDTIME = TIME STEP FOR COIL WALL AND SOIL FROZEN REGION: MIN
C  ZMAX = LENGTH OF THE GROUND COIL: FT
C  TINFIN = DEFAULT VALUE OF INITIAL GROUND AND FLUID TEMPERATURE
C  TH2O = DEFAULT VALUE OF FLUID INLET TEMPERATURE: NOT
C         NECESSARILY CONSTANT: F
C  NZ = NO. OF NODAL POINTS IN VERTICAL DIRECTION: FT
C  NPIPE = NO. OF NODAL POINTS OF COIL WALL
C  NFREEZ = NO. OF NODAL POINTS OF SOIL FROZEN REGION
C  NSOIL = NO. OF NODAL POINTS IN SOIL NON-FROZEN REGION
```

```
C  DRSOIL = DISTANCE BETWEEN NODAL POINTS IN SOIL NON-FROZEN
C           REGION: DOES NOT NECESSARILY BE CONSTANT: INCH
C     DIST = DISTANCE BETWEEN THE TWO VERTICALLY ARRANGED COILS: INCH
C  TFREEZ = SOIL FREEZING TEMPERATURE: F
      DATA      RKF, RHOF, CPF  /.36D0, 64.6D0, .925D0/
      DATA RK1, RHO1, CP1, H1/.125D0, 58.66D0, .52D0, 125.0D0/
      DATA RK2, RHO2, CP2/1.260D0, 113.12D0, .2956D0/
      DATA RK3, RHO3, CP3/1.260D0, 113.12D0, .2956D0/
C
      DATA IOUT/7/, OLDATA/.FALSE./, STOP/.FALSE./
      DATA TIMMAX, TIMPRT /672.0D0, 24.0D0/
      DATA GPM/6.67D0/
      DATA R1,R2,R4/.805D0, .95D0, 60.0D0/
      DATA DTIME/20.0D-1/,PDTIME/10.0D-2/
      DATA ZMAX/380.0D0/
      DATA NZ/7/, NPIPE/2/,NSOIL/11/, NRAD/18/
        DATA DRSOIL/3.D0,3.D0,6.D0,8.D0,4.D0,4.D0,6.D0,
     &              10.D0,12.D0,15.D0/
        DATA TE,DTE,PHASE,TYEAR /60.D0,20.D0,.44D0,0.0D0/
        DATA DPTH,RFAR/72.D0,72.D0/
        DATA DIST/24.95D0/
C
      WRITE(IOUT,2)
    2 FORMAT(2X,'GROUND COIL WITH THERMAL INTERFERENCE')
C
      NSOIL1=NSOIL-1
      NPM1=NPIPE-1
      NFZM1=NFREEZ-1
      NZM1=NZ-1
        NRAD1=NRAD-1
        DANGLE(1)=DRSOIL(5)/DIST
        DO 9 M=3,NRAD1
9       DANGLE(M)=PI/DBLE(NRAD-2)
        DANGLE(2)=DANGLE(3)-DANGLE(1)
C
      TIME=0.
      BTUSY1=0.0D0
      BTUSY2=0.0D0
      DZ=ZMAX/DBLE(NZM1)
      HFLUX1=0.0D0
        HFLUX2=0.0D0
        AQGR=0.0D0
C
C       DTHY IS THE ANGLE BETWEEN SOIL INTERNAL HEAT SOURCE AND
C       ADJACENT KNODAL POINT IN CIRCONFERIANTIAL DIRECTION
C
        DTHY=0.0345833D0
        DRPIPE=(R2-R1)/DBLE(NPM1)
C
C       READ IN FROM FORT9 THE GROUND TEMPERATURE EACH HOUR
C       AT 2,3,4, AND 10 FEET BELOW SURFACE
C       THE ONE USED HERE IS THE EXPERIMENTAL DATA PROVIDED
C       BY UNIV. OF TENNESSEE, IN DEG. C
C
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```
        READ(9,3002)TG2,TG3,TG4,TG10
        TG2=TG2*1.8D0+32.0D0
        TG3=TG3*1.8D0+32.0D0
        TG4=TG4*1.8D0+32.0D0
        TG10=TG10*1.8D0+32.0D0
3002    FORMAT(4F10.4)
      DO 40 K=1,2
        DO 11 J=1,NZ
        DO 12 I=1,NSOIL
        IF(I .EQ. 1)R=R2
        IF(I .NE. 1)R=R+DRSOIL(I-1)
        DO 14 M=1,NRAD
        IF(M.EQ.1)ANGLE=0.0D0
        IF(M.NE.1)ANGLE=ANGLE+DANGLE(M-1)
        ZZ=(DPTH-R*DSIN(PI/2.0D0-ANGLE))/12.D0
        IF(ZZ .LE. 3.0D0)S(I,J,M,K)=(TG3-TG2)*(ZZ-2.0D0)+TG2
        IF(ZZ .GT. 3.0D0 .AND. ZZ .LE. 4.0D0)S(I,J,M,K)=
     &    (TG4-TG3)*(ZZ-3.0D0)+TG3
        IF(ZZ .GT. 4.0D0)S(I,J,M,K)=
     &    (TG10-TG4)/6.0D0*(ZZ-4.0D0)+TG4
        SOILT(M)=S(NSOIL,1,M,K)
C           Z=ZZ*DSQRT(PI/(RK2/(RHO2*CP2)*8766.D0))
C  S(I,J,M,K)=TE-DTE*DEXP(-Z)*DCOS(PI*TYEAR/4383.D0-Z-PHASE)
C        SOILT(I,J,M)=S(I,J,M,K)
C        CALL FARTEM(TIME,ZZ,S(I,J,M,K))
14      CONTINUE
12      CONTINUE
        DO 50 I=1,NPIPE
   T1(I,J,K)=S(6,J,1,K)
50      T2(I,J,K)=S(1,J,9,K)
        U1(J,K)=T1(1,J,K)
        U2(J,K)=T2(1,J,K)
11      CONTINUE
   40 CONTINUE
      IF(OLDATA)READ(19,2001,END=41)TIME,BTUSY,HFLUX,
     &    T1,T2,S,U1,U2
   41 CONTINUE
 2001 FORMAT(8(1PE11.4))
      DZ=12.0D0*ZMAX/DBLE(NZM1)
C
C  SET VELOCITY OF FLUID
C
      VINNER=1728.0D0*(GPM*.1337D0)/(PI*R1*R1)
      DO 60 IZ=1,NZ
      DEPTH(IZ)=DBLE(IZ-1)*DZ/12.0D0
   60 CONTINUE
C
C   PRINT DATA
C
      WRITE(IOUT,1001)R1,R2,R4,ZMAX
 1001 FORMAT('0GEOMETRIC DATA :',/,
     &    5X,' R1      - INTERNAL RADIUS OF PIPE    ',5X,F7.3,
     &                                               ' INCHES',/,
     &    5X,' R2      - EXTERNAL RADIUS OF PIPE    ',5X,F7.3,
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     &                                                  ' INCHES',/,
     &    5X,' R4      = DISTANCE FROM PIPE TO        ',/,
     &    5X,'           UNDISTURBED SOIL             ',5X,F7.3,
     &                                                 ' INCHES',/,
     &    5X,' ZMAX    - DEPTH OF WELL                ',5X,F7.3,
     &                                                 ' FEET')
      R4=R2 + 12.0D0*R4
      WRITE(IOUT,1002)NPIPE,DRPIPE,NSOIL,DRSOIL,
     &                NZ,DZ
 1002 FORMAT('0GEOMETRIC GRID :',/,
     &    5X,' NPIPE  - NUMBER OF MESH POINTS IN PIPE   ',I3,/,
     &    5X,' DRPIPE - RADIAL SPACING OF MESH POINTS    ',/,
     &    5X,'          IN PIPE                         ',F7.3,
     &                                                   ' INCHES',/,
     &    5X,' NSOIL  - NUMBER OF POINTS IN OUTER SOIL   ',I3,/,
     &    5X,' DRSOIL - RADIAL SPACING OF POINTS IN      ',/,
     &    5X,'          OUTER SOIL                       ',10F7.3,/,
     &                                                   ' INCHES',/,
     &    5X,' NZ     - NUMBER OF VERTICAL MESH POINTS   ',I3,/,
     &    5X,' DZ     - VERTICAL SPACING OF POINTS       ',F7.2)
C
      WRITE(IOUT,1003)TIMMAX,TIMPRT,DTIME
 1003 FORMAT('0TIME PARAMETERS:',/,
     &    5X,' TIMMAX - LENGTH OF SIMULATION             ',F7.2,
     &                                                   ' HOURS',/,
     &    5X,' TIMPRT - TIMING OF PRINTED INFORMATION     ',F7.4,
     &                                                   ' HOURS',/,
     &    5X,' DTIME  = TIME STEP                         ',F7.5,
     &                                                   ' MINUTES')
      V1FT=VINNER/12.0D0
      WRITE(IOUT,1004)GPM,V1FT
 1004 FORMAT('0PUMPING DATA:',/,
     &    5X,' GPM    - PUMPING RATE                     ',F7.3,
     &                                         ' GALLONS/MINUTE',/,
     &    5X,' BINNER - VELOCITY OF FLUID                ',F7.3,
     &                                         ' FEET/MINUTE')
C
      ALPHA1 = RK1/(RHO1*CP1)
      ALPHA2 = RK2/(RHO2*CP2)
      ALPHA3 = RK3/(RHO3*CP3)
C
      WRITE(IOUT,1006)
 1006 FORMAT('0MATERIAL PROPERTIES:')
      WRITE(IOUT,1007)
 1007 FORMAT('0PIPE:')
      WRITE(IOUT,1008)RK1,H1,RHO1,CP1,ALPHA1
 1008 FORMAT(
     &    5X,' CONDUCTIVITY                              ',F7.3,
     &                                   ' BTU/HR-FT-F',/,
     &    5X,' HEAT TRANSFER RATE                        ',F7.3,
     &                                   ' BTU/HR-FT2-F',/,
     &    5X,' DENSITY                                   ',F7.3,
     &                                   ' LBM/FT3',/,
     &    5X,' SPECIFIC HEAT                             ',F7.3,
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     &                                    ' BTU/LBM-F',/,
     &    5X,' ALPHA                                    ',F7.5,
     &                                    ' FT2/HR')
C
      WRITE(IOUT,1009)
 1009 FORMAT('0FROZEN AREA:')
      WRITE(IOUT,1008)RK2,H2,RHO2,CP2,ALPHA2
      WRITE(IOUT,1010)
 1010 FORMAT('0SOIL:')
      WRITE(IOUT,1008)RK3,H3,RHO3,CP3,ALPHA3
C
      WRITE(IOUT,1011)RHOF,CPF
 1011 FORMAT('0WORKING FLUID:',/,
     &    5X,' RHOF   -DENSITY                          ',F7.3,
     &                                        ' LBM/FT3',/,
     &    5X,'CPF     - SPECIFIC HEAT                   ',F7.3,
     &                                        ' BTU/LBM-F')
C
C   CHANGE UNITS TO MINUTES AND INCHES
C
      TIMMAX=60.0D0*TIMMAX+TIME
      NPRINT=(60.0D0*TIMPRT+DTIME/2.0D0)/DTIME
      ZMAX=12.0D0*ZMAX
        RKF=RKF/(60.D0*12.D0)
      RK1=RK1/(60.0D0*12.0D0)
      RK2=RK2/(60.0D0*12.0D0)
      RK3=RK3/(60.0D0*12.0D0)
C
      H1=H1/(60.0D0*144.0D0)
      H2=H2/(60.0D0*144.0D0)
      H3=H3/(60.0D0*144.0D0)
C
      RHOF=RHOF/1728.0D0
      RHO1=RHO1/1728.0D0
      RHO2=RHO2/1728.0D0
      RHO3=RHO3/1728.0D0
C
      ALPHA1=RK1/(RHO1*CP1)
      ALPHA2=RK2/(RHO2*CP2)
      ALPHA3=RK3/(RHO3*CP3)
C
C   SET CONSTANTS USED IN THE CALCULATIONS
C
      DTDZ=PDTIME/DZ
      BETA2=VINNER*DTDZ
      BETA3=2.0D0*H1*PDTIME/(RHOF*CPF*R1)
      BETA1=1.0D0-BETA2-BETA3
      A1DTDR=ALPHA1*PDTIME/DRPIPE
      GAMMA2=A1DTDR*(2.0D0/DRPIPE+1.0D0/R1)
      GAMMA3=2.0D0*A1DTDR*H1/RK1
      GAMMA1=1.0D0-GAMMA2-GAMMA3
      IF(NPM1 .LT. 2)GO TO 72
      DO 70 I=2,NPM1
      R=R1+(DBLE(I)-1.0D0)*DRPIPE
```

```
      EATA2(I)=A1DTDR*(1.0D0/DRPIPE+1.0D0/R)
   EATA3(I)=A1DTDR/DRPIPE
   EATA1(I)=1.0D0-EATA2(I)-EATA3(I)
   70 CONTINUE
72      DMU12=2.0D0*RK2*A1DTDR/RK1/(DRSOIL(5)-R2)
   DMU13=A1DTDR*(2.0D0/DRPIPE-1.0D0/R2)
   DMU11=1.0D0-DMU12-DMU13
       DMU22=2.0D0*A1DTDR*RK2/RK1/DRSOIL(1)
   DMU23=A1DTDR*(2.0D0/DRPIPE-1.0D0/R2)
   DMU21=1.0D0-DMU22-DMU23
C        A2DTDR=ALPHA2*DTIME/DRSOIL
        A2DT=ALPHA2*DTIME
        R=R2
        DO 2000 I=2,NSOIL1
        R=R+DRSOIL(I-1)
        DRAVG=(DRSOIL(I)+DRSOIL(I-1))*.5D0
        E2R(I)=A2DT/DRSOIL(I)*(1.0D0/DRAVG+1.0D0/R)
        E3R(I)=A2DT/DRSOIL(I-1)/DRAVG
C        E4R(I)=A2DT/((R*DANGLE)**2)
        E1R(I)=A2DT/DRSOIL(I)*(2.0D0/DRSOIL(I-1)+
     &          1.D0/R)
        DO 2002 M=1,NRAD
        IF(M.EQ.1)GO TO 2003
        IF(M.EQ.NRAD)GO TO 2004
        DMAVG=(DANGLE(M)+DANGLE(M-1))*.5D0
        E1M(I,M)=2.0D0*A2DT/R**2/(DANGLE(M)*DANGLE(M-1))
        E2M(I,M)=A2DT/DMAVG/(R**2*DANGLE(M))
        E3M(I,M)=E2M(I,M)*DANGLE(M)/DANGLE(M-1)
        GO TO 2002
2003    E1M(I,M)=2.0D0*A2DT/(R*DANGLE(M))**2
        E2M(I,M)=E1M(I,M)*.5D0
        E3M(I,M)=E2M(I,M)
        GO TO 2002
2004    E1M(I,M)=2.0D0*A2DT/(R*DANGLE(M-1))**2
        E2M(I,M)=E1M(I,M)*.5D0
        E3M(I,M)=E2M(I,M)
2002    CONTINUE
2000    CONTINUE
C
C
      ITIME=0
      HOURS=(TIME+.5/60.)/60.
      DAYS=HOURS/24
      HOURS=HOURS-24*DAYS
      MINUTE=TIME-60*(HOURS+24.0D0*DAYS)
      SECOND=60.*(TIME-60*(HOURS+24.0D0*DAYS)-MINUTE)
      WRITE(IOUT,1901)
1901  FORMAT('   DEPTH    H2O',6X,'PIPE',8X,'DEPTH',3X,'H2O',
     &  6X,'PIPE',31X,'SOIL',/,'   FT.     ',16X,101('-'))
C
      DO 99 J=1,NZ
      JJ=NZ-J+1
      WRITE(IOUT,1902)DEPTH(J),U1(J,1),T1(1,J,1),T1(2,J,1),
     &  DEPTH(JJ),U2(JJ,1),T2(1,JJ,1),T2(2,JJ,1),
```

```
     &  (S(I+1,J,1,1),I=1,NSOIL1),
     &  ((S(I+1,J,M,1),I=1,NSOIL1),M=2,NRAD,4)
 1902 FORMAT(' ',F5.1,2X,' I',3F6.2,' I ',F5.1,2X,3F6.2,' I',10F6.2,
     &    /,56X,' I',10F6.2,/,56X,' I',10F6.2,/,56X,' I',10F6.2,
     &    /,56X,' I',10F6.2,/,56X,' I',10F6.2)
   99 CONTINUE
C
C   BEGIN TRANSIENT CALCULATIONS
C
        KK=DTIME/PDTIME+.1D0
 1000 INOW=MOD(ITIME,2)+1
      ITHEN=MOD(ITIME+1,2)+1
      ITIME=ITIME+1
        IF(DMOD(TIME,60.0D0) .GE. DTIME/2.0D0)GO TO 103
C
C       READ IN MEASURED ENERGY EXCHANGED BETWEEN COIL AND GROUND, QGR,
C       HEAT PUMP POWER CONSUMPTION OF THE HOUR, HPP, MEASURED INLET
C       FLUID TEMP. C, OUTLET TEMP. C, AND AMBIENT TEMP. C.
C       THE ONE USED HERE, FORT10 DATA FILE IS THE EXPERIMENTAL DATA
C       PROVIDED BY UNIVERSITY OF TENNESSEE
C       QGR IS USED TO DETERMINE FLUID INLET TEMP. IN CASE THE MEASURED
C       VALUE IS TOO HIGH COMPARED WITH THE GROUND TEMP. HPP IS USED TO
C       DETERMINE THE FRACTION OF HEAT PUMP "ON" TIME PER HOUR. THOUT AND
C       AMB ARE FOR REFERENCE ONLY
C
        READ(10,3003)QGR,HPP,ATH2O,THOUT,AMB
        READ(9,3002)TG2,TG3,TG4,TG10
        TG2=TG2*1.8D0+32.0D0
        TG3=TG3*1.8D0+32.0D0
        TG4=TG4*1.8D0+32.0D0
        TG10=TG10*1.8D0+32.0D0
        THOUT=THOUT*1.8D0+32.0D0
        ATH2O=ATH2O*1.8D0+32.0D0
        AMB=AMB*1.8D0+32.0D0
3003    FORMAT(5F10.4)
        QGR=QGR*3.413D0
        AQGR=AQGR+QGR
        IF(HPP .LT. 2320.0D0)ONT=HPP/2320.0D0*60.0D0
        IF(HPP .GE. 2320.0D0)ONT=60.0D0
C        CALL FCYCLE(TIME,VINNER,V1,ON)
C        CALL FLUID2(TIME,TH2O)
        LT=ONT/DTIME
        FRACT=ONT-DTIME*DBLE(LT)
        IF(LT .EQ. 0)GO TO 102
        AFRACT=1.0D0+FRACT/DTIME/DBLE(LT)
102     IF(LT .EQ. 0)AFRACT=1.0D0+ONT/DTIME
        TH2O=ATH2O
103     V1=VINNER
      TIME=TIME+DTIME
        IF(DMOD(TIME,60.0D0) .GT. ONT)V1=0.0D0
      IF(TIME .GT. TIMMAX)STOP=.TRUE.
        IF(TIME .GT. TIMMAX)GO TO 2200
        IF(TH2O .LE. U1(1,INOW))GO TO 1401
        IF(TH2O .GT. U1(1,INOW))TH2O=U1(1,INOW)
```

```
      IF(ONT .LT. 0.01D0)V1=0.0D0
      IF(ONT .LT. 0.01D0)GO TO 1401
      TH2O=U2(1,INOW)-QGR/ONT/(GPM*.1337D0*RHOF*CPF)/1728.0D0
      IF(V1 .LT. 0.1D-1)TH2O=U1(1,INOW)
C
1401  DO 1300 J=1,NZ
C
C     CALCULATE THE SOIL TEMPERATURE AROUND UPPER COIL
C     AT A DISTANCE OF DRSOIL(5)-R2, 5 POINTS.
C
      SUM1(J)=S(6,J,2,INOW)+
     &        (S(7,J,1,INOW)+S(5,J,1,INOW))*.5D0
      SUM1(J)=SUM1(J)/2.0D0
C
C  CALCULATE FLUID TEMPERATURE IN UPPER COIL
C
   DO 1100 K=1,KK
      IF(V1 .LE. 1.0D-1) GO TO 1104
      TH2O=35.0D0
      U1(1,ITHEN)=TH2O
      IF(J .NE. 1)U1(J,ITHEN)=BETA1*U1(J,INOW)+BETA2*U1(J-1,INOW)
     &  +BETA3*T1(1,J,INOW)
C
C  CALCULATE UPPER COIL WALL TEMPERATURE
C
C  1. UPPER COIL INSIDE WALL EDGE TEMPERATURE
C
   T1(1,J,ITHEN)=GAMMA1*T1(1,J,INOW)+GAMMA2*T1(2,J,INOW)
     &  +GAMMA3*U1(J,INOW)
   IF (J .EQ. NZ) GO TO 1105
   HFLUX1=HFLUX1+PI*R1*PDTIME*DZ*H1*(T1(1,J+1,INOW)+T1(1,J,INOW)
     &  -U1(J+1,INOW)-U1(J,INOW))*AFRACT
   GO TO 1105
1104  U1(J,ITHEN)=2.0D0*RK1*PDTIME*(T1(2,J,INOW)-T1(1,J,INOW))/
     &  DRPIPE/(RHOF*CPF*R1)+U1(J,INOW)
C
C  THE CONDITION IMPOSED NEXT IS ASSUMED NO THERMAL RESISTANCE
C  BETWEEN FLUID AND COIL WALL WHEN FLUID VELOCITY = 0.0
C
   T1(1,J,ITHEN)=U1(J,ITHEN)
C
C  2. CALCULATE UPPER COIL WALL TEMPERATURE
C
1105  IF(NPM1 .LT. 2) GO TO 1120
   DO 1110 I=2,NPM1
   T1(I,J,ITHEN)=EATA1(I)*T1(I,J,INOW)+EATA2(I)*T1(I+1,J,INOW)
     &  +EATA3(I)*T1(I-1,J,INOW)
1110  CONTINUE
C
C  3. CALCULATE UPPER COIL OUTSIDE WALL EDGE TEMPERATURE
C
C     NEXT 3 COMMENTED CARDS ARE FOR PIPE TEMP. CALCULATION
C     WITH 6 INCH FIXED SOIL RADIAL KNODAL SPACING
C
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```
1120    T1(NPIPE,J,ITHEN)=DMU11*T1(NPIPE,J,INOW)+DMU12*SUM1(J)
     &    +DMU13*T1(NPM1,J,INOW)
        U1(J,INOW)=U1(J,ITHEN)
        DO 1200 I=1,NPIPE
        T1(I,J,INOW)=T1(I,J,ITHEN)
1200     CONTINUE
1100     CONTINUE
1300    CONTINUE
C
C  CALCULATE FLUID TEMPERATURE IN LOWER COIL
C
   DO 1400 J=1,NZ
   JJ=NZ-J+1
C
C  CALCULATE THE AVERAGE SOIL TEMPERATURE AROUND LOWER COIL
C
   SUM(JJ)=0.0D0
   DO 1405 M=3,NRAD1
1405    SUM(JJ)=SUM(JJ)+S(2,JJ,M,INOW)
   SUM(JJ)=SUM(JJ)+(S(2,JJ,1,INOW)+S(2,JJ,NRAD,INOW))*.5D0
   SUM(JJ)=SUM(JJ)/DBLE(NRAD1-1)
        DO 1420 K=1,KK
        IF(V1 .LE. 1.0D-1) GO TO 1410
C
C       CALCULATE LOWER COIL FLUID TEMP. WHEN FLUID IS FLOWING
C
        U2(NZ,ITHEN)=U1(NZ,ITHEN)
   IF(JJ .NE. NZ)U2(JJ,ITHEN)=BETA1*U2(JJ,INOW)+BETA2*
     &    U2(JJ+1,INOW)+BETA3*T2(1,JJ,INOW)
C
C  CALCULATE LOWER COIL WALL TEMPERATURE
C
C  1. LOWER COIL INSIDE EDGE TEMPERATURE
C
   T2(1,JJ,ITHEN)=GAMMA1*T2(1,JJ,INOW)+GAMMA2*T2(2,JJ,INOW)+
     &    GAMMA3*U2(JJ,INOW)
   IF(JJ .EQ. 1) GO TO 1440
   HFLUX2=HFLUX2+PI*R1*PDTIME*DZ*H1*(T2(1,JJ-1,INOW)+
     &    T2(1,JJ,INOW)-U2(JJ-1,INOW)-U2(JJ,INOW))*AFRACT
   GO TO 1440
C
C  CALCULATE LOWER COIL FLUID TEMPERATURE WHEN VELOCITY = 0
C
1410    U2(JJ,ITHEN)=2.0D0*RK1*PDTIME*(T2(2,JJ,INOW)-T2(1,JJ,INOW))
     &    /DRPIPE/(RHOF*CPF*R1)+U2(JJ,INOW)
C
C       CONIDITION IMPOSED NEXT IS ASSUMED THAT NO THERMAL RESISTANCE
C       BETWEEN FLUID AND WALL WHEN FLUID VELOCITY = 0.0
C
        T2(1,JJ,ITHEN)=U2(JJ,ITHEN)
C
C  CALCULATE LOWER COIL WALL TEMPERATURE
C
1440    IF(NPM1 .LT. 2)GO TO 1450
```

```
   DO 1460 I=2,NPM1
   T2(I,JJ,ITHEN)=EATA1(I)*T2(I,JJ,INOW)+EATA2(I)*
     &    T2(I+1,JJ,INOW)+EATA3(I)*T2(I-1,JJ,INOW)
1460    CONTINUE
C
C  3. CALCULATE LOWER COIL OUTSIDE EDGE TEMPERATURE
C
1450    T2(NPIPE,JJ,ITHEN)=DMU21*T2(NPIPE,JJ,INOW)+DMU22*SUM(JJ)+
     &    DMU23*T2(NPM1,JJ,INOW)
   U2(JJ,INOW)=U2(JJ,ITHEN)
   DO 1470 I=1,NPIPE
        T2(I,JJ,INOW)=T2(I,JJ,ITHEN)
1470    CONTINUE
1420    CONTINUE
1400    CONTINUE
C        WRITE(IOUT,5554)
5554    FORMAT(' UP TO 1400, STILL WORKING')
C
C  CALCULATE THE SOIL TEMPERATURE
C
        DO 4440 J=1,NZ
        JJ=NZ-J+1
C
C       NEXT LINESARE FOR VARIABLE FARFIELD TEMPERATURE WITH KUSUDA
C  AND ACHENBACH'S CORRELATION
C
        IF(DMOD(TIME,60.0D0) .GT. .001D0)GO TO 3125
C        DO 3000 I=1,NSOIL
C        IF(I .EQ. 1)R=R2
C  IF(I .NE. 1)R=R+DRSOIL(I-1)
        R=DPTH
        DO 3050 M=1,NRAD
        IF(M.EQ.1)ANGLE=0.0D0
        IF(M.NE.1)ANGLE=ANGLE+DANGLE(M-1)
   ZZ=(DPTH-R*DSIN(PI/2.D0-ANGLE))/12.D0
        IF(ZZ .LE. 3.0D0)SOILT(M)=(TG3-TG2)*(ZZ-2.0D0)+TG2
        IF(ZZ .GT. 3.0D0 .AND. ZZ .LE. 4.0D0)SOILT(M)=
     &    (TG4-TG3)*(ZZ-3.0D0)+TG3
        IF(ZZ .GT. 4.0D0)SOILT(M)=
     &    (TG10-TG4)/6.0D0*(ZZ-4.0D0)+TG4
C        CALL FARTEM(TIME,ZZ,S(NSOIL,JJ,M,ITHEN))
C
C       3652.5=60*8766/144
C
C        Z=ZZ*DSQRT(PI/ALPHA2/3652.5D0)
C        SOILT(I,JJ,M)=TE-DTE*DEXP(-Z)*DCOS(PI*(TYEAR+TIME
C     &    /60.D0)/4383.D0-Z-PHASE)
3050    CONTINUE
C3000    CONTINUE
C
C  CALCULATE THE SOIL TEMPERATURE WITH INTERNAL HEAT SOURCE
C
3125    S(6,JJ,1,ITHEN)=T1(NPIPE,JJ,ITHEN)
        S(6,JJ,1,INOW)=T1(NPIPE,JJ,INOW)
```

```
      DO 3100 M=1,NRAD
C  S(NSOIL,JJ,M,ITHEN)=SOILT(M)
   S(1,JJ,M,ITHEN)=T2(NPIPE,JJ,ITHEN)
      S(1,JJ,M,INOW)=T2(NPIPE,JJ,INOW)
      R=R2
      DO 3150 I=2,NSOIL1
      R=R+DRSOIL(I-1)
      IF(M.EQ.1 .AND. I.EQ.6)GO TO 3150
      IF(M.EQ.1 .AND. I.EQ.5)GO TO 3151
      IF(M.EQ.1 .AND. I.EQ.7)GO TO 3152
      IF(M.EQ.2 .AND. I.EQ.2)GO TO 3150
      IF(M.EQ.2 .AND. I.EQ.3)GO TO 3150
      IF(M.EQ.2 .AND. I.EQ.6)GO TO 3153
      IF(M.EQ.1)S(I,JJ,M,ITHEN)=(1.0D0-E1R(I)-E1M(I,M))*S(I,JJ,M,INOW)
     & +E2R(I)*S(I+1,JJ,M,INOW)+E3R(I)*S(I-1,JJ,M,INOW)+2.0D0*E2M(I,M)
     & *S(I,JJ,M+1,INOW)
      IF(M.EQ.NRAD)S(I,JJ,M,ITHEN)=(1.0D0-E1R(I)-E1M(I,M))*
     & S(I,JJ,M,INOW)+E2R(I)*S(I+1,JJ,M,INOW)+E3R(I)*S(I-1,JJ,M,INOW)
     & +2.0D0*E2M(I,M)*S(I,JJ,M-1,INOW)
      IF(M.NE.1 .AND. M.NE.NRAD)
     & S(I,JJ,M,ITHEN)=(1.0D0-E1R(I)-E1M(I,M))*S(I,JJ,M,INOW)+
     &   E2R(I)*S(I+1,JJ,M,INOW)+E3R(I)*S(I-1,JJ,M,INOW)+
     &   E2M(I,M)*S(I,JJ,M+1,INOW)+E3M(I,M)*S(I,JJ,M-1,INOW)
      GO TO 3150
3151  S(I,JJ,M,ITHEN)=(1.0D0-E1R(I)*DRSOIL(I)/(DRSOIL(I)-R2)
     & -E1M(I,M))*S(I,JJ,M,INOW)+A2DT/(DRSOIL(I)-R2)*(2.D0/(DRSOIL(I)
     & -R2+DRSOIL(I-1))+1.D0/R)*S(I+1,JJ,M,INOW)+2.D0*A2DT/DRSOIL(I-1)/
     & (DRSOIL(I)-R2+DRSOIL(I-1))*S(I-1,JJ,M,INOW)+
     & 2.D0*E2M(I,M)*S(I,JJ,M+1,INOW)
      GO TO 3150
3152  S(I,JJ,M,ITHEN)=(1.D0-A2DT/DRSOIL(I)*(2.D0/(DRSOIL(I-1)-R2)
     & +1.D0/R)-E1M(I,M))*S(I,JJ,M,INOW)+A2DT/DRSOIL(I)
     & *(2.0D0/(DRSOIL(I)+DRSOIL(I-1)-R2)+1.D0/R)*S(I+1,JJ,M,INOW)+
     & 2.D0*A2DT/(DRSOIL(I)+DRSOIL(I-1)-R2)/(DRSOIL(I-1)-R2)
     & *S(I-1,JJ,M,INOW)+2.D0*E2M(I,M)*S(I,JJ,M+1,INOW)
      GO TO 3150
3153  S(I,JJ,M,ITHEN)=(1.D0-E1R(I)-E1M(I,M)*DANGLE(M-1)/(DANGLE(M-1)-
     & DTHY))*S(I,JJ,M,INOW)+E2R(I)*S(I+1,JJ,M,INOW)+E3R(I)*
     & S(I-1,JJ,M,INOW)+2.D0*A2DT/(DANGLE(M)+DANGLE(M-1)-DTHY)/R**2/
     & DANGLE(M)*S(I,JJ,M+1,INOW)+2.D0*A2DT/(DANGLE(M)+DANGLE(M-1)-
     & DTHY)/R**2/(DANGLE(M-1)-DTHY)*S(I,JJ,M-1,INOW)
3150  CONTINUE
3100  CONTINUE
      S(2,JJ,2,ITHEN)=(DANGLE(1)*S(2,JJ,3,ITHEN)+DANGLE(2)*
     & S(2,JJ,1,ITHEN))/(DANGLE(1)+DANGLE(2))
      S(3,JJ,2,ITHEN)=(DANGLE(1)*S(3,JJ,3,ITHEN)+DANGLE(2)*
     & S(3,JJ,1,ITHEN))/(DANGLE(1)+DANGLE(2))
4440  CONTINUE
C
C     ADD ENERGY EXCHANGE OF UPPER AND LOWER COILS TOGETHER
C
      HFLUX=HFLUX1+HFLUX2
C
C  CALCULATE THE ENERGY TRANSFER FROM SOIL TO COILS
```

```
C
C  1. TOP COIL
C
        IF(V1 .LT. 1.0D-1)GO TO 1499
   DO 1500 J=1,NZM1
   JJ=NZ-J+1
        BTUSY1=BTUSY1+R2*PI*DTIME*DZ*RK2*(SUM1(J)+
     &  SUM1(J+1)-T1(NPIPE,J,INOW)-T1(NPIPE,J+1,INOW))/
     &  (DRSOIL(5)-R2)*AFRACT
C
C  2. LOWER COIL
C
        BTUSY2=BTUSY2+PI*RK2*R2*DTIME*DZ*(SUM(JJ)+
     &    SUM(JJ-1)-T2(NPIPE,JJ,INOW)-T2(NPIPE,JJ-1,INOW))/
     &    DRSOIL(1)*AFRACT
1500    CONTINUE
1499    CONTINUE
C
C       ADD UPPER AND LOWER COIL SENSIBLE HEAT TOGETHER
C
        BTUSY=BTUSY1+BTUSY2
        ERROR=(BTUSY-HFLUX)/HFLUX*100.0D0
      IF(STOP) GO TO 190
C
C   ROUND TIME TO THE NEXT HIGHEST HOUR:MINUTE:SECOND
C
        IF(DMOD(TIME,60.0D0) .GT. DTIME/2.0D0)GO TO 2101
  190 TIME2=TIME+.5/60.
      HOURS=TIME2/60.
      DAYS=HOURS/24
      HOURS=HOURS-24*DAYS
      MINUTE=TIME2-60.*(HOURS+24.0D0*DAYS)
      SECOND=60.*(TIME2-60.*(HOURS+24.0D0*DAYS)-MINUTE)
C
      WRITE(IOUT,490)DAYS,HOURS,MINUTE,SECOND
      WRITE(6,490)DAYS,HOURS,MINUTE,SECOND
        IF(ITIME .LT. NPRINT)GO TO 2100
        ITIME=0
      WRITE(IOUT,1901)
  490 FORMAT(/1H0,'TIME = ',I3,' DAYS ',I3,' HOURS ',I3,
     &       ' MINUTES ',I3,' SECONDS')
      DO 499 J=1,NZ
        JJ=NZ-J+1
      WRITE(IOUT,1902)DEPTH(J),U1(J,ITHEN),T1(1,J,ITHEN),
     &  T1(2,J,ITHEN),DEPTH(JJ),U2(JJ,ITHEN),T2(1,JJ,ITHEN),
     &          T2(2,JJ,ITHEN),(S(I+1,J,1,ITHEN),I=1,NSOIL1),
     &            ((S(I+1,J,M,ITHEN),I=1,NSOIL1),M=2,NRAD,4)
  499 CONTINUE
2100    WRITE(IOUT,997)HFLUX1,HFLUX2,BTUSY1,BTUSY2,HFLUX,BTUSY,
     &               ERROR,TH2O,U1(1,ITHEN),AQGR
        WRITE(6,997)HFLUX1,HFLUX2,BTUSY1,BTUSY2,HFLUX,BTUSY,
     &               ERROR,TH2O,U1(1,ITHEN),AQGR
  997 FORMAT(
     &    ' UPPER COIL HEAT FROM PIPE TO FLUID  ',F15.2,/,
```

```
     &    ' LOWER COIL HEAT FROM PIPE TO FLUID  ',F15.2,/,
     &    ' UPPER COIL SENSIBLE ENERGY          ',F15.2,/,
     &    ' LOWER COIL SENSIBLE ENERGY          ',F15.2,/,
     &    ' TOTAL HEAT FROM PIPE TO FLUID       ',F15.2,/,
     &    ' TOTAL SENSIBLE ENERGY               ',F15.2,/,
     & 1X,' ERROR                               ',E14.4,5X,
     &      'INLET FLUID TEMP ',F10.2,'   UPPER COIL INSIDE WALL
     & TEMP.',F10.2,/,
     &    'MEASURED ENERGY FROM GROUND          ',F15.2)
        WRITE(IOUT,996)ONT,AFRACT
        WRITE(6,996)ONT,AFRACT
996     FORMAT(  ' ON TIME: MIN/HR         ',F10.3,'
     &  FRACTION OF ON TIME',F10.3)
        WRITE(IOUT,9992)SUM1(NZ),SUM(NZ)
        WRITE(6,9992)SUM1(NZ),SUM(NZ)
9992    FORMAT(' SOIL TEMP AROUND COIL1 & COIL2',2F10.3)
C        IF(TIME .LT. (TIMMAX-DTIME)) GO TO 2101
C        DO 5000 J=1,NZ
C        WRITE(IOUT,999)DEPTH(J),((S(I+1,J,M,ITHEN),I=1,NSOIL1),
C     &        M=1,NRAD)
C5000    CONTINUE
C999     FORMAT(3X,F6.2,5X,10F8.2/(14X,10F8.2))
C      REWIND 20
C      WRITE(20,2001)TIME,BTUSY,HFLUX,T1,T2,
C     &    S,U1,U2
 2101 IF(STOP)GO TO 2200
        GO TO 1000
 2200 STOP
      END
```

```
      SUBROUTINE FLUID2(TIME,TH2O)
C
C     THIS PROGRAM IS FLUID2.TEM.  IT IS USED FOR GROUND COIL
C     FLUID INLET TEMPERATURE INPUT.
C     THIS PROGRAM IS WRITTEN TO SIMULATE THE FLUID INLET TEMP.
C     OF THE FLEMING ASSOC.'S FIELD EXPERIMENTAL DATA OF
C     TWO COIL TRENCH SYSTEM
C
      IMPLICIT REAL*8(A-H,O-Z)
      A=TIME/60.0D0
      IF(A.GE.0.D0 .AND. A.LT.8.D0)
     & TH2O=26.4D0-.2875D0*A
      IF(A.GE.8.D0 .AND. A.LT.23.0D0)
     & TH2O=24.42D0-.04D0*A
      IF(A.GE.23.0D0 .AND. A.LT.27.0D0)
     & TH2O=12.575D0+.475D0*A
      IF(A.GE.27.0D0 .AND. A.LT.29.0D0)
     & TH2O=53.75D0-1.05D0*A
      IF(A.GE.29.0D0 .AND. A.LT.37.0D0)
     & TH2O=25.1125D0-.0625*A
      IF(A.GE.37.0D0 .AND. A.LT.48.0D0)
     & TH2O=22.8D0
      IF(A.GE.48.0D0 .AND. A.LT.50.0D0)
     & TH2O=-3.6D0+.55D0*A
      IF(A.GE.50.0D0 .AND. A.LT.54.0D0)
     & TH2O=41.4D0-.35D0*A
      IF(A.GE.54.0D0 .AND. A.LT.70.0D0)
     & TH2O=22.8375D0-.00625D0*A
      IF(A.GE.70.0D0 .AND. A.LT.73.0D0)
     & TH2O=-19.6D0+.6D0*A
      IF(A.GE.73.0D0 .AND. A.LT.77.0D0)
     & TH2O=53.4D0-.4D0*A
      IF(A.GE.77.0D0 .AND. A.LT.91.0D0)
     & TH2O=24.8D0-.02875D0*A
      IF(A.GE.91.0D0 .AND. A.LT.97.0D0)
     & TH2O=-49.083D0+.7833D0*A
      IF(A.GE.97.0D0 .AND. A.LT.102.0D0)
     & TH2O=73.46D0-.48D0*A
      IF(A.GE.102.D0 .AND. A.LT.103.D0)
     & TH2O=-230.5D0+2.5D0*A
      IF(A.GE.103.0D0 .AND. A.LT.106.5D0)
     & TH2O=97.629D0-.6875D0*A
      IF(A.GE.106.5D0 .AND. A.LT.116.0D0)
     & TH2O=27.963D0-.0316D0*A
      IF(A.GE.116.0D0 .AND. A.LT.121.0D0)
     & TH2O=-1.22D0+.22D0*A
      IF(A.GE.121.0D0 .AND. A.LT.124.0D0)
     & TH2O=17.333D0+.0667D0*A
      IF(A.GE.124.0D0 .AND. A.LT.127.0D0)
     & TH2O=-3.3333D0+.2333D0*A
      IF(A.GE.127.0D0 .AND. A.LT.131.0D0)
     & TH2O=45.35D0-.15D0*A
      IF(A.GE.131.0D0 .AND. A.LT.144.0D0)
     & TH2O=27.715D0-.01538D0*A
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```
      IF(A.GE.144.0D0 .AND. A.LT.146.0D0)
  &   TH2O=-17.7D0+.3D0*A
      IF(A.GE.146.0D0 .AND. A.LT.150.0D0)
  &   TH2O=77.2D0-.35D0*A
      IF(A.GT.150.0D0)
  &   TH2O=24.7D0
      RETURN
END
```

```
      SUBROUTINE FCYCLE(TIME,VINNER,V1,ON)
C
C     THIS IS FCYCLE.1.  IT IS USED FOR CYCLING SCHEDULE INPUT.
C     THIS PROGROM IS THE CYCLING SCHEDULE WRITTEN FOR THE
C     FIELD EXPERIMENTAL DATA PROVIDED BY FLEMING ASSOC
C     FOR TWO COIL TRENCH SYSTEM
C
  IMPLICIT REAL*8(A-H,O-Z)
      LHOUR=TIME/60.0D0
      DMIN=TIME-60.0D0*DBLE(LHOUR)
      A=TIME/60.0D0
C
C     ON TIME IS PERCENTAGE OF ON TIME FOR THE HOUR
C
      IF(A.GE.0.0D0 .AND. A.LT.1.0D0)ON=60.0D0
      IF(A.GE.1.0D0 .AND. A.LT.2.0D0)ON=86.0D0
      IF(A.GE.2.0D0 .AND. A.LT.6.0D0)ON=100.0D0
      IF(A.GE.6.0D0 .AND. A.LT.7.0D0)ON=75.0D0
      IF(A.GE.7.0D0 .AND. A.LT.23.0D0)ON=100.0D0
      IF(A.GE.23.0D0 .AND. A.LT.24.0D0)ON=85.0D0
      IF(A.GE.24.0D0 .AND. A.LT.25.0D0)ON=65.0D0
      IF(A.GE.25.0D0 .AND. A.LT.26.0D0)ON=91.0D0
      IF(A.GE.26.0D0 .AND. A.LT.27.0D0)ON=61.0D0
      IF(A.GE.27.0D0 .AND. A.LT.28.0D0)ON=68.0D0
      IF(A.GE.28.0D0 .AND. A.LT.29.0D0)ON=95.0D0
      IF(A.GE.29.0D0 .AND. A.LT.45.0D0)ON=100.0D0
      IF(A.GE.45.0D0 .AND. A.LT.46.0D0)ON=91.0D0
      IF(A.GE.46.0D0 .AND. A.LT.49.0D0)ON=100.0D0
      IF(A.GE.49.0D0 .AND. A.LT.50.0D0)ON=80.0D0
      IF(A.GE.50.0D0 .AND. A.LT.52.0D0)ON=90.0D0
      IF(A.GE.52.0D0 .AND. A.LT.71.0D0)ON=100.0D0
      IF(A.GE.71.0D0 .AND. A.LT.72.0D0)ON=80.0D0
      IF(A.GE.72.0D0 .AND. A.LT.73.0D0)ON=88.0D0
      IF(A.GE.73.0D0 .AND. A.LT.74.0D0)ON=73.0D0
      IF(A.GE.74.0D0 .AND. A.LT.75.0D0)ON=80.0D0
      IF(A.GE.75.0D0 .AND. A.LT.77.0D0)ON=90.0D0
      IF(A.GE.77.0D0 .AND. A.LT.91.0D0)ON=100.0D0
      IF(A.GE.91.0D0 .AND. A.LT.92.0D0)ON=81.0D0
      IF(A.GE.92.0D0 .AND. A.LT.93.0D0)ON=58.0D0
      IF(A.GE.93.0D0 .AND. A.LT.94.0D0)ON=76.0D0
      IF(A.GE.94.0D0 .AND. A.LT.95.0D0)ON=70.0D0
      IF(A.GE.95.0D0 .AND. A.LT.96.0D0)ON=51.0D0
      IF(A.GE.96.0D0 .AND. A.LT.97.0D0)ON=50.0D0
      IF(A.GE.97.0D0 .AND. A.LT.98.0D0)ON=45.0D0
      IF(A.GE.98.0D0 .AND. A.LT.99.0D0)ON=51.0D0
      IF(A.GE.99.0D0 .AND. A.LT.100.0D0)ON=58.0D0
      IF(A.GE.100.0D0 .AND. A.LT.102.0D0)ON=100.0D0
      IF(A.GE.102.0D0 .AND. A.LT.103.0D0)ON=33.0D0
      IF(A.GE.103.0D0 .AND. A.LT.104.0D0)ON=40.0D0
      IF(A.GE.104.0D0 .AND. A.LT.105.0D0)ON=60.0D0
      IF(A.GE.105.0D0 .AND. A.LT.106.0D0)ON=70.0D0
      IF(A.GE.106.0D0 .AND. A.LT.107.0D0)ON=80.0D0
      IF(A.GE.107.0D0 .AND. A.LT.108.0D0)ON=88.0D0
      IF(A.GE.108.0D0 .AND. A.LT.109.0D0)ON=78.0D0
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      IF(A.GE.109.0D0 .AND. A.LT.110.0D0)ON=90.0D0
      IF(A.GE.110.0D0 .AND. A.LT.111.0D0)ON=80.0D0
      IF(A.GE.111.0D0 .AND. A.LT.112.0D0)ON=90.0D0
      IF(A.GE.112.0D0 .AND. A.LT.113.0D0)ON=88.0D0
      IF(A.GE.113.0D0 .AND. A.LT.114.0D0)ON=80.0D0
      IF(A.GE.114.0D0 .AND. A.LT.115.0D0)ON=90.0D0
      IF(A.GE.115.0D0 .AND. A.LT.116.0D0)ON=76.0D0
      IF(A.GE.116.0D0 .AND. A.LT.117.0D0)ON=78.0D0
      IF(A.GE.117.0D0 .AND. A.LT.118.0D0)ON=80.0D0
      IF(A.GE.118.0D0 .AND. A.LT.119.0D0)ON=73.0D0
      IF(A.GE.119.0D0 .AND. A.LT.120.0D0)ON=76.0D0
      IF(A.GE.120.0D0 .AND. A.LT.121.0D0)ON=71.0D0
      IF(A.GE.121.0D0 .AND. A.LT.123.0D0)ON=65.0D0
      IF(A.GE.123.0D0 .AND. A.LT.124.0D0)ON=70.0D0
      IF(A.GE.124.0D0 .AND. A.LT.126.0D0)ON=60.0D0
      IF(A.GE.126.0D0 .AND. A.LT.130.0D0)ON=55.0D0
      IF(A.GE.130.0D0 .AND. A.LT.131.0D0)ON=66.0D0
      IF(A.GE.131.0D0 .AND. A.LT.132.0D0)ON=70.0D0
      IF(A.GE.132.0D0 .AND. A.LT.133.0D0)ON=63.0D0
      IF(A.GE.133.0D0 .AND. A.LT.134.0D0)ON=66.0D0
      IF(A.GE.134.0D0 .AND. A.LT.135.0D0)ON=71.0D0
      IF(A.GE.135.0D0 .AND. A.LT.136.0D0)ON=63.0D0
      IF(A.GE.136.0D0 .AND. A.LT.137.0D0)ON=66.0D0
      IF(A.GE.137.0D0 .AND. A.LT.138.0D0)ON=70.0D0
      IF(A.GE.138.0D0 .AND. A.LT.139.0D0)ON=61.0D0
      IF(A.GE.139.0D0 .AND. A.LT.141.0D0)ON=70.0D0
      IF(A.GE.141.0D0 .AND. A.LT.142.0D0)ON=61.0D0
      IF(A.GE.142.0D0 .AND. A.LT.143.0D0)ON=76.0D0
      IF(A.GE.143.0D0 .AND. A.LT.144.0D0)ON=78.0D0
      IF(A.GE.144.0D0 .AND. A.LT.145.0D0)ON=61.0D0
      IF(A.GE.145.0D0 .AND. A.LT.146.0D0)ON=50.0D0
      IF(A.GE.146.0D0 .AND. A.LT.147.0D0)ON=56.0D0
      IF(A.GE.147.0D0 .AND. A.LT.148.0D0)ON=75.0D0
      IF(A.GE.148.0D0 .AND. A.LT.149.0D0)ON=78.0D0
      IF(A.GE.149.0D0 .AND. A.LT.151.0D0)ON=80.0D0
      IF(A.GE.151.0D0 .AND. A.LT.152.0D0)ON=90.0D0
      IF(A.GE.152.0D0 .AND. A.LT.155.0D0)ON=80.0D0
      IF(A.GE.155.0D0 .AND. A.LT.156.0D0)ON=90.0D0
      IF(A.GT.156.0D0)ON=80.0D0
      ON=ON*.6D0
      VI=0.0D0
      IF(DMIN .GT. ON)RETURN
      V1=VINNER
      RETURN
END
```

```
      SUBROUTINE FARTEM(TIME,ZZ,S)
C
C     THIS PROGRAM IS FARTEM.1.  IT IS USED FOR FARFIELD
C     GROUND TEMPERATURE INPUT.
C     THIS PROGRAM WAS WRITTEN TO SIMULATE THE FLEMING ASSOC.
C     GROUND COIL HEAT PUMP FIELD TEST WITH 2 COIL TRENCH
C     FARFIELD TEMPERATURE
C
      IMPLICIT REAL*8(A-H,O-Z)
      ATIME=TIME/60.0D0+48.0D0
      IF(ZZ.GE.0.0D0 .AND. ZZ.LT.1.0D0)GO TO 10
      IF(ZZ.GE.1.0D0 .AND. ZZ.LT.2.0D0)GO TO 20
      IF(ZZ.GE.2.0D0 .AND. ZZ.LT.3.0D0)GO TO 30
      IF(ZZ.GE.3.0D0 .AND. ZZ.LT.4.0D0)GO TO 40
      IF(ZZ.GE.4.0D0 .AND. ZZ.LT.5.0D0)GO TO 50
      IF(ZZ.GE.5.0D0 .AND. ZZ.LT.6.0D0)GO TO 60
      IF(ZZ.GE.6.0D0 .AND. ZZ.LT.7.0D0)GO TO 70
      IF(ZZ.GE.7.0D0 )GO TO 80
10    TB=33.5D0-0.2D0*ZZ
      TA=33.75D0-0.35D0*ZZ
      GO TO 90
20    TB=32.7D0+0.6D0*ZZ
      TA=32.6D0+0.8D0*ZZ
      GO TO 90
30    TB=31.2D0+1.35D0*ZZ
      TA=30.9D0+1.65D0*ZZ
      GO TO 90
40    TB=31.8D0+1.15D0*ZZ
      TA=31.65D0+1.4D0*ZZ
      GO TO 90
50    TB=32.4D0+ZZ
      TA=32.65D0+1.15D0*ZZ
      GO TO 90
60    TB=32.4D0+ZZ
      TA=32.9D0+1.1D0*ZZ
      GO TO 90
70    TB=33.6D0+0.8D0*ZZ
      TA=34.7D0+0.8D0*ZZ
      GO TO 90
80    TB=28.0D0+1.6D0*ZZ
      TA=31.67D0+1.233D0*ZZ
90    A=(TB-TA)/504.0D0
      S=A*ATIME+TA
      RETURN
      END
```

D.2. Sample Calculation

```
 GROUND COIL WITH THERMAL INTERFERENCE

GEOMETRIC DATA :
     R1     - INTERNAL RADIUS OF PIPE          0.805 INCHES
     R2     - EXTERNAL RADIUS OF PIPE          0.950 INCHES
     R4     = DISTANCE FROM PIPE TO
              UNDISTURBED SOIL                60.000 INCHES
     ZMAX   - DEPTH OF WELL                   300.000 FEET

GEOMETRIC GRID :
     NPIPE  - NUMBER OF MESH POINTS IN PIPE     2
     DRPIPE - RADIAL SPACING OF MESH POINTS
              IN PIPE                           0.145 INCHES
     NSOIL  - NUMBER OF POINTS IN OUTER SOIL    11
     DRSOIL - RADIAL SPACING OF POINTS IN
              OUTER SOIL                         3.000  3.000  6.000  8.000  4.000  4.000  5.000  8.000  9.000  9.000 INCHES
     NZ     - NUMBER OF VERTICAL MESH POINTS     7
     DZ     - VERTICAL SPACING OF POINTS        600.00

TIME PARAMETERS:
     TIMMAX - LENGTH OF SIMULATION               6.00 HOURS
     TIMPRT - TIMING OF PRINTED INFORMATION      6.0000 HOURS
     DTIME  = TIME STEP                         2.00000 MINUTES

PUMPING DATA:
     GPM    - PUMPING RATE                      3.667 GALLONS/MINUTE
     BINNER - VELOCITY OF FLUID                34.679 FEET/MINUTE

MATERIAL PROPERTIES:

PIPE:
     CONDUCTIVITY                              0.266 BTU/HR-FT-F
     HEAT TRANSFER RATE                      125.000 BTU/HR-FT2-F
     DENSITY                                  58.660 LBM/FT3
     SPECIFIC HEAT                             0.520 BTU/LBM-F
     ALPHA                                   0.00872 FT2/HR

FROZEN AREA:
     CONDUCTIVITY                              1.260 BTU/HR-FT-F
     HEAT TRANSFER RATE                        0.000 BTU/HR-FT2-F
     DENSITY                                 113.120 LBM/FT3
     SPECIFIC HEAT                             0.296 BTU/LBM-F
     ALPHA                                   0.03768 FT2/HR

SOIL:
     CONDUCTIVITY                              1.260 BTU/HR-FT-F
     HEAT TRANSFER RATE                        0.000 BTU/HR-FT2-F
     DENSITY                                 113.120 LBM/FT3
     SPECIFIC HEAT                             0.296 BTU/LBM-F
     ALPHA                                   0.03768 FT2/HR

WORKING FLUID:
     RHOF   - DENSITY                          64.600 LBM/FT3
     CPF    - SPECIFIC HEAT                     0.925 BTU/LBM-F
```

DEPTH FT.	H2O	PIPE		DEPTH	H2O	PIPE		SOIL									
0.0	35.66	35.66	35.66	300.0	38.29	38.29	38.29	37.93	37.65	37.06	36.14	35.66	35.12	34.45	33.78	33.47	33.72
								37.94	37.66	37.08	36.18	35.71	35.18	34.51	33.82	33.45	33.70
								38.04	37.84	37.44	36.85	36.52	36.20	35.79	35.03	34.17	33.76
								38.30	38.30	38.30	38.30	38.30	38.30	38.30	38.30	38.30	38.30
								38.56	38.75	39.14	39.58	39.77	39.96	40.20	40.79	41.47	42.14
								38.66	38.94	39.46	39.99	40.30	40.72	41.25	42.09	43.04	43.99
50.0	35.66	35.66	35.66	250.0	38.29	38.29	38.29	37.93	37.65	37.06	36.14	35.66	35.12	34.45	33.78	33.47	33.72
								37.94	37.66	37.08	36.18	35.71	35.18	34.51	33.82	33.45	33.70
								38.04	37.84	37.44	36.85	36.52	36.20	35.79	35.03	34.17	33.76
								38.30	38.30	38.30	38.30	38.30	38.30	38.30	38.30	38.30	38.30
								38.56	38.75	39.14	39.58	39.77	39.96	40.20	40.79	41.47	42.14
								38.66	38.94	39.46	39.99	40.30	40.72	41.25	42.09	43.04	43.99
100.0	35.66	35.66	35.66	200.0	38.29	38.29	38.29	37.93	37.65	37.06	36.14	35.66	35.12	34.45	33.78	33.47	33.72
								37.94	37.66	37.08	36.18	35.71	35.18	34.51	33.82	33.45	33.70
								38.04	37.84	37.44	36.85	36.52	36.20	35.79	35.03	34.17	33.76
								38.30	38.30	38.30	38.30	38.30	38.30	38.30	38.30	38.30	38.30
								38.56	38.75	39.14	39.58	39.77	39.96	40.20	40.79	41.47	42.14
								38.66	38.94	39.46	39.99	40.30	40.72	41.25	42.09	43.04	43.99
150.0	35.66	35.66	35.66	150.0	38.29	38.29	38.29	37.93	37.65	37.06	36.14	35.66	35.12	34.45	33.78	33.47	33.72
								37.94	37.66	37.08	36.18	35.71	35.18	34.51	33.82	33.45	33.70
								38.04	37.84	37.44	36.85	36.52	36.20	35.79	35.03	34.17	33.76
								38.30	38.30	38.30	38.30	38.30	38.30	38.30	38.30	38.30	38.30
								38.56	38.75	39.14	39.58	39.77	39.96	40.20	40.79	41.47	42.14
								38.66	38.94	39.46	39.99	40.30	40.72	41.25	42.09	43.04	43.99
200.0	35.66	35.66	35.66	100.0	38.29	38.29	38.29	37.93	37.65	37.06	36.14	35.66	35.12	34.45	33.78	33.47	33.72
								37.94	37.66	37.08	36.18	35.71	35.18	34.51	33.82	33.45	33.70
								38.04	37.84	37.44	36.85	36.52	36.20	35.79	35.03	34.17	33.76
								38.30	38.30	38.30	38.30	38.30	38.30	38.30	38.30	38.30	38.30
								38.56	38.75	39.14	39.58	39.77	39.96	40.20	40.79	41.47	42.14
								38.66	38.94	39.46	39.99	40.30	40.72	41.25	42.09	43.04	43.99
250.0	35.66	35.66	35.66	50.0	38.29	38.29	38.29	37.93	37.65	37.06	36.14	35.66	35.12	34.45	33.78	33.47	33.72
								37.94	37.66	37.08	36.18	35.71	35.18	34.51	33.82	33.45	33.70
								38.04	37.84	37.44	36.85	36.52	36.20	35.79	35.03	34.17	33.76
								38.30	38.30	38.30	38.30	38.30	38.30	38.30	38.30	38.30	38.30
								38.56	38.75	39.14	39.58	39.77	39.96	40.20	40.79	41.47	42.14
								38.66	38.94	39.46	39.99	40.30	40.72	41.25	42.09	43.04	43.99
300.0	35.66	35.66	35.66	0.0	38.29	38.29	38.29	37.93	37.65	37.06	36.14	35.66	35.12	34.45	33.78	33.47	33.72
								37.94	37.66	37.08	36.18	35.71	35.18	34.51	33.82	33.45	33.70
								38.04	37.84	37.44	36.85	36.52	36.20	35.79	35.03	34.17	33.76
								38.30	38.30	38.30	38.30	38.30	38.30	38.30	38.30	38.30	38.30
								38.56	38.75	39.14	39.58	39.77	39.96	40.20	40.79	41.47	42.14
								38.66	38.94	39.46	39.99	40.30	40.72	41.25	42.09	43.04	43.99

TIME = 0 DAYS 1 HOURS 0 MINUTES 0 SECONDS

UPPER COIL HEAT FROM PIPE TO FLUID	4167.41
LOWER COIL HEAT FROM PIPE TO FLUID	4039.66
UPPER COIL SENSIBLE ENERGY	3969.42
LOWER COIL SENSIBLE ENERGY	3830.83
TOTAL HEAT FROM PIPE TO FLUID	8207.06
TOTAL SENSIBLE ENERGY	7800.25
ERROR	-0.4957E+01

INLET FLUID TEMP 26.11 UPPER COIL INSIDE WALL TEMP. 26.11

```
MEASURED ENERGY FROM GROUND                    0.00

 ON TIME: MIN/HR            51.600                    FRACTION OF ON TIME     1.032
 SOIL TEMP AROUND COIL1 & COIL2    34.293    35.935

TIME =   0 DAYS   2 HOURS   0 MINUTES   0 SECONDS

 UPPER COIL HEAT FROM PIPE TO FLUID          8053.60
 LOWER COIL HEAT FROM PIPE TO FLUID          7962.87
 UPPER COIL SENSIBLE ENERGY                  7838.06
 LOWER COIL SENSIBLE ENERGY                  7730.14
 TOTAL HEAT FROM PIPE TO FLUID              16016.47
 TOTAL SENSIBLE ENERGY                      15568.20
  ERROR                                  -0.2799E+01    INLET FLUID TEMP      25.82   UPPER COIL INSIDE WALL TEMP. 25.82

MEASURED ENERGY FROM GROUND                    0.00

 ON TIME: MIN/HR            60.000                    FRACTION OF ON TIME     1.000
 SOIL TEMP AROUND COIL1 & COIL2    33.590    34.887

TIME =   0 DAYS   3 HOURS   0 MINUTES   0 SECONDS

 UPPER COIL HEAT FROM PIPE TO FLUID         11665.10
 LOWER COIL HEAT FROM PIPE TO FLUID         11572.32
 UPPER COIL SENSIBLE ENERGY                 11436.63
 LOWER COIL SENSIBLE ENERGY                 11323.74
 TOTAL HEAT FROM PIPE TO FLUID              23237.42
 TOTAL SENSIBLE ENERGY                      22760.36
  ERROR                                  -0.2053E+01    INLET FLUID TEMP      25.54   UPPER COIL INSIDE WALL TEMP. 25.54

MEASURED ENERGY FROM GROUND                    0.00

 ON TIME: MIN/HR            60.000                    FRACTION OF ON TIME     1.000
 SOIL TEMP AROUND COIL1 & COIL2    33.124    34.240

TIME =   0 DAYS   4 HOURS   0 MINUTES   0 SECONDS

 UPPER COIL HEAT FROM PIPE TO FLUID         15203.83
 LOWER COIL HEAT FROM PIPE TO FLUID         15077.50
 UPPER COIL SENSIBLE ENERGY                 14964.17
 LOWER COIL SENSIBLE ENERGY                 14815.88
 TOTAL HEAT FROM PIPE TO FLUID              30281.33
 TOTAL SENSIBLE ENERGY                      29780.04
  ERROR                                  -0.1655E+01    INLET FLUID TEMP      25.25   UPPER COIL INSIDE WALL TEMP. 25.25

MEASURED ENERGY FROM GROUND                    0.00

 ON TIME: MIN/HR            60.000                    FRACTION OF ON TIME     1.000
 SOIL TEMP AROUND COIL1 & COIL2    32.760    33.746

TIME =   0 DAYS   5 HOURS   0 MINUTES   0 SECONDS

 UPPER COIL HEAT FROM PIPE TO FLUID         18710.32
 LOWER COIL HEAT FROM PIPE TO FLUID         18519.56
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UPPER COIL SENSIBLE ENERGY                 18460.40
LOWER COIL SENSIBLE ENERGY                 18246.42
TOTAL HEAT FROM PIPE TO FLUID              37229.89
TOTAL SENSIBLE ENERGY                      36706.83
 ERROR                                   -0.1405E+01    INLET FLUID TEMP      24.96   UPPER COIL INSIDE WALL TEMP. 24.96

MEASURED ENERGY FROM GROUND                     0.00

ON TIME: MIN/HR            60.000                       FRACTION OF ON TIME     1.000
SOIL TEMP AROUND COIL1 & COIL2    32.451    33.335

TIME =   0 DAYS   6 HOURS   0 MINUTES   0 SECONDS

  DEPTH    H2O      PIPE        DEPTH   H2O      PIPE                                SOIL
  FT.                 ----------------------------------------------------------------------------------------------------
  0.0   I 24.67 24.92 26.18 I 300.0   26.65 26.88 28.09 I 33.55 35.19 35.59 31.70 26.18 30.75 33.29 33.78 33.64 33.72
                                                         I 33.55 35.22 35.73 33.32 31.48 32.85 33.85 33.89 33.65 33.70
                                                         I 33.66 35.49 36.70 36.59 36.37 36.11 35.73 35.07 34.37 33.75
                                                         I 33.92 35.99 37.69 38.19 38.25 38.27 38.28 38.28 38.29 38.29
                                                         I 34.16 36.43 38.50 39.46 39.75 40.00 40.31 40.84 41.48 42.14
                                                         I 34.25 36.60 38.81 39.96 40.37 40.76 41.26 42.10 43.04 44.00
 50.0   I 25.03 25.27 26.49 I 250.0   26.99 27.22 28.40 I 33.40 35.12 35.60 31.84 26.49 30.90 33.35 33.79 33.64 33.72
                                                         I 33.41 35.14 35.74 33.42 31.62 32.94 33.89 33.90 33.65 33.70
                                                         I 33.52 35.41 36.68 36.59 36.37 36.11 35.73 35.07 34.37 33.75
                                                         I 33.78 35.91 37.67 38.18 38.25 38.27 38.28 38.28 38.29 38.29
                                                         I 34.01 36.35 38.48 39.45 39.75 40.00 40.31 40.84 41.48 42.14
                                                         I 34.10 36.52 38.79 39.95 40.37 40.76 41.26 42.10 43.04 44.00
100.0   I 25.38 25.60 26.79 I 200.0   27.33 27.55 28.69 I 33.25 35.04 35.60 31.99 26.79 31.06 33.40 33.80 33.65 33.72
                                                         I 33.26 35.06 35.74 33.51 31.76 33.03 33.92 33.90 33.65 33.70
                                                         I 33.37 35.33 36.66 36.59 36.38 36.11 35.73 35.07 34.37 33.75
                                                         I 33.63 35.83 37.65 38.18 38.25 38.27 38.28 38.28 38.29 38.29
                                                         I 33.86 36.26 38.45 39.45 39.75 40.00 40.31 40.84 41.48 42.14
                                                         I 33.95 36.43 38.77 39.95 40.37 40.76 41.26 42.10 43.04 44.00
150.0   I 25.71 25.93 27.08 I 150.0   27.65 27.87 28.98 I 33.10 34.96 35.61 32.12 27.08 31.20 33.44 33.81 33.65 33.72
                                                         I 33.11 34.98 35.74 33.60 31.90 33.11 33.95 33.91 33.66 33.70
                                                         I 33.22 35.24 36.64 36.59 36.38 36.11 35.73 35.07 34.37 33.75
                                                         I 33.47 35.74 37.62 38.18 38.25 38.27 38.28 38.28 38.29 38.29
                                                         I 33.71 36.17 38.43 39.45 39.75 40.00 40.31 40.84 41.48 42.14
                                                         I 33.80 36.35 38.74 39.94 40.37 40.76 41.26 42.10 43.04 44.00
200.0   I 26.03 26.25 27.36 I 100.0   27.97 28.18 29.26 I 32.95 34.87 35.61 32.25 27.36 31.34 33.49 33.82 33.65 33.72
                                                         I 32.95 34.90 35.74 33.69 32.03 33.19 33.98 33.91 33.66 33.70
                                                         I 33.06 35.15 36.62 36.59 36.38 36.11 35.73 35.07 34.37 33.75
                                                         I 33.31 35.65 37.59 38.17 38.25 38.27 38.28 38.28 38.29 38.29
                                                         I 33.55 36.08 38.40 39.44 39.75 40.00 40.31 40.84 41.48 42.14
                                                         I 33.64 36.25 38.71 39.94 40.37 40.76 41.26 42.10 43.04 44.00
250.0   I 26.35 26.56 27.63 I  50.0   28.27 28.48 29.53 I 32.78 34.78 35.61 32.38 27.63 31.48 33.54 33.82 33.65 33.72
                                                         I 32.79 34.81 35.73 33.77 32.16 33.26 34.01 33.92 33.66 33.70
                                                         I 32.89 35.06 36.60 36.59 36.38 36.11 35.73 35.07 34.37 33.75
                                                         I 33.15 35.55 37.57 38.17 38.25 38.27 38.28 38.28 38.29 38.29
                                                         I 33.38 35.99 38.37 39.44 39.75 40.00 40.31 40.84 41.48 42.14
                                                         I 33.47 36.16 38.69 39.93 40.36 40.76 41.26 42.10 43.04 44.00
```

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300.0   I 26.65 26.85 27.90 I   0.0   28.57 28.77 29.79 I 32.61 34.69 35.60 32.50 27.90 31.61 33.58 33.83 33.65 33.72
                                                        I 32.62 34.71 35.73 33.85 32.28 33.34 34.04 33.92 33.66 33.70
                                                        I 32.72 34.96 36.57 36.59 36.38 36.11 35.73 35.07 34.37 33.75
                                                        I 32.98 35.45 37.54 38.16 38.25 38.27 38.28 38.28 38.29 38.29
                                                        I 33.21 35.89 38.34 39.43 39.74 40.00 40.31 40.84 41.48 42.14
                                                        I 33.30 36.06 38.66 39.93 40.36 40.76 41.26 42.10 43.04 44.00
 UPPER COIL HEAT FROM PIPE TO FLUID          22210.39
 LOWER COIL HEAT FROM PIPE TO FLUID          21926.00
 UPPER COIL SENSIBLE ENERGY                  21950.77
 LOWER COIL SENSIBLE ENERGY                  21642.31
 TOTAL HEAT FROM PIPE TO FLUID               44136.38
 TOTAL SENSIBLE ENERGY                       43593.08
  ERROR                                    -0.1231E+01    INLET FLUID TEMP      24.67   UPPER COIL INSIDE WALL TEMP. 24.67

MEASURED ENERGY FROM GROUND                       0.00

 ON TIME: MIN/HR             45.000                       FRACTION OF ON TIME     1.023
 SOIL TEMP AROUND COIL1 & COIL2    32.175    32.978
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