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A THEORETICAL AND EXPERIMENTAL ANALYSIS OF VERTICAL, CONCENTRIC-TUBE GROUND-COUPLED HEAT EXCHANGERS

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NOMENCLATURE

C_p	specific heat
Gr	Grashof number, $g\frac{\beta}{\nu^2}\, l^3\, \Delta T$
g	constant of gravitational acceleration
h_1	convective heat transfer coefficient between fluid and inner wall of inner tube
h_2	convective heat transfer coefficient between fluid and outer wall of inner tube
h_3	convective heat transfer coefficient between fluid and inner wall of outer casing
k	thermal conductivity
l	characteristic length, $2(r_3 - r_2)$
L	length of the ground heat exchanger
Pr	Prandtl number
Ra	Rayleigh number, GrPr
r	radial distance from the center of the heat exchanger
r_1	inner tube inside radius
r_2	inner tube outside radius
r_3	outer casing inside radius
r_4	outer casing outside radius
r_5	far-field distance
t	time
T	temperature
v_1	fluid velocity in inner tube
v_2	fluid velocity in annulus region
z	vertical coordinate

Greek Symbols

ρ	density
α	thermal diffusivity $= \frac{k}{\rho C_p}$
β	fluid thermal expansion coefficent
ν	fluid kinematic viscosity

Subscripts

1	inner tube
2	outer casing
3	ground
f	fluid
f_1	fluid in inner tube
f_2	fluid in annulus region

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ABSTRACT

An experimental and analytical project to study the design of vertical, concentric-tube ground-coupled heat exchangers for use in heat pump applications is described. A mathematical model was developed and converted into a computer program to simulate the operation of the ground-coupled heat exchanger. The experimental apparatus consisted of a concentric configuration of two 47.2-m (155-ft) polyvinyl chloride (PVC) pipes (sealed at both ends with connections so that hot or cold water could be pumped through the system) with instrumentation to measure heat transfer. This heat exchanger was placed in a 0.20-m (8-in.) inside diameter (ID) well and backfilled with sand to establish good thermal contact with the surrounding ground. Heat transfer was measured for heat exchanger operation under several sets of operating conditions. Data collected using the experimental apparatus were used to validate the computer program, and the computer model was then used to study the effects of variations in heat exchanger length and diameter, flow rate, and tube and ground thermal conductivities on the heat exchanger performance. Results are presented.

1. INTRODUCTION

The realization that conventional energy resources are limited urges us to increase efforts to use nonrenewable sources more efficiently. One of several alternatives available is to search for energy-saving modifications in the existing heating, ventilating, and air-conditioning (HVAC) processes.

Heat pumps have long been considered effective devices to extract heat from or reject heat to the environment. The majority of heat pumps use ambient air as the heat source and sink, but their energy efficiency is limited by the thermal capacity and temperature of the air. Groundwater is a better heat source and sink because of its superior thermal capacity and stable temperature. However, its use is limited in many areas of the country by poor quality and insufficient quantity of groundwater or by pumping and disposal costs and other associated problems that make its use economically unattractive. Another alternative is to use the ground itself as the heat source and sink for a heat pump.

Extensive research on horizontal ground-coupled heat pump systems was performed in the 1930s and 1940s. Although this research indicated their high potential for energy conservation, these systems saw little practical application because of the low cost of energy during that period. Rising energy costs have improved the economics of heat pumps. At the present time, horizontal ground-coupled heat pumps are popular in Europe, where they are used for heating only. They have not been used very much in the United States, where the heat exchanger must operate for both space heating and cooling. This is largely because the required heat rejection into the soil through a horizontal ground-coupled heat exchanger during the the cooling season decreases the moisture content of the adjacent soil, thereby lowering its thermal conductivity. The lower thermal conductivity in turn decreases the effectiveness of the heat exchanger.

Ground-coupled heat exchangers of a vertical, concentric tube-in-tube configuration are an alternative to the horizontal configuration. They were first proposed by Ambrose[1] for heat pump applications in 1946. The vertical configuration has certain advantages over a horizontal ground coil. First of all, it occupies a much smaller amount of surface area; and, second, the ground in most areas is saturated with moisture a short distance below the surface and provides a good heat transfer medium for most of the length of the heat exchanger. In shallow, horizontal heat exchangers, moisture migration occurs as a result of heating the unsaturated surface soil. This type of moisture migration affects only a small section of a deep-well vertical heat exchanger.

Bose et al.[2-4] described a geothermal well used for heat pump application in Oklahoma. Although the design and performance of vertical ground-coupled heat exchangers was discussed in their work, little theoretical analysis was provided on the heat exchanger design. Oliver and Brand[5] derived a closed-form analytical solution for the concentric, vertical ground-coupled heat exchanger under steady-state operation by assuming an

isothermal ground surface 1.0 m (3.3 ft) away from the center of the heat exchanger. Their theory tends to give an overly conservative design, and in practical application the ground reaction to heat pump cyclic operation is highly transient. It is therefore unrealistic to design the heat exchanger on the basis of its steady-state operation.

In this study, a 47.2-m (155-ft) vertical, tube-in-tube ground-coupled heat exchanger was installed and tested. A mathematical model describing the heat exchanger's operation, as well as the ground's reaction to the energy transfer, was developed and transformed into a computer code to simulate the heat exchanger's performance. To validate the model, six laboratory tests were performed with the ground-coupled heat exchanger and simulated with the computer program. A parametric study was performed with the model to examine the effect of some design factors on the performance of the heat exchanger. This computer code is easy to use and is intended as a design tool for future installation of vertical ground-coupled heat exchangers.

Ground-coupled heat exchanger analysis, so far, has generally been handled by line source (or cylindrical source) theory. However, with variable fluid temperature in the heat exchanger, the assumption that the strength of the source is constant is not justified. Furthermore, irregular cycling schedules make it very difficult to apply line source theory. This report, for the first time in this field, theoretically analyzes such systems in detail with enough flexibility built into the model so that cyclic operations, variable inlet fluid temperature, different heat exchanger wall materials, and off-cycle ground recovery can be readily taken into account. The model is easy to understand, and, more important, it will provide more accurate performance predictions than the old analytical methods.

2. THEORETICAL DEVELOPMENT

In operation of this ground-coupled heat exchanger, the fluid from the heat pump is pumped down the center tube, as shown in Fig. 1, and flows upward in the annulus; it transfers energy to or from the ground as it rises. Energy is transferred between the fluid and tube wall by convection when the fluid is flowing and by conduction when the flow is stopped. The flow of heat within the walls of the tubes and the ground is assumed to be radial conduction with no vertical heat transfer.

The following assumptions have been made to simplify the analysis:

1. The fluid is well mixed: its temperature is uniform in both the center tube and the annular area perpendicular to the axis of the flowing column.
2. The thermal and physical properties of the fluid, tube, and ground are constant, or independent of temperature and pressure variations.
3. Heat transfer by radiation is neglected.
4. The entire system has cylindrical symmetry about the axis of the fluid column.

The following mathematical model was constructed based on energy balances and the foregoing assumptions.

Heat flow in the water within the inner tube and at the tube wall:

$$-v_1 \frac{\partial T_{f_1}}{\partial z} + \frac{2k_1}{\rho_f C_{p_f} r_1} \frac{\partial T_1}{\partial r}\bigg|_{r=r_1} = \frac{\partial T_{f_1}}{\partial t} . \tag{1}$$

Heat flow within the inner pipe:

$$\frac{\partial^2 T_1}{\partial r^2} + \frac{1}{r}\frac{\partial T_1}{\partial r} = \frac{1}{\alpha_1}\frac{\partial T_1}{\partial t} \quad (r_1 \leqslant r \leqslant r_2,\ 0 \leqslant z) . \tag{2}$$

Heat flow in the water in the annulus and at the tube walls:

$$v_2 \frac{\partial T_{f_2}}{\partial z} - \frac{2r_2 k_1}{(r_3^2 - r_2^2)\rho_f C_{p_f}} \frac{\partial T_1}{\partial r}\bigg|_{r=r_2} + \frac{2r_3 k_2}{(r_3^2 - r_2^2)\rho_f C_{p_f}} \frac{\partial T_2}{\partial r}\bigg|_{r=r_2} = \frac{\partial T_{f_2}}{\partial t} . \tag{3}$$

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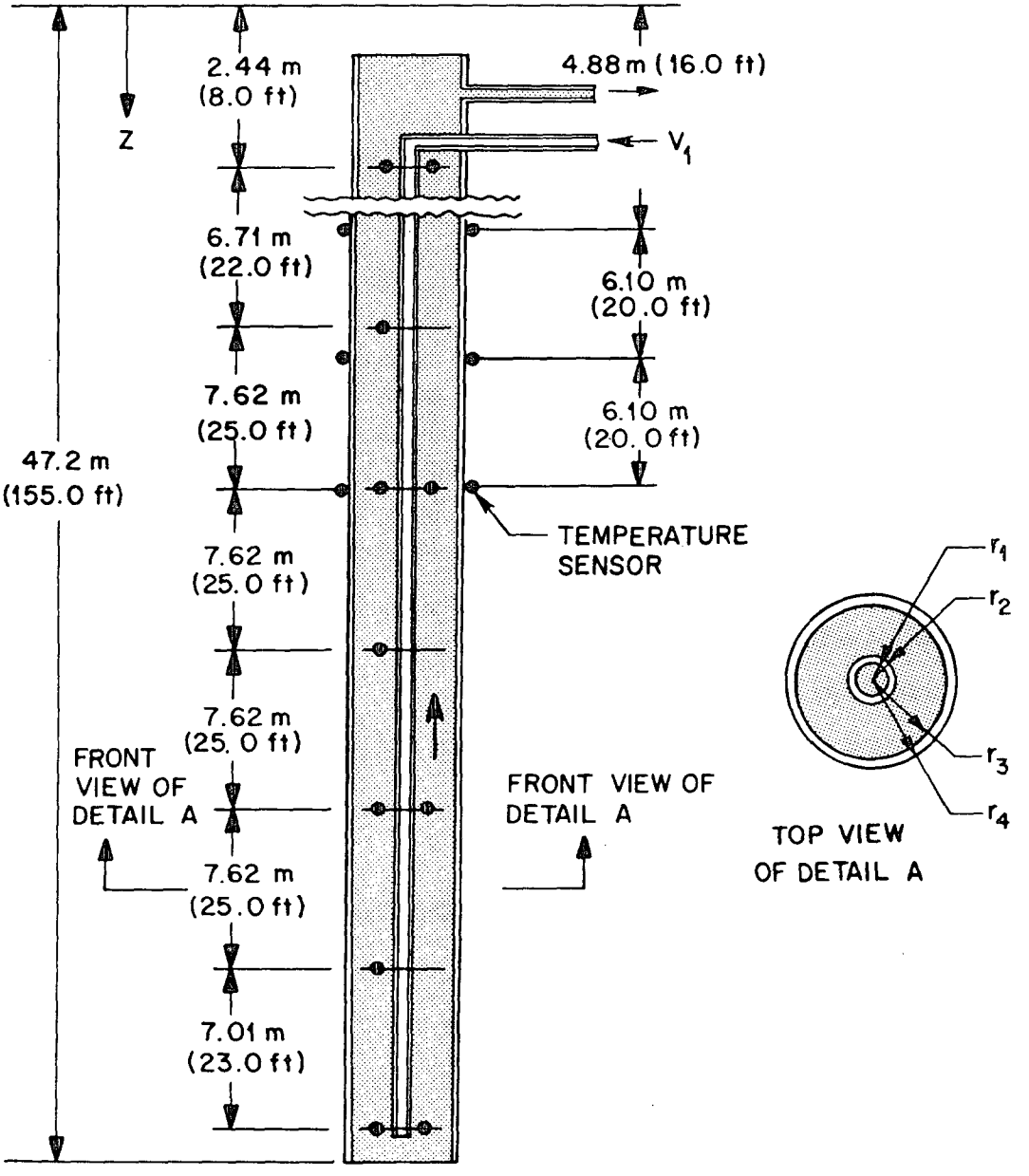

Fig. 1. Schematic of vertical, concentric-tube ground-coupled heat exchanger.

Heat flow within the outer tube:

$$\frac{\partial^2 T_2}{\partial r^2} + \frac{1}{r}\frac{\partial T_2}{\partial r} = \frac{1}{\alpha_2}\frac{\partial T_2}{\partial t} \quad (r_3 \leqslant r \leqslant r_4,\ 0 \leqslant z)\ . \tag{4}$$

Heat flow in the ground:

$$\frac{\partial^2 T_3}{\partial r^2} + \frac{1}{r}\frac{\partial T_3}{\partial r} = \frac{1}{\alpha_3}\frac{\partial T_3}{\partial t} \quad (r_4 \leqslant r \leqslant r_5,\ 0 \leqslant z)\ . \tag{5}$$

Conditions at initial time ($t = 0$):

$$T_1(z) = T_2(z) = T_3(z) = T_{f_1}(z) = T_{f_2}(z) \text{ are known.} \tag{6}$$

Inlet condition at the surface ($z = 0$):

$$T_{f_1}(t,0) = f(t) \text{ is a known function of time.} \tag{7}$$

End condition at the bottom of the heat exchanger ($z = L$):

$$T_{f_1}(t,L) = T_{f_2}(t,L) \ . \tag{8}$$

Boundary condition at the interface between the water and the inner pipe:

$$k_1 \frac{\partial T_1}{\partial r} \bigg|_{r=r_1} = h_1(T_1 - T_{f_1}) \ . \tag{9}$$

Boundary condition at the interface between the water in the annulus and the inner pipe:

$$k_1 \frac{\partial T_1}{\partial r} \bigg|_{r=r_2} = h_2(T_{f_2} - T_1) \ . \tag{10}$$

Boundary condition at the interface between the water in the annulus and the outer pipe:

$$-k_2 \frac{\partial T_2}{\partial r} \bigg|_{r=r_2} = h_3(T_{f_2} - T_2) \ . \tag{11}$$

Boundary conditions at the interface between the outer pipe and the ground:

$$T_2 = T_3 \ , \qquad (r = r_4) \ , \tag{12}$$

$$k_2 \frac{\partial T_2}{\partial r} \bigg|_{r=r_4} = k_3 \frac{\partial T_3}{\partial r} \bigg|_{r=r_4} \ . \tag{13}$$

Boundary condition at the assumed far-field distance from the heat exchanger:

$$T_3 = T_3(z) \qquad (r \geqslant r_5) \ . \tag{14}$$

Equations 9 to 11 are the boundary conditions for convective flow. When the fluid flow is stopped, such as between cycles, the heat transfer mechanism from fluid to tube walls

changes from convection to conduction. The following conditions should be applied under these circumstances:

Heat flow at the interface between the water and the inner pipe:

$$\frac{\partial T_{f_1}}{\partial t} = \frac{2k_1}{\rho_f C_{p_f} r_1} \frac{\partial T_1}{\partial r} \bigg|_{r=r_1} . \tag{15}$$

Heat flow between the water in the annulus and the inner and outer pipes:

$$\frac{\partial T_{f_2}}{\partial t} = \frac{2r_3 k_2}{(r_3^2 - r_3^2)\rho_f C_{p_f}} \frac{\partial T_2}{\partial r} \bigg|_{r=r_3} - \frac{2r_2 k_1}{(r_3^2 - r_2^2)\rho_f C_{p_f}} \frac{\partial T_1}{\partial r} \bigg|_{r=r_2} . \tag{16}$$

Boundary conditions at the interfaces between the water in the inner pipe and the annulus and the walls of the inner pipe:

$$T_1 = T_{f_1} \qquad (r = r_1) , \tag{17}$$

$$T_1 = T_{f_2} \qquad (r = r_2) , \tag{18}$$

$$T_2 = T_{f_2} \qquad (r = r_3) . \tag{19}$$

Equations 15 through 19 assume that the temperatures of the fluid in the center and annular area are uniform. In addition, they do not account for a contact resistance between the fluid and center tube. Since the thermal conductivity of the center pipe should be kept as small as possible to minimize energy short-circuiting, the assumptions made in Eqs. 17 and 19 that there are no temperature gradients between the water and the walls of the inner pipe should not cause any serious error. Equations 15 through 19 replace Eqs. 1, 3, and 9 through 11 when the fluid is still.

The convective heat transfer coefficients for the water in the annulus need to be calculated depending on the vertical position of the water in the heat exchanger. These computations are based on the work by Heaton, Reynolds, and Kays[6] with the consideration of developing temperature and velocity fields in laminar flow and uniform heat flux on either inner or outer tube. The convective heat transfer coefficient is shown in Table 1 in terms of Nu (Nusselt number) and as a function of the product of Re and Pr (Reynolds and Prandtl numbers), hydraulic diameter, and the distance from the bottom of the well. While Table 1 is for an inner-to-outer tube diameter ratio (r^*) of 0.1 and fluid Pr of 10.0, we conclude from the data shown in ref. 6 that Table 1 can also be applied for $r^* = 0.25$ and other Pr since the Nu is not a strong function of Pr within a Pr range of 0.07 to 10.0 for a water temperature range of 0 to 43°C (32 to 109°F). Pr varies from around 4.5 to 11 in our tests. At the bottom of the heat exchanger, where the water in the annulus just starts to rise, the value of h is very high because the velocity and temperature profiles are just starting to develop. The heat transfer coefficient then decreases as laminar flow is established as the water rises in the annulus.

Table 1. Nusselt number as a function of X[a]

X	Nu
0.0001	39.7
0.001	14.9
0.0025	10.64
0.005	8.48
0.010	6.86
0.025	5.54
0.050	4.98
0.10	4.85
0.25	4.83
∞	4.83

[a]$X = (\chi/Dh)/(RePr)$,
Re = Reynolds number,
Pr = Prandtl number,
Dh = hydraulic diameter,
χ = distance from bottom of well.
$Nu = hDh/K$,
K = thermal conductivity of fluid.

3. COMPUTER MODEL

A finite difference computer program was written to solve the mathematical model numerically for either continuous or cyclic operation. It consists of five partial differential equations that describe the temperature distribution in the water, the pipes, and the ground in terms of time, depth, and the distance from the heat exchanger. These are coupled radially by the boundary conditions imposed at the surface interfaces and vertically by the flow of the working fluid in the heat exchanger. 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 pipes, water, and ground. It employs a fixed time step and a fixed relative vertical spacing of nodes used for the solution while permitting a variable radial spacing of nodes in the ground. A check of the computations is made by calculating the amount of heat removed from the ground, pipes, and "resident" water (what is in the heat exchanger at start-up) and comparing it with the heat removed from the system integrated over time (i.e., $\int \dot{m} C_p \Delta T dt$).

Variable h values were adopted even though the mathematical model assumes uniform temperature and velocity profiles. Theoretically, the h values are different for the inner and outer tube walls of the annulus, but since the difference is small,[6] the values calculated for the outer tube wall were used for the inner tube wall as well. The fluid flow in the inner pipe is well within the region for turbulent flow, and an appropriate heat transfer coefficient is used: 3490 $W/(m^2 \cdot K)$ [615 $Btu/(h \cdot ft^2 \cdot {}^\circ F)$].[7] The computer code will calculate the h values for laminar flow. For turbulent flow, the h values have to be input.

The computer program has been written so that it is easy to use and does not require familiarity with the partial differential equations. The input data consist of

1. the geometric specifications of the heat exchanger (i.e., the length and the inside and outside diameters of the pipes);
2. the physical properties of the materials used for the heat exchanger (i.e., the density, specific heat, and thermal conductivity);
3. the flow rate, density, and specific heat of the working fluid;
4. the number of vertical nodes to be used and the number and spacing of nodes in the ground.

There are also options that allow a uniform initial temperature distribution in the ground or one that varies with depth. The user can also specify the inlet water temperature and flow rate as functions of time. The output from the program consists of a printed summary of the temperature distribution at fixed time intervals and also the average capacity of the heat exchanger.

The program is written in ANSI standard FORTRAN IV and requires 21K words of memory. It can require a lot of computer time to perform a long simulation since it must be able to model very rapidly changing transients. In most applications, however, the response of the ground to the heat exchanger approaches an asymptote, and it should be possible to take advantage of this behavior in lieu of performing long simulations (in excess of 24 h). A complete listing of the program is provided in Appendix A.

4. TEST APPARATUS AND PROCEDURE

The authors installed a ground-coupled heat exchanger for testing. Core samples were taken at the test site to a depth of 76 m (250 ft). The sample indicated that the ground was limestone to this depth, except for the first 5.5 m (18 ft), which was clay (see Fig. 2). The water table (the level at which the soil is saturated with water) at the test site was 4.3 m (14 ft) below the surface. Two ground core samples of solid limestone, one from the top and one from the bottom of the drilling, were tested for their thermal properties,* which were as follows:

1. thermal conductivity: 3.03 W/(m·K) [1.751 Btu/(h·ft·°F)],
2. density: 2.7 g/cm^3 (168.5 lb/ft^3),
3. specific heat: 1.065 J/(g·K) [0.255 Btu/(lb·°F)].

The material selected for the ground-coupled heat exchanger itself was schedule-40 polyvinyl chloride (PVC) pipe. Other types of pipe materials, such as high-density polyethylene, might have higher thermal conductivity. However, PVC is very easily glued together, while polyethylene pipe requires welding. The outer casing had a 0.127-m (5.0-in.) inside diameter (ID), and the inner tube a 0.025-m (1.0-in.) ID (see Fig. 3). The thermal conductivities of the PVC pipes, determined experimentally* by steady-state heat transfer methods, were

1. thermal conductivity (inner pipe): 0.175 W/(m·K) [0.101 Btu/(h·ft·°F)],
2. thermal conductivity (outer pipe): 0.188 W/(m·K) [0.109 Btu/(h·ft·°F)],
3. density (both pipes): 1.23 g/cm^3 (77.0 lb/ft^3).

The specific heat of PVC was found to be about 1.51 J/(g·K) [0.36 Btu/(lb·°F)].[8] Table 2 shows the detailed thermal property test results.

Water was used as the working fluid throughout the tests; its flow rate was kept at 0.32 L/s (5.0 gpm) for five tests. This limit was established to maintain laminar flow in the annulus region and to avoid the transition region of fluid flow so that computer simulations could be performed. The sixth test was run at 1.1 L/s (17.4 gpm) to check the model in the turbulent flow region. The ground exchanger's inlet water supply was connected to the laboratory process water supply mains for five tests so that either cold or hot water could be used at a relatively constant temperature. In one test the exchanger was coupled to a heat pump to check the model with variable inlet water temperature. The inlet water supply

*Thermal properties of rock and PVC pipes were tested by the Physical Property Group, Material Science Section, Metals and Ceramics Division, Oak Ridge National Laboratory.

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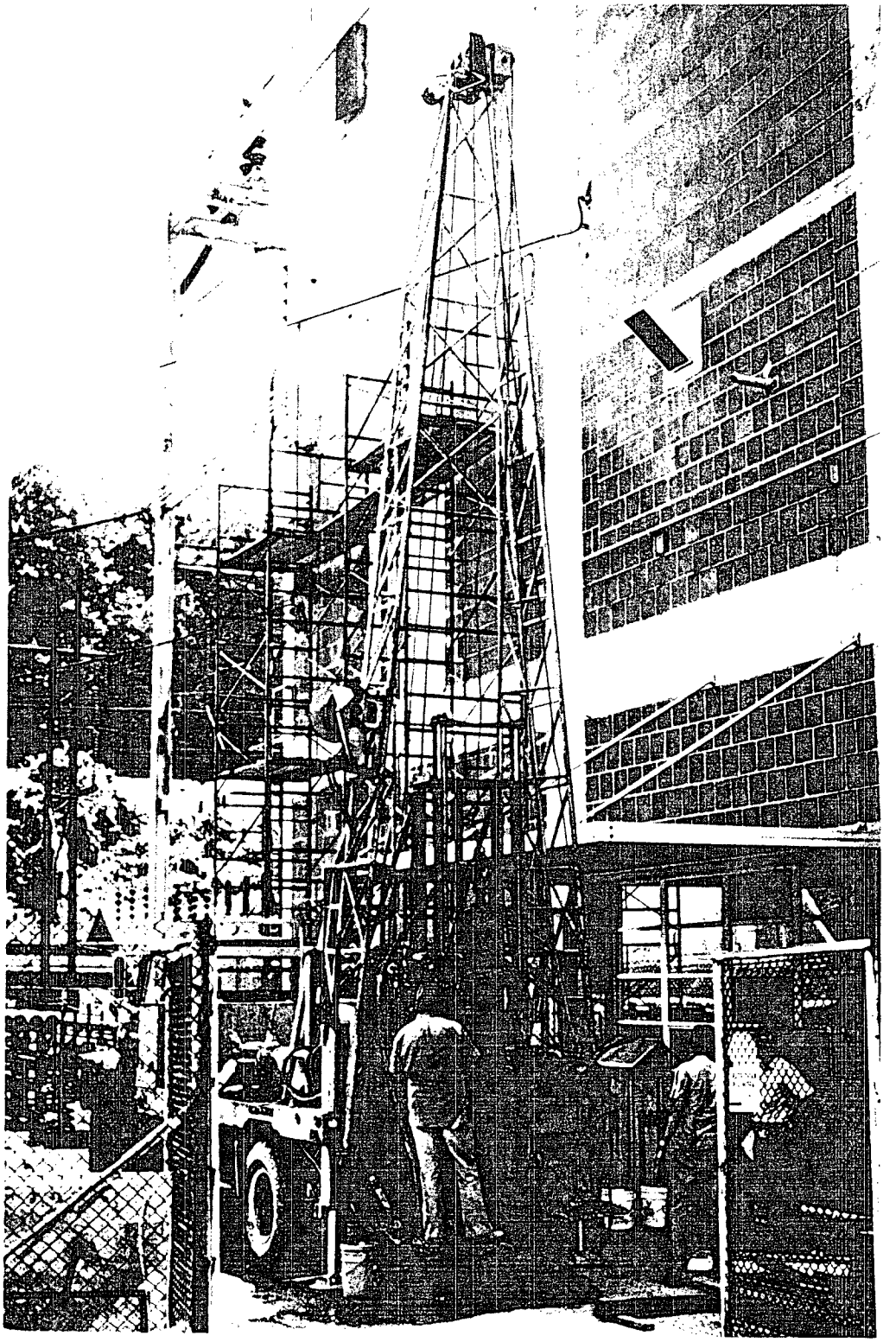

Fig. 2. Ground core sampling.

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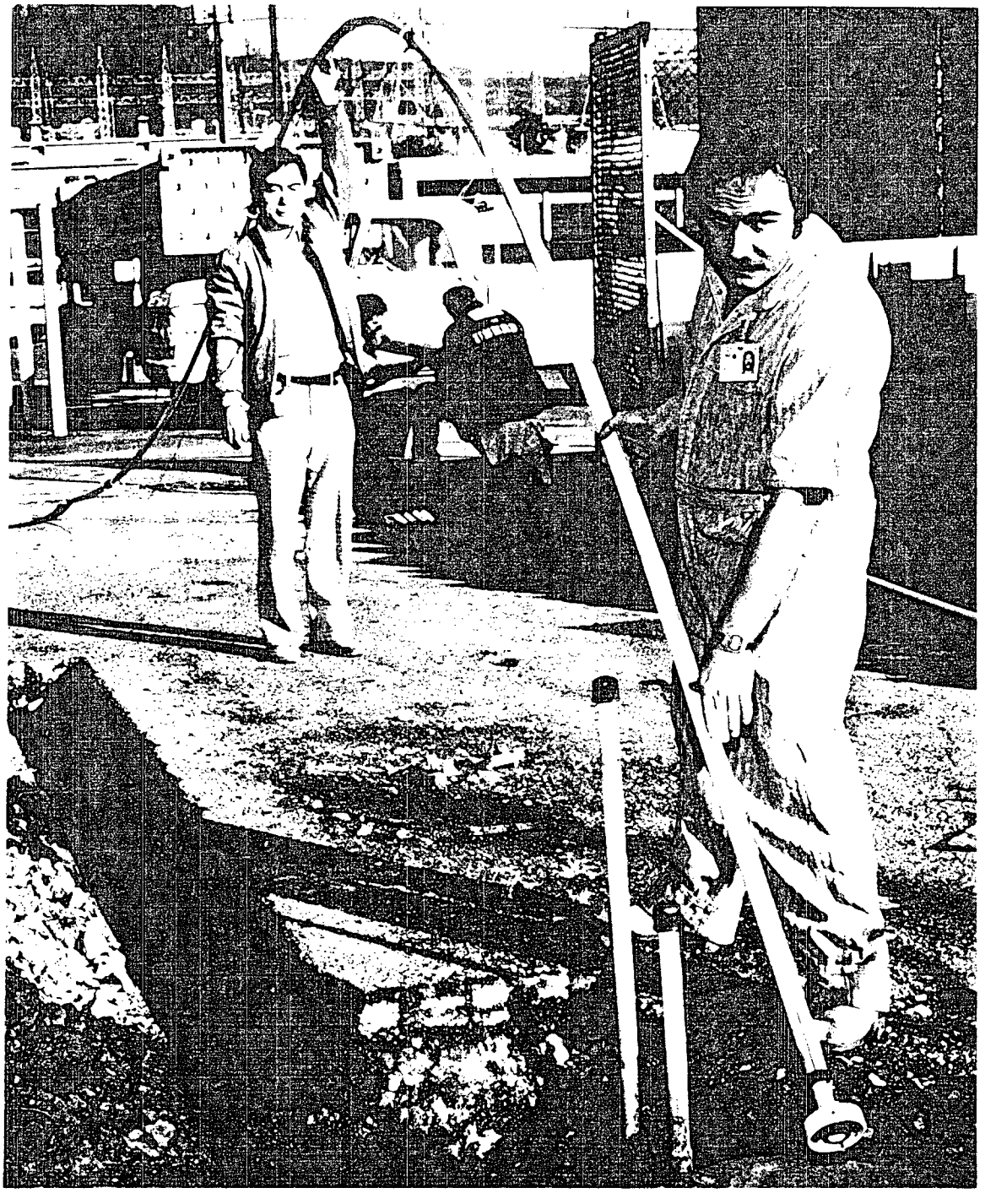

Fig. 3. Installation of ground-coupled heat exchanger.

Table 2. Thermal property measurements on rock and PVC pipe specimens[a]

Specimen	Density		Thermal conductivity		Thermal diffusivity		Specific heat	
	g/cm^3	lb/ft^3	W/(m·°C)	Btu/(h·ft·°F)	m^2/h	ft^2/h	J/(kg·K)	Btu/(lb·°F)
1. Limestone (top)	2.7	168.5	3.10	1.791	3.857×10^{-3}	4.152×10^{-2}	1.07×10^3	0.256
2. Limestone (bottom)	2.7	168.5	2.96	1.710	3.712×10^{-3}	3.995×10^{-2}	1.06×10^3	0.254
3. PVC (inner tube)	1.2	77					*1.26×10^3	*0.3
at 7.5°C (45.5°F)			0.168	0.097	3.901×10^{-4}	4.199×10^{-3}		
at 30.6°C (87.0°F)			0.179	0.103	4.143×10^{-4}	4.459×10^{-3}		
at 48.4°C (119.2°F)			0.177	0.102	4.103×10^{-4}	4.416×10^{-3}		
4. PVC (outer casing)	1.2	77					*1.26×10^3	*0.3
at 6.9°C (44.5°F)			0.183	0.106	4.263×10^{-4}	4.589×10^{-3}		
at 30.6°C (87.0°F)			0.193	0.111	4.464×10^{-4}	4.805×10^{-3}		
at 48.4°C (119.2°F)			0.187	0.108	4.344×10^{-4}	4.675×10^{-3}		

[a]Information in entries preceded by asterisks was taken from ref. 7.

was also connected to a 3.8-m^3 (1000-gal) ice tank so that water close to the freezing point, 0°C (32°F), could be pumped to the heat exchanger for low-temperature inlet water operation. A calibrated rotameter was used to measure the flow rate of the water.

Figure 1 shows a schematic of the ground exchanger used for the tests. The exchanger is 47.2 m (155 ft) in length, and the annular region between the pipes has inner and outer diameters of 0.033 m (1.31 in.) and 0.127 m (5.0 in.) respectively. Circular spacers were bonded to the inner tube, and temperature sensors were attached to the spacers. Figure 1 also shows both the depths at which temperature sensors were located in the annular area between the two pipes and the location of the sensors on the outside of the outer tube. All the sensors were four-wire platinum resistance temperature detectors (RTDs) except those for the inlet and outlet water temperature measurements, which were thermocouples. The RTDs and thermocouples were calibrated to accuracies of ±0.3°C (±0.5°F) and ±0.5°C (±1°F), respectively.

The data acquisition system used in the test consisted of a digital computer with an 8K word memory coupled with a floppy-disk drive, an integrating digital voltmeter with an ohm converter, and a reed relay scanner. The programs used by the computer were written in the FOCAL language, which has had some modifications made to facilitate data acquisition.

5. TEST RESULTS AND MODEL VALIDATION

Six tests were conducted using the test apparatus previously described to obtain data to validate the mathematical model. These consisted of heat exchanger operation with hot and cold inlet water under continuous and cycling operation (cycling was for 2 cycles/h with equal on and off times). The tests are summarized in Table 3. The temperatures were recorded every 2 min during the first, third, fourth, fifth, and sixth tests listed in Table 3 and every 10 min for the cold inlet water test with continuous operation. The flow rate was kept at 0.32 L/s (5.0 gpm) for all the tests except the sixth test, which was run at 1.1 L/s (17.4 gpm).

The ground temperature at the test site was expected to be around 13 to 14°C (55 to 57°F); however, an oddly shaped ground temperature profile was observed. All points within 6.1 m (20 ft) of the surface were found to be influenced by the ambient conditions. Below 6.1 m (20 ft) the temperature rises with the depth until it reaches a maximum of 17.5°C (63.5°F) at 15.2 m (50 ft). It then decreases with further depth, as shown in Fig. 4. The ground temperature at 47.2 m (155 ft) was around 16.7°C (62°F), which was also higher than expected. It is conjectured that the elevated and oddly shaped temperature profile was caused by the heat released from a large building 3.7 m (12 ft) from the heat exchanger. The ground-temperature profile was measured before each test and was used as the initial conditions for each of the validation runs of the computer program.

The simulations required specifications of convective heat transfer coefficients at the water-tube wall interfaces. The convective heat transfer coefficient for the inner tube wall

Table 3. Summary of validation tests showing maximum and average magnitude of temperature difference between observed and calculated water temperatures in the annulus 16.8 m (55 ft) below the surface for continuous and cycling heat exchanger operation

Test no.	Inlet water temperature		Operating conditions	Duration (h)	Maximum ΔT^a		Average ΔT^a	
	°C	°F			C°	F°	C°	F°
1	42.8	109	Continuous	10	1.68	3.03	0.46	0.83
2	4.4	40	Continuous	10	0.48	0.86	0.33	0.59
3	43.3	110	Cyclic	6	13.7	24.6	1.15	2.06
					1.81[b]	3.26	0.69[b]	1.24
4	1.1	34	Cyclic	6	0.40	0.73	0.17	0.30
5	21.1 to 41.7 (variable)	70 to 107 (variable)	Continuous	1.67	2.08	3.75	0.49	0.88
6	38.3	101	Continuous (turbulent)	1.0	3.71	6.68	0.58	1.05

[a]Fluid inlet and outlet temperature differential throughout the test.
[b]After the first hour of operation.

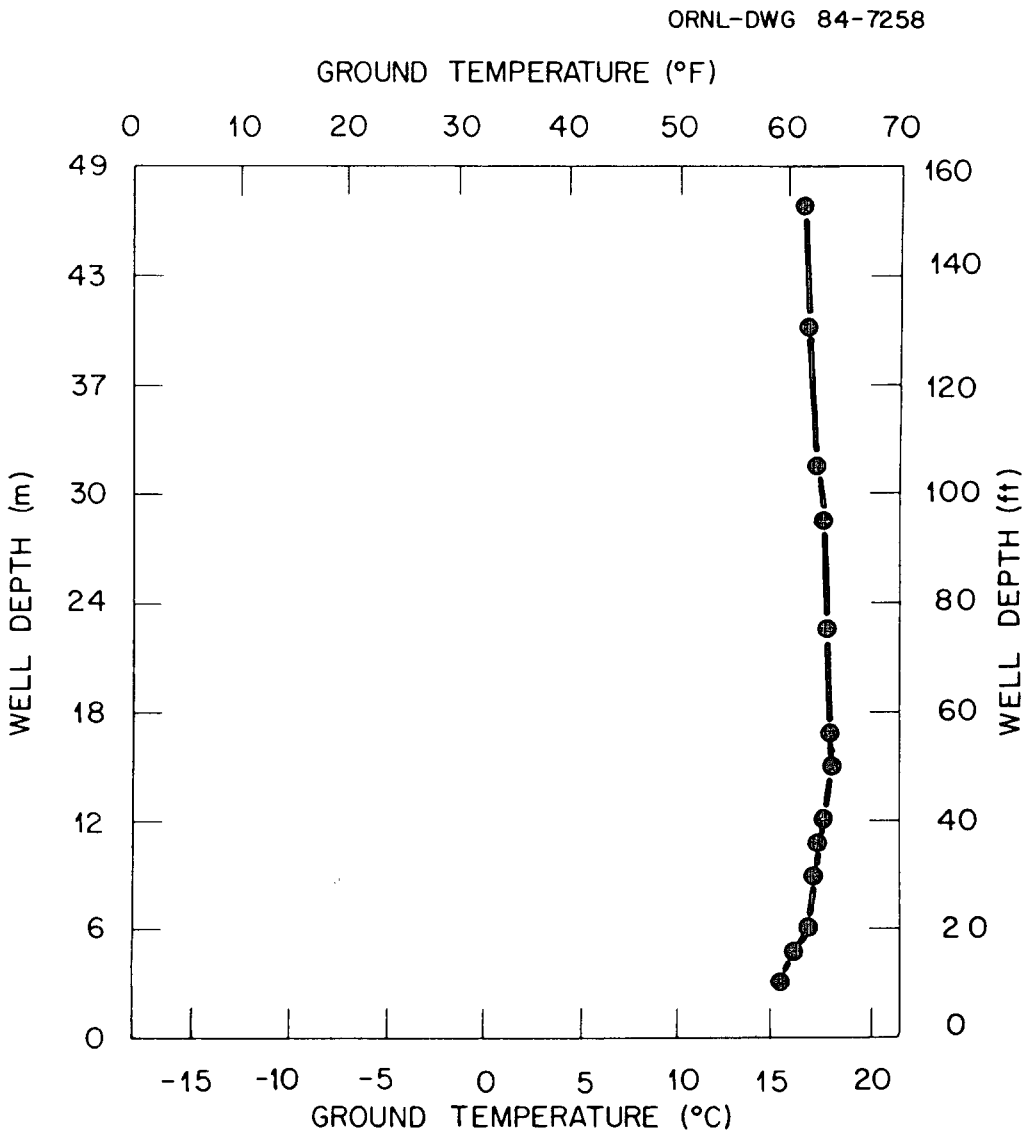

Fig. 4. Ground temperature distribution along well depth.

was easily calculated[8] (since this flow is in the turbulent region) and was equal to 3490 W/(m^2·K) [615 Btu/(h·ft^2·°F)]. The Reynolds number for fluid flow in the annular region for the hot inlet water tests was equal to 3500, which was in the transition zone,[9] but it was very close to the laminar region. The Reynolds number for the water in the annulus for the cold water tests was in the laminar region (Re < 2200). Consequently, we used the work of Heaton, Reynolds, and Kays[6] to compute the heat transfer coefficients for the walls of the annular region, as previously mentioned.

The fifth test was performed at 0.32 L/s (5.0 gpm) with the ground exchanger coupled to a heat pump. In such an arrangement, the exchanger inlet water temperature is a function of time.

The sixth test was run at a 1.1-L/s (17.4-gpm) flow rate. The fluid flow in the annulus region is turbulent with a Reynolds number of 11,820 and an average Prandtl number of

4.85. In the turbulent zone the flow entrance and velocity profile effect is greatly reduced, and the convective heat transfer is drastically increased. Based on the work by Leung, Kays, and Reynolds,[10] the h value should be around 454.2 W/(m^2·K) [80.0 Btu/(h·ft^2·°F)].

5.1 VALIDATION OF CONTINUOUS OPERATION WITH CONSTANT INLET WATER TEMPERATURE

Figure 5 shows the observed data and computer calculations for the two tests of continuous operation with hot and with cold inlet water. The water in the annulus and the shell temperatures at 16.8 m (55 ft) from the surface were chosen for validation of the model

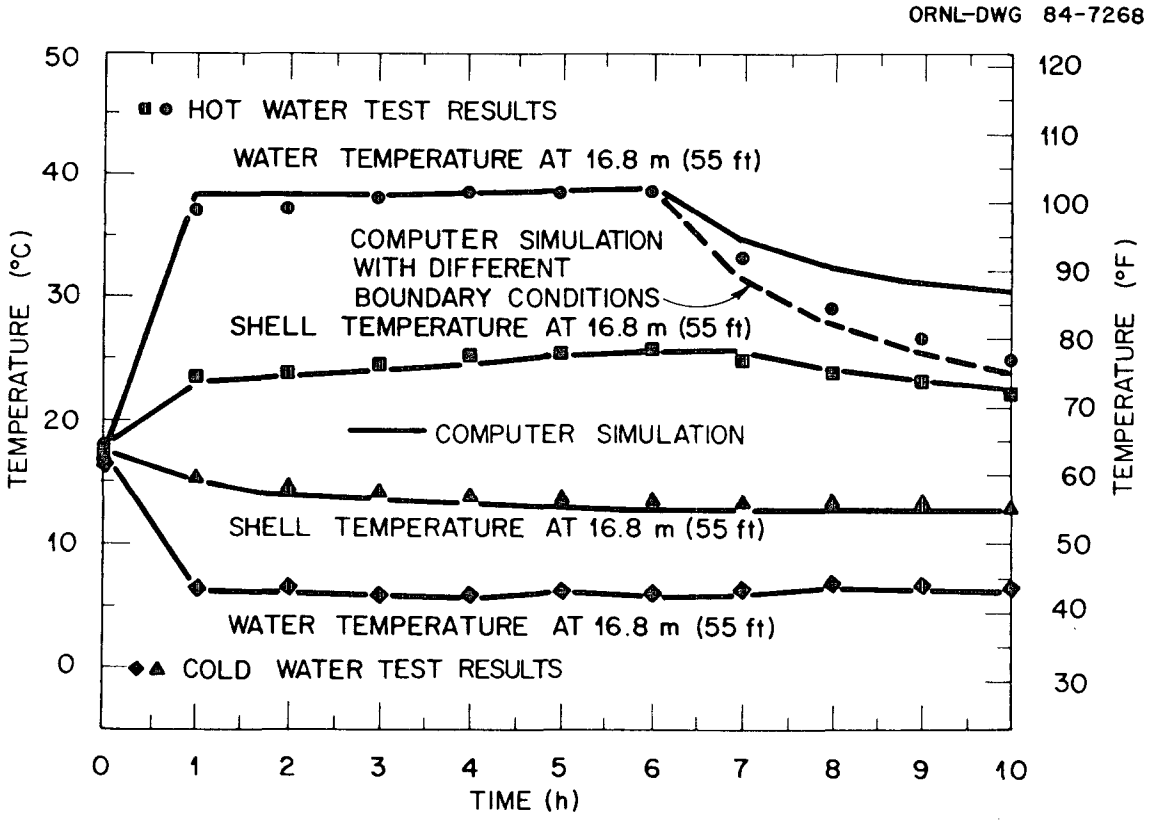

Fig. 5. Validation of hot and cold inlet water continuous operation.

because they are the most fundamental measurements taken. The top two curves show the test results for 6 h of continuous operation with hot inlet water at 41.7°C (107°F) and then 4 h of ground recovery. The solid lines are the calculated temperatures, and the markers are used for the observed temperatures.

The computer program does not predict the test data very well at the beginning of heat exchanger operation when the water and shell temperatures change abruptly. The model simulates the experimental results much better, however, after 2 h of heat exchanger operation as long as the water is flowing. However, when the water flow is stopped after 6 h of operation, the computer model overpredicts the water temperature during the recovery

period (as shown by the solid line). When a boundary condition is added to the program that eliminates the temperature gradient between the water and the inner wall of the outer casing (the water temperature is set to equal the temperature of the outside wall), the computer calculation matches the test results very well, as shown by the dashed lines in Fig. 5. The added condition does, however, underpredict the test result for the first half hour of water-temperature recovery. This makes the added condition undesirable for cyclic operation if the off-cycle time is less than 1 h.

It appears that when the water flow is stopped, a temperature differential between the water and the inner wall of the casing persists, but for a period of less than 1 h. Since the heat exchanger was not adequately instrumented to allow further study of this question, it can only be assumed that this temperature differential is the source of the discrepancy between the observed and calculated temperatures.

Figure 5 also shows the data from 10 h of continuous coil operation with cold inlet water at around 4.4°C (40°F). This test was continued for 6 d of operation and then for 6 d of recovery, although not all of the data are shown. It can be seen that after the first hour of operation, the temperature profile becomes very stable. The fluctuation of water temperature (as appears at 2 h in Fig. 5) was due to minor changes in the inlet water temperature. The water inlet and outlet temperature differential was 1.6°C (2.8°F) at the end of 10 h of operation, and it was maintained even after 6 d of heat exchanger operation. The temperature of the shell's outer edge was much higher than the water temperature at the same depth, as shown in Fig. 5. These data show that PVC has an insulating effect and is not a good material for this type of heat exchanger.

The model predicts the annulus water temperature for the cold water test at 16.8 m (55 ft) below the surface within 0.6°C (1°F) of the test results. It also predicts the temperature of the casing's outer edge within 0.7°C (1.3°F) of the measured temperature. Predicted temperatures at other depths agreed with the observed values at least as well as they did at 16.8 m (55 ft).

5.2 VALIDATION OF CYCLIC OPERATION

Figure 6 shows the test results of cyclic operation of the heat exchanger with hot and cold inlet water. The water entering the ground coil was turned on during the first 30 min of each hour and then shut off to allow the ground to recover for the next 30 min. For the test with hot inlet water, the top two curves represent the water temperature in the annulus and the temperature at the outer edge of the shell 16.8 m (55 ft) from the surface. The bottom two curves are the temperatures at the same points for the cold inlet water test. Again, the solid lines are computed temperatures, and the markers are observed values.

Although Fig. 6 shows only the fluctuations of annulus water temperature that occurred 16.8 m (55 ft) below the surface, results indicate that temperature fluctuations occurred at all water levels. This figure shows that the peak temperature for the hot water test occurred at the end of each on cycle and that the water temperature started dropping as soon as the water flow was stopped.

The temperature of the shell's outer edge at 16.8 m (55 ft) below the surface showed a nearly asymptotic rising or falling trend for the two tests, and only a slight temperature fluctuation was observed during the cycles. This was caused by two factors. First, the PVC

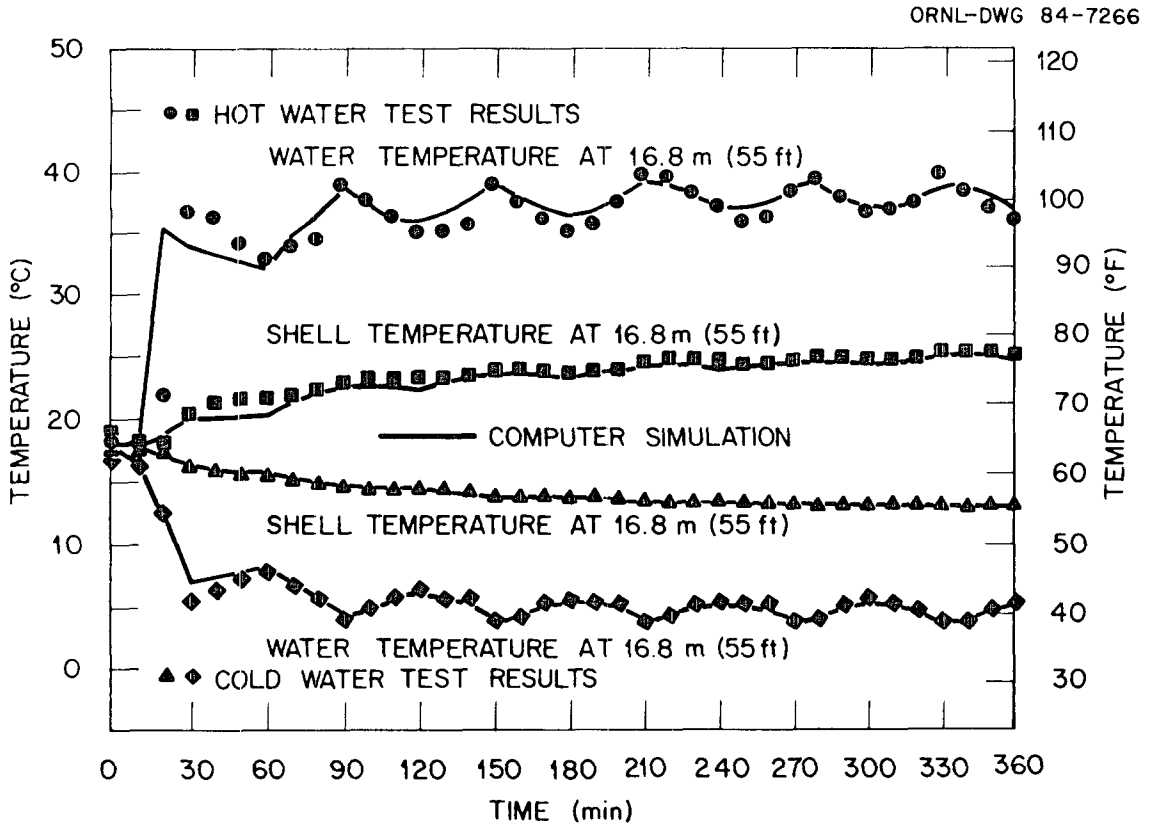

Fig. 6. Validation of hot and cold inlet water cyclic operation.

material had a low thermal conductivity. Second, when the water flow was stopped, the temperature of the water in the heat exchanger was still very different from the ground temperature, which caused the ground temperature near the pipe to change continuously.

At the beginning of the first cycle, the model underpredicts the water temperature by almost 2.8°C (5.0°F) for the hot water test. After this cycle, however, the predictions are within 1.1°C (2.0°F) of each peak temperature. The model overpredicts the water temperature at the end of the off cycle by as much as 1.4°C (2.5°F). The reason seems to be that the nature of heat transfer immediately following termination of the water flow is not well understood and consequently cannot be modeled accurately.

The calculated water temperature matches the test results very well except at the beginning of the first cycle of the cold water test, where the computer calculation differs from the test results by 1.4°C (2.5°F). One possible explanation for this discrepancy is that at the start of the cycle, the fluid everywhere along the annulus region has not established either a velocity or a temperature profile yet. So the local convective heat transfer coefficients should be much higher than the input values for laminar flow. After 6 h of cyclic operation, the water flow was stopped. The model underpredicts the water temperature rise during this period (not shown in Fig. 6), again because of a lack of understanding of the characteristics of heat transfer immediately following water-flow stoppage.

Although the simulations were presented as the temperatures of the water and the outer edge of the casing 16.8 m (55 ft) below the surface, they match the annulus water temperature at almost all levels equally well. The exception to this is the top 3.0 m (10 ft) of the heat exchanger where the influence of the ambient temperature change and moisture migration in the unsaturated soil could not be handled by the model.

Based on the foregoing results, it has been concluded that the mathematical model predicts the test results very well when the heat exchanger is operated continuously. By changing a boundary condition, the program also predicts the recovery temperature well if the heat exchanger is allowed to rest for at least 1 h. For cyclic operation with a 30-min recovery period, the model does not predict the coil recovery rate as accurately as would be desired, particularly for hot inlet water. The calculation of water temperature at the beginning of each off cycle could be improved if there were a better understanding of the heat transfer between water and tube wall when the water flow is stopped abruptly.

5.3 VALIDATION OF CONTINUOUS OPERATION WITH VARIABLE INLET WATER TEMPERATURE

In order to achieve variable fluid inlet temperature into the ground exchanger, the exchanger was connected to a heat pump. Figure 7 shows the exchanger inlet water temperature variation over a period of 100 min during the operation of the heat pump in the cooling mode. This variable inlet water temperature is treated as a function of time and is

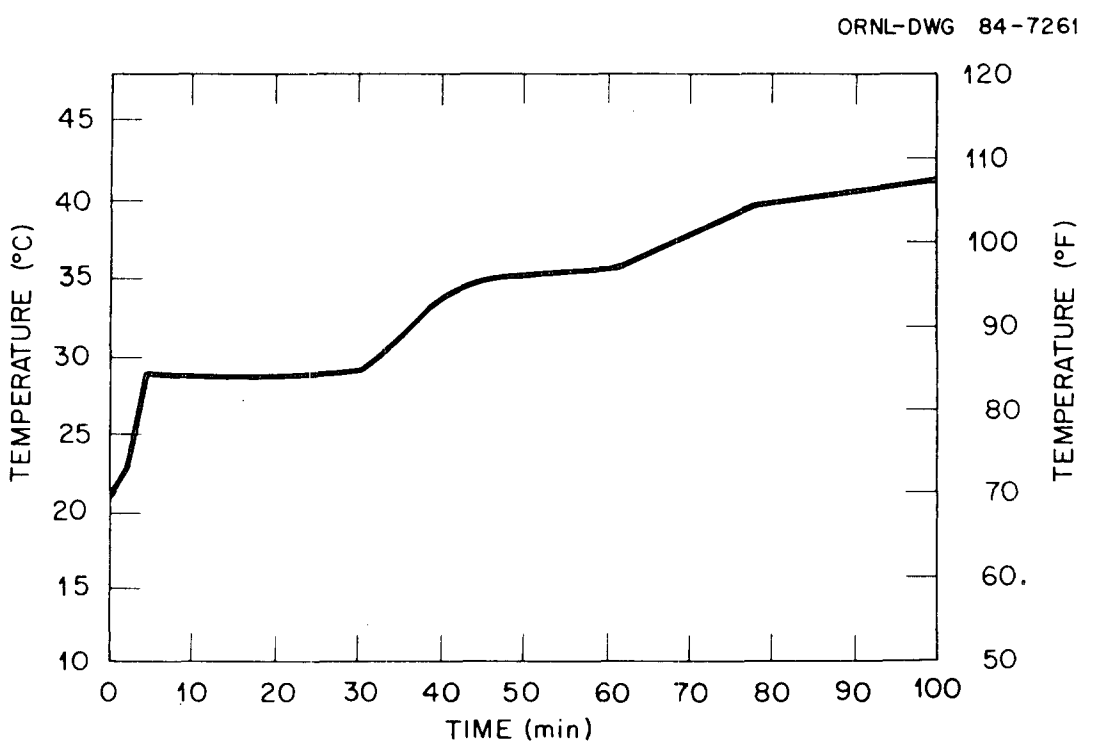

Fig. 7. Variable water inlet temperature as a function of time.

part of input data to the computer code. The measured and calculated water temperatures at 16.8 m (55 ft) below ground, as shown in Fig. 8, match each other very well. However, the measured shell temperatures at the same depth are higher than the calculated ones by about 1.1°C (2.0°F). It could mean that the actual convective heat transfer coefficient was slightly higher than the ones we calculated.

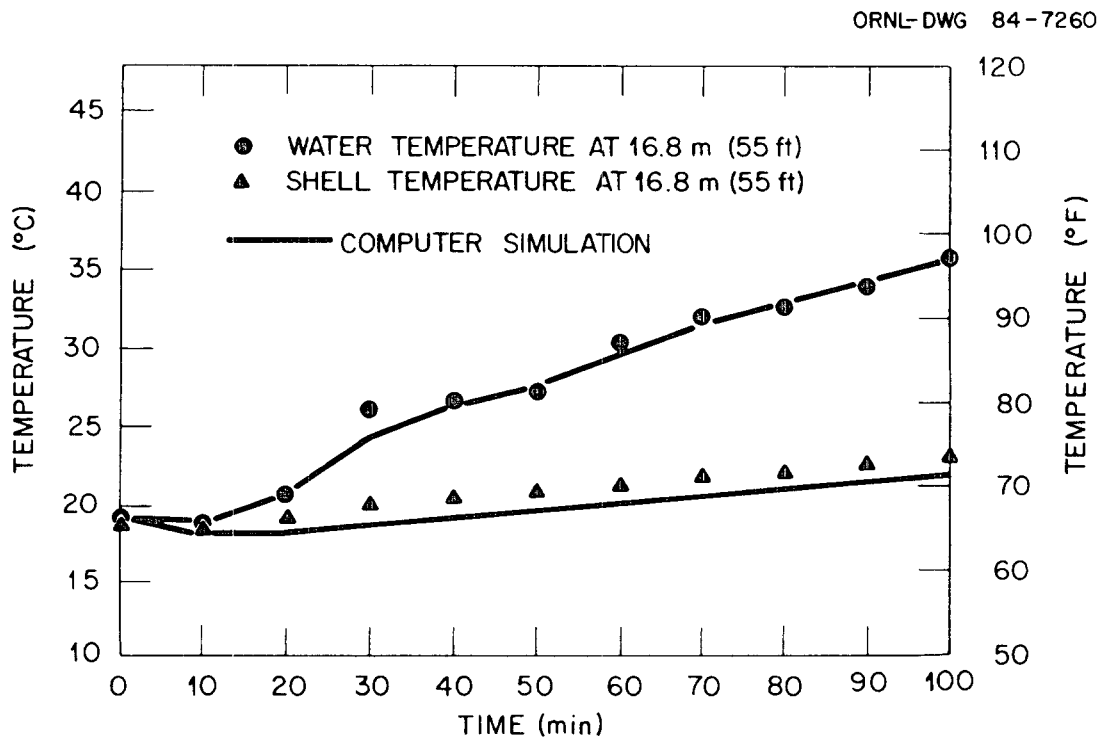

Fig. 8. Validation of variable water inlet temperature test.

5.4 VALIDATION OF CONTINUOUS OPERATION AT HIGH FLOW RATE

Figure 9 shows the comparison of the calculated and test results at high water flow rate. The test was run at 1.1 L/s (17.4 gpm) water flow rate so that the flow in the annular region was turbulent[9] (Re = 11,820), which would have a much higher convective heat transfer coefficient than those of laminar flow [h = 454 W/(m^2·K) or 80 Btu/(h·ft^2·°F) for turbulent flow test]. The calculated water temperatures matched the measured ones well, but the calculated shell temperatures were higher than the test results. This could be caused by the fact that the temperature sensors bonded on the outer shell surface were not insulated so that the readings were affected by the ambient ground temperatures. This effect is much more serious when the flow is turbulent because of higher heat transfer across the outer casing wall. However, judging from the excellent match between the measured and calculated water temperatures, the model handled the the turbulent flow very well. The water temperature mismatch at the beginning again is probably caused by the transient effect of local h values, which is not considered in the model.

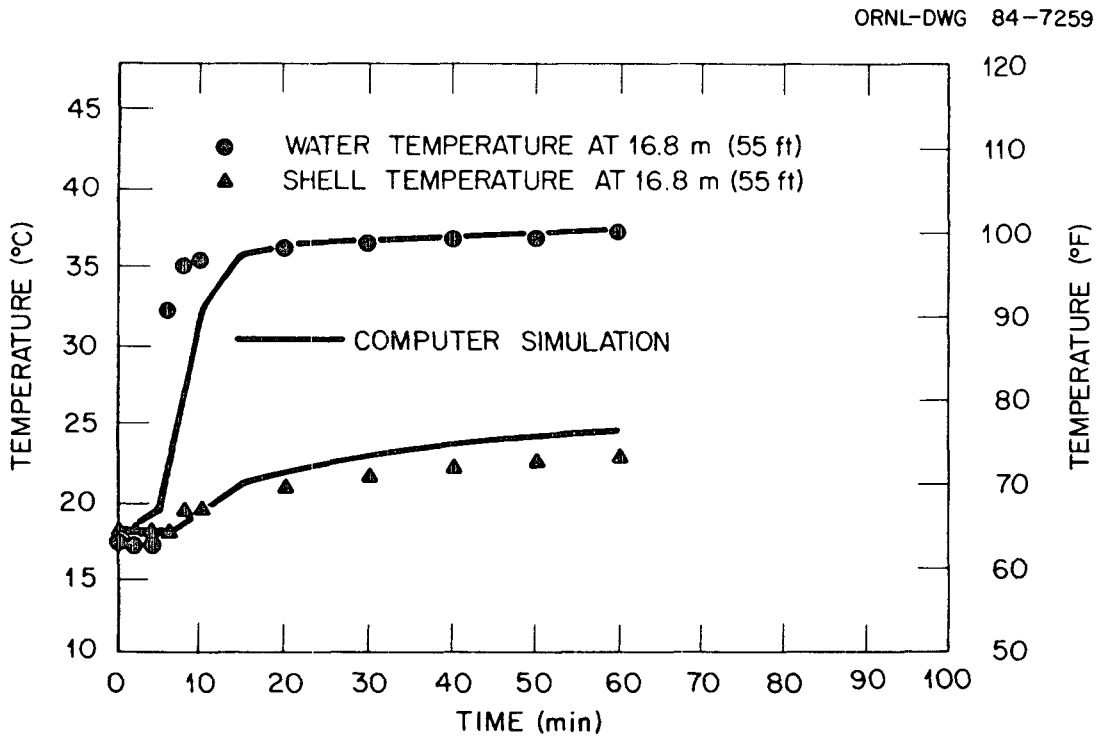

Fig. 9. Validation of hot water inlet temperature at high water flow rate—turbulent annulus flow.

6. PARAMETRIC ANALYSIS

A parametric analysis was performed to investigate the effect of variations in design parameters on system performance. The parameters involved in the actual system design that are of interest for this kind of analysis are the inner pipe and outer shell casing materials, the size of the outer casing pipe, the water flow rate, and the length of the heat exchanger. The model is limited to some extent in its application because as the water flow rate is increased, the Reynolds number also increases. In addition, the flow can change from the laminar to the transitional region, where heat transfer coefficients cannot be modeled accurately. Information about the convective heat transfer coefficient, h, in the transitional region is extremely hard to find. For turbulent flow, the fluid flow rate will be too high for practical application. The water flow rate involved in the analysis is therefore limited to 0.32 L/s (5.0 gpm) or less. The maximum flow rate the model can handle will be higher for other working fluids (e.g., a glycol solution) than it is for water and may in fact accommodate all the flow rates that would be of interest to the user.

Figure 10 shows the effect of the change of thermal conductivity values of the outer casing for continuous coil operation with hot inlet water [42°C (107°F)]. The figure shows that when the casing's thermal conductivity increases from 0.189 to 6.056 W/(m·°C) [0.109 to 3.5 Btu/(h·ft·°F)], the water temperature in the annulus 16.8 m (55 ft) below the surface shows an appreciable drop. In the first hour of operation it falls from 38.3 to 35.3°C (101 to 95.5°F), although the temperature differential becomes smaller as heat exchanger operation continues. At the end of 5 h, the temperature varied from 38.7 to 37.3°C (101.6 to 99.2°F). The greatest rate of improvement came from the change of the thermal conductivity (k) value from 0.189 to 0.460 W/(m·°C) [0.109 to 0.266 Btu/(h·ft·°F)], which corresponds to using high-density polyethylene for the outer casing instead of PVC. Further increases in the casing's thermal conductivity show a diminished effect on water temperature and, hence, heat exchanger capacity. Although metal casings have superior thermal conductivity, their use would not be justified based on this analysis because their performance is only slightly better than that of high-density polyethylene and their cost is significantly higher.

Figure 11 shows the effect of the diameter of the outer casing on the heat exchanger's capacity. These data were computed for heat exchangers made of high-density polyethylene (solid lines) and PVC (dashed lines) with inlet water at 42°C (107°F), a flow rate of 0.32 L/s (5 gpm), and an inlet water to far-field ΔT of 25°C (45°F). The data indicate that a larger casing diameter does improve heat exchanger performance, although not in proportion to the increase in surface area.

Table 4 shows this effect for PVC more directly. The third column is the ratio of the capacities of four points on the top dashed curve in Fig. 11 to the capacities of the corresponding points on the middle dashed line. Although the surface area of the heat exchanger has been increased by 60%, the rate of heat rejection for the 0.20-m (8-in.) ID

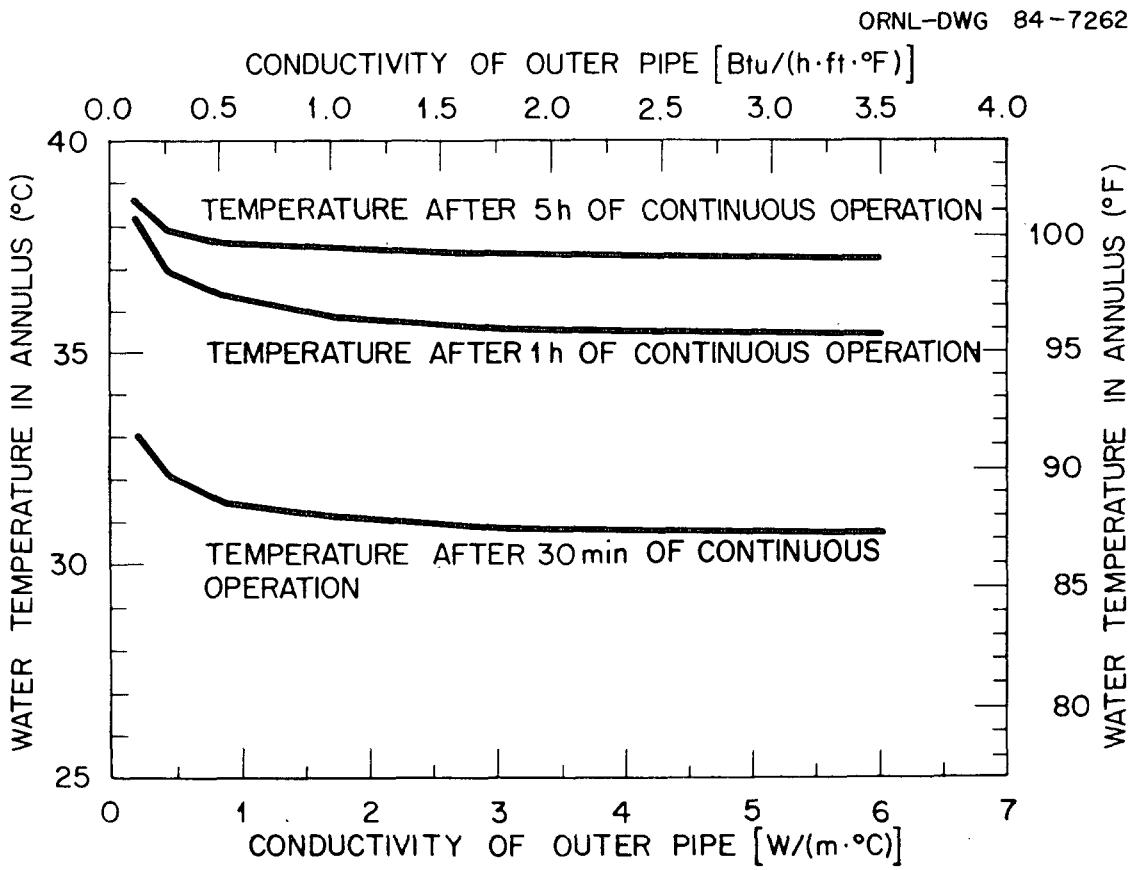

Fig. 10. Effect of outer casing thermal conductivity on heat exchanger performance.

heat exchanger is at most 36% larger than that for the 0.13-m (5-in.) ID heat exchanger. The fourth and fifth columns of Table 4 show similar results when a 0.13-m (5-in.) ID and a 0.20-m (8-in.) ID heat exchanger, respectively, are compared with a 0.076-m (3-in.) ID heat exchanger. The reason that the heat rejection rate does not move in direct proportion to the ratio of surface areas for the heat exchangers is that the water velocities change as a result of larger annular area. This in turn affects the Reynolds numbers and, hence, the heat transfer coefficients.

Figure 12 shows the sensitivity of heat exchanger capacity to uncertainties in the soil thermal conductivity. A 100% increase in thermal conductivity from 3.03 W/(m·K) [1.75 Btu/(h·ft·°F)] to 6.06 W/(m·K) [3.50 Btu/(h·ft·°F)] produces anywhere from an 11 to a 29% increase in heat exchanger capacity (for the PVC heat exchanger with 33% on-time and the high-density polyethylene heat exchanger running continuously, respectively). A 43% reduction in thermal conductivity produces a 12–27% reduction in capacity (which happens to correspond with the same two cases). Consequently, small errors in the value of soil thermal conductivity will produce minor, but not insignificant, errors in the predicted heat exchanger capacity. Figure 12 can also be used to assess the error in case there is uncertainty in the ground thermal conductivity.

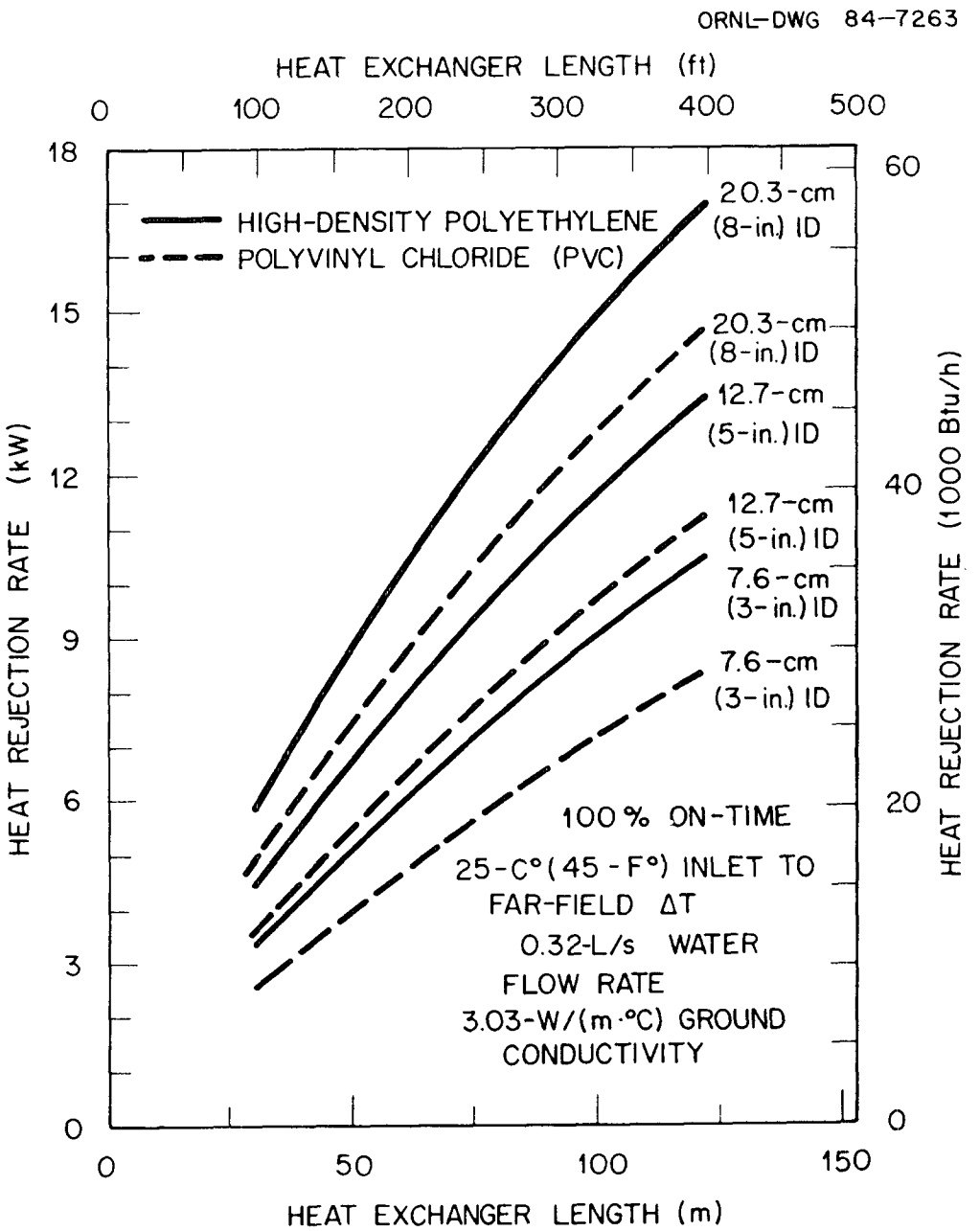

Fig. 11. Effect of casing size on heat rejection rate.

Figure 13 has two sets of curves that show the calculated average capacity per unit length for tube-in-tube vertical ground-coupled heat exchangers as functions of the length of the heat exchanger and of the operating time and volumetric flow rate. All six of these curves are for heat exchangers made of PVC. The three solid lines are for a flow rate of 0.32 L/s (5 gpm) for continuous operation, for operation at 50% on-time (and 3 cycles/h), and for operation at 33% on-time (also at 3 cycles/h). The dashed lines represent the

Table 4. Comparison of relative heat rejection rates for heat exchangers of different lengths and diameters

Length of HX		Heat rejection rate		
m	ft	1.60[a]	1.67[a]	2.67[a]
30.5	100	1.36	1.41	1.91
61.0	200	1.34	1.38	1.85
91.5	300	1.32	1.36	1.80
121.9	400	1.31	1.34	1.75

[a]Ratio of surface areas (ratio of diameters squared).

corresponding capacities for a water flow rate of 0.19 L/s (3 gpm). Some observations can be made about the capacity per unit length from this figure:

1. It is as much as 90% as high at 0.19 L/s (3 gpm) as it is at 0.32 L/s (5 gpm).
2. Under cyclic operation it does not decrease in proportion to the operating time (i.e., the heat exchanger rejects 48% as much heat to the ground when it runs 20 min out of each hour as it does when it runs continuously).

These computations were done for hot inlet water at a temperature of 42°C (107°F), a ground temperature of 16.7°C (62°F), and schedule-40 PVC for both pipes.

The decrease in heat exchanger performance per unit length is a result of the variations in heat transfer coefficients at the interface between the water in the annulus and the outer casing. In our application the correlation that was used for heat transfer in regions of developing laminar flow gives the heat transfer coefficients in terms of the distance from the bottom of the heat exchanger. Consequently, for example, the heat transfer coefficients for the bottom 61 m (200 ft) of a 122-m (400-ft) heat exchanger are the same as those for the entire length of a 61-m (200-ft) heat exchanger. However, since laminar flow is fully developed by 61 m (200 ft), the heat transfer coefficients for the top 61 m (200 ft) are significantly less and hence decrease the average performance per unit length of the heat exchanger.

Figure 14 is a plot of the average capacity of a 61-m (200-ft) heat exchanger with a 0.32-L/s (5-gpm) flow rate at several inlet water temperature to far-field temperature ΔTs and schedules of operation (continuous operation, 50% on-time, and 33% on-time). The solid lines are for a heat exchanger made of high-density polyethylene and the dashed lines for one made of PVC (note that the polyethylene pipe with 33% on-time and the PVC pipe with 50% on-time are nearly identical). In each case the ambient ground temperature was assumed to be 16.7°C (62°F), and the inlet water temperature of the heat exchanger was varied above or below this. The performance was found to be independent of the sign of the temperature differential and was nearly linear with the temperature differential.

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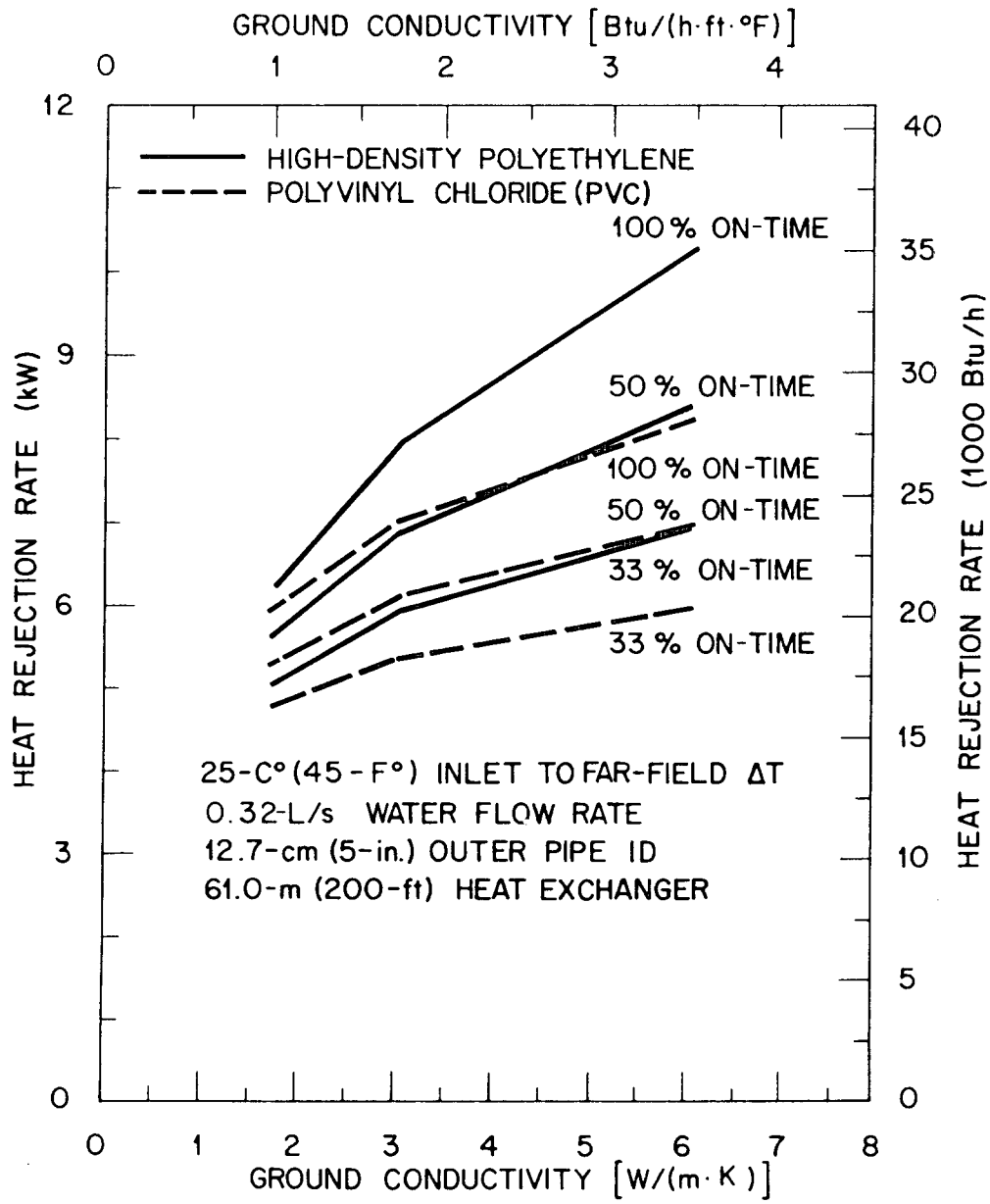

Fig. 12. Effect of ground thermal conductivity on heat exchanger performance.

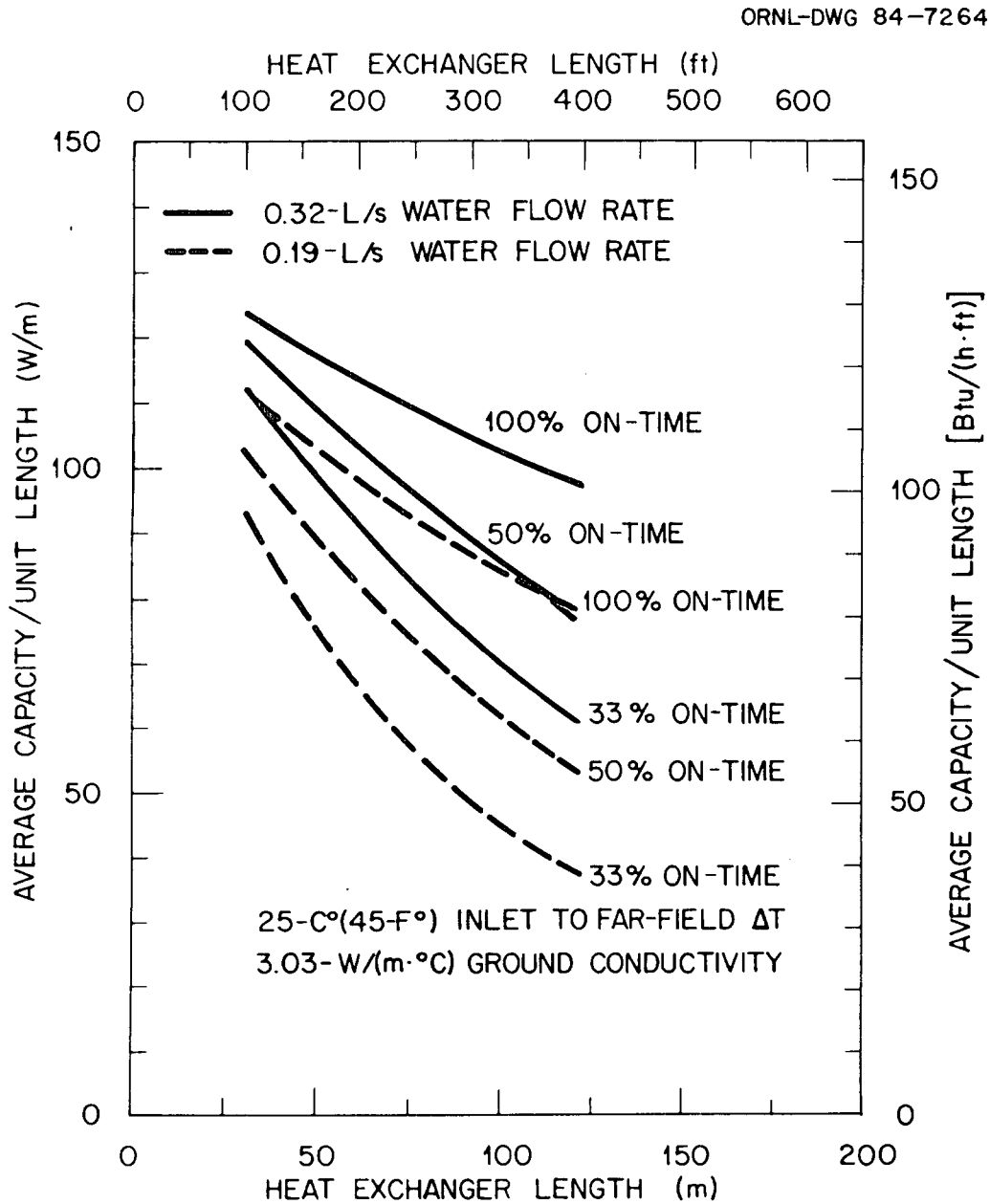

Fig. 13. Effect of well depth on heat exchanger performance.

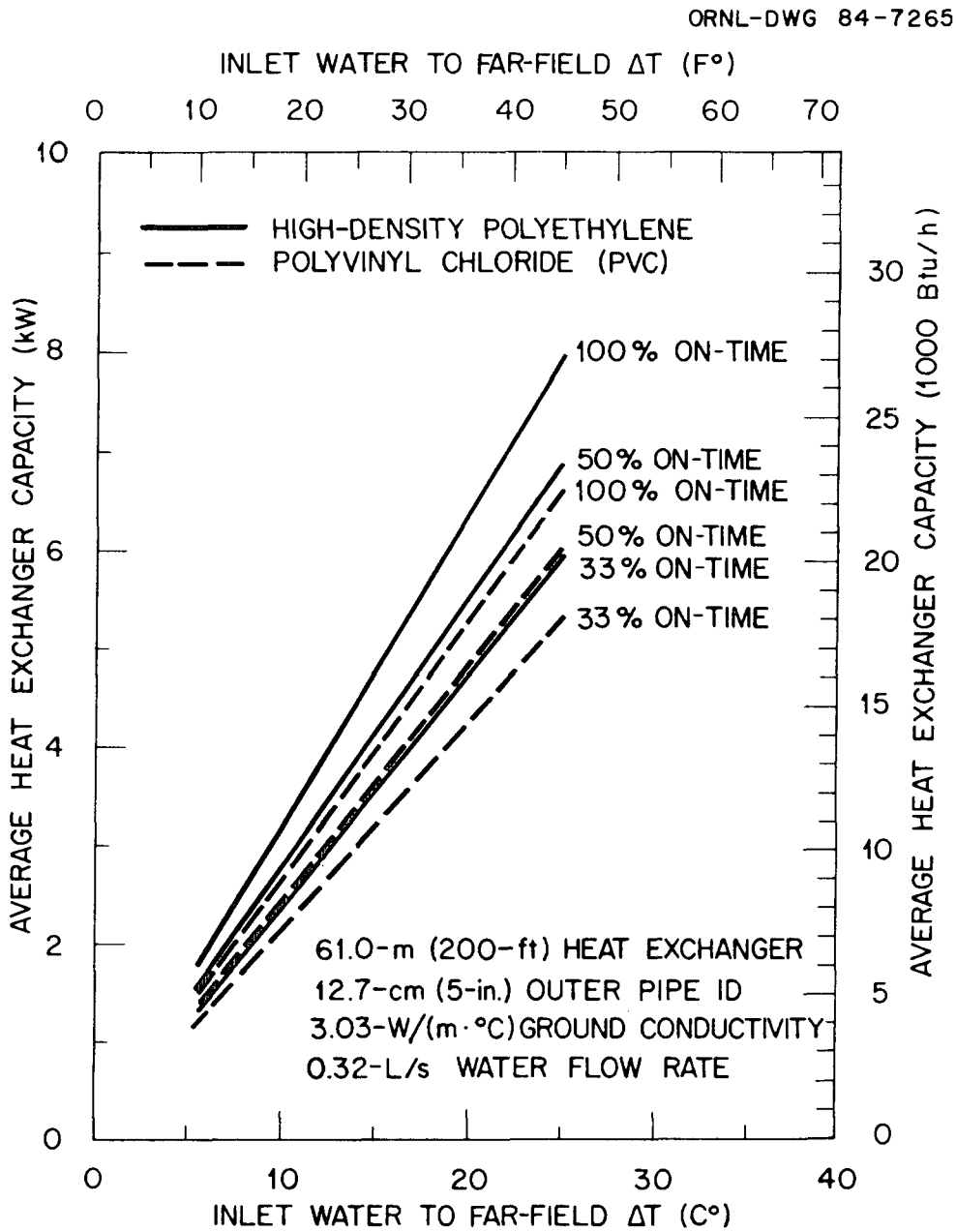

Fig. 14. Effect of temperature differential between inlet water and far field on heat exchanger performance.

7. DISCUSSION AND CONCLUSION

The mathematical model for the vertical, ground-coupled heat exchanger has been validated by laboratory tests for both continuous and cyclic operation. The parametric study shows that using a material with high thermal conductivity will increase the amount of energy exchange between the heat exchanger and the ground, but the improvement becomes negligible when the casing's thermal conductivity is close to or higher than that of the ground. In other words, it would not be cost-effective to use metal casing for its high thermal conductivity value.

The parametric study also shows several possible ways of designing a heat exchanger with higher capacity:

1. increase the flow rate of the working fluid,
2. increase the diameter of the outer casing, or
3. increase the length of the heat exchanger.

There are other factors that need to be taken into account, however, when making any one of these changes independently.

Increasing the flow rate will increase the amount of heat transfer because of the increase in convective heat transfer coefficients between the water and the wall of the casing. However, the overall rate of heat rejection does not necessarily increase in proportion to the flow rate. The effect of changing the flow rates is greater for long heat exchangers than it is for short ones and is also more significant during cyclic operation than it is for continuous operation. This result has not been fully explained. A 67% increase in flow rate from 0.19 L/s (3 gpm) to 0.32 L/s (5 gpm) increases the heat transfer coefficient between the water in the annulus and the outer casing by 15–24%. The increase in capacity, however, can range from 6% for a 30-m (100-ft) heat exchanger running continuously to 56% for a 122-m (400-ft) heat exchanger cycling with a 33% on-time. Heat exchanger operation appears to be limited under some circumstances by the thermal conductivity of both the outer casing and the ground. The ground can absorb or give up only so much heat regardless of how great the flow rate of water is through the heat exchanger. This limit is reached during continuous operation, even at low flow rates, and there is nothing to be gained by a higher flow rate. Cyclic operation permits some time for the ground to recover between periods of heat exchanger operation, and, consequently, the limit is higher. This amount of heat may not be able to be absorbed or rejected at the lower flow rates, and the flow rate can be the limiting feature instead of the ground's thermal conductivity. Further study is needed to understand this interaction better.

The length of the heat exchanger affects its capacity, and the effective length of a heat exchanger can be increased by making a longer single tube or by putting several heat

exchangers together either in series or in parallel. The decreasing heat transfer rate per unit length of heat exchanger, as shown in Fig. 13, would suggest that several shorter heat exchangers would be better than a single long one. Unfortunately, this conclusion assumes that each of the multiple heat exchangers has the same flow rate and entering water temperature as the single long one. Further analysis shows that the advantage of multiple heat exchangers over a single longer one is very small when these factors are taken into account.

Figures 13 and 14 can be used to compare two 61-m (200-ft) PVC heat exchangers with a single 122-m (400-ft) one. This comparison assumes continuous operation with a flow rate of 0.32 L/s (5 gpm), inlet water temperature of 42°C (107°F), and 25°C (45°F) inlet water to far-field ΔT. If the two heat exchangers are connected in series, the first one will have a capacity of 6.59 kW (22,500 Btu/h), and the exit water temperature can be computed to be 37°C (98°F). This gives a 20°C (36°F) inlet water to far-field ΔT for the second heat exchanger, which would then have a capacity of 5.57 kW (19,000 Btu/h). The combined capacity is 11.86 kW (40,500 Btu/h) compared with 11.72 kW (40,000 Btu/h) for a single 122-m (400-ft) heat exchanger under comparable conditions.

If the heat exchangers are connected in parallel, the flow rate into each would have to be one-half that of the single longer heat exchanger so that the two cases could be compared. Extrapolation from the two curves in Fig. 13 gives a capacity of 5.71 kW (19,500 Btu/h) for each of two 61-m (200-ft) heat exchangers at 0.16 L/s (2.5 gpm) for a combined capacity of 11.43 kW (39,000 Btu/h). This is actually less than the capacity of the 122-m (400-ft) heat exchanger, although that may be because of the uncertainty resulting from the extrapolation. Consequently, it appears that if multiple heat exchangers offer an advantage over a single long one, the advantage is at best marginal.

There are five areas in which the computer model needs to be refined:

1. During the start of the on cycle, the reestablishment of velocity and temperature profiles at every location along the annulus region causes the local convective heat transfer coefficients to be transients, while we only input a fixed h value (varies along the vertical axis) at each location. This transient behavior of h values has to be understood before we can model cyclic operation more accurately. However, the present way of calculation, without including transient h values, makes the results conservative.

2. During the off cycle period, the temperature differential between the water in the inner tube and annulus region might cause natural convective heat transfer. The maximum Ra in the test was estimated to be around 1.8×10^6 without considering the effect of the ground. Based on ref. 11, it would have a natural convective heat transfer coefficient around 22 $W/(m^2 \cdot K)$ [3.9 $Btu/(h \cdot ft^2 \cdot °F)$]. This explains why assuming the inner wall temperature of the outer casing is equal to the water temperature in the annulus provides a better match to the measured water temperature in the annulus. However, since Ra is not a constant and decreases as the temperature differential decreases, the effect of natural heat convection cannot be estimated accurately without measuring both wall temperatures in the annulus region as fractions of time. The effect of natural convection during the off cycle period should be added to the code.

3. Convective heat transfer when the flow is in the transitional region cannot be modeled as the program is written, and a correlation for this region is needed.

4. Heat transfer in unsaturated soil near the surface (where moisture migration and the influence of the ambient air temperature affect performance) cannot be modeled accurately. This effect needs to be accounted for.

5. The time step of the computer code is very small. It could be costly for long periods of simulation.

The idea of using tube-in-tube type ground-coupled heat exchangers is not a new one.[1] However, it is only recently that this idea has been put into practical application.[2-4] The design of this type of heat exchanger, up to now, is still mainly dependent on field experience, which might serve well in one locality but could become highly uncertain in applying the experience to other places.

This report, based on heat transfer theories, is believed to be the first detailed theoretical analysis of the operation of this type of ground-coupled heat exchangers. While there is room for improvement, this model, nevertheless, represents a new approach from the old design methods. It will provide better understanding of the ground reaction as well as the limit of such systems under a set of design conditions. Most important, this model is easy to understand so that it can benefit anyone who is interested in designing this type of system.

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Appendix A

COMPUTER CODE LISTING

```
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            C-----------------------------------------------------------------------C
            C                                                                       C
            C     TRANS.NEW_6137,172'                                               C
            C             SOURCE PROGRAM FOR VERTICAL GROUND-COUPLED HEAT EXCHANGER C
            C             MODIFIED 10/1/82                                          C
            C                     COMPUTATION OF HEAT TRANSFER COEFFICIENT IN THE   C
            C                     ANNULAR REGION ADDED                              C
            C                                                                       C
            C                     STORING OF DATA FOR PROCESSING INTO PLOTS USING   C
            C                     "PLOT.NEW" ADDED                                  C
            C             MODIFIED 7/13/82                                          C
            C                     CYCLING CAPABILITIES ENHANCED                     C
            C             MODIFIED 7/22/81                                          C
            C                     LOOPS ADDED TO INCLUDE COMPUTATIONS FOR OUTER PIPE C
            C                                                                       C
            C-----------------------------------------------------------------------C
ISN 0003          DOUBLE PRECISION MU1,MU2,MU3
ISN 0004          LOGICAL OLDATA,STOP
ISN 0005          INTEGER DAYS,HOURS,MINUTE,SECOND
            C
ISN 0006          DIMENSION CON2(30),CHI2(30),CHI3(30),E1(30),E3(30),E4(30)
ISN 0007          DIMENSION TITLE(20),VOL(30),H2(30),H3(30),ZETA1(30),ZETA3(30)
ISN 0008          DIMENSION PSY1(5),PSY2(5),P(5,30,2)
ISN 0009          DIMENSION C1R(5),C2R(5),C3R(30),C4R(30)
ISN 0010          DIMENSION SOIL(30),DEPTH(30),SHALF(9),WEIGHT(9,2),
                &           DRSOIL(9),OMEGA3(30),OMEGA4(30),HFLX(30),TMPDIF(30)
ISN 0011          DIMENSION U(30,2),V(30,2),T(10,30,2),S(10,30,2),TINFIN(30)
            C
            C
ISN 0012          NAMELIST /INPUT/ TIMMAX, TIMPRT, DTIME,  RHOF,   CPF,    RK1,
                &                  RHO1,   CP1,    H1,     RK2,    RHO2,   CP2,H2,
                &                  H2,     RK3,    RHO3,   CP3,    H3,     R1,
                &                  R2,     R3,     R4,     ZMAX,   TINFIN, GPM,
                &                  DRSOIL, NZ,     NPIPE,  NPIPE2, NSOIL,  OLDATA,
                &                  TH2U,   CPH,    PCTON,  PLTSP2
            C
            C     CPF = SPECIFIC HEAT OF FLUID
            C     CP1 = SPECIFIC HEAT OF INNER TUBE
            C     CP2 = SPECIFIC HEAT OF OUTER TUBE
            C     CP3 = SPECIFIC HEAT OF GROUND
            C     CPH = HEAT PUMP OPERATING CYCLES PER HOUR
            C     DRSOIL = SOIL RADIAL DISTANCE BETWEEN NODAL POINTS
            C     DTIME = TIME STEP OF CODE CALCULATION
            C     GPM = FLUID FLOW RATE
            C     H1 = CONVECTIVE HEAT TRANSFER COEFFICIENT BETWEEN INNER TUBE
            C          INNER WALL AND FLUID
            C     H2 = CONVECTIVE HEAT TRANSFER COEFFICIENT BETWEEN INNER TUBE
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C            OUTER WALL AND FLUID
C       H3 = CONVECTIVE HEAT TRANSFER COEFFICIENT BETWEEN OUTER TUBE
C            INNER WALL AND FLUID
C       NPIPE = NUMBER OF NODAL POINT OF INNER TUBE WALL
C       NPIPE2 = NUMBER OF NODAL POINT OF OUTER TUBE WALL
C       NSOIL = NUMBER OF NODAL POINT OF GROUND
C       NZ = NUMBER OF NODAL POINT IN VERTICAL DIRECTION, GROUND
C            SURFACE IS NOT CONDERED AS A NODAL POINT
C       PCTON = HEAT PUMP ON TIME PER CYCLE
C       R1 = INSIDE RADIUS OF INNER TUBE
C       R2 = OUTSIDE RADIUS OF INNER TUBE
C       R3 = INSIDE RADIUS OF OUTER TUBE
C       R4 = OUTSIDE RADIUS OF OUTER TUBE
C       RHOF = DENSITY OF FLUID
C       RHO1 = DENSITY OF INNER TUBE
C       RHO2 = DENSITY OF OUTER TUBE
C       RHO3 = DENSITY OF GROUND
C       RK1 = THERMAL CONDUCTIVITY OF INNER TUBE
C       RK2 = THERMAL CONDUCTIVITY OF OUTER TUBE
C       RK3 = THERMAL CONDUCTIVITY OF GROUND
C       TH2O = FLUID INLET TEMPERATURE
C       TIMMAX = MAXIMUM COMPUTER CODE RUN TIME, IN HOUR
C       TIMPRT = TIME INTERVAL FOR DATA PRINT OUT, IN HOUR
C       TINFIN = INITIAL GROUND VERTICAL TEMPERATURE DISTRIBUTION
C       ZMAX = TOTAL WELL DEPTH
C
ISN 0013      DATA PLTSP2 / 180.0 /, TMPLT2 / 0. /
ISN 0014      DATA HFLX / 30*0.0D+00 /, TMPDIF / 30*0.0D+00 /
C
ISN 0015      DATA IOUT / 6 /, OLDATA / .FALSE. /, STOP / .FALSE. /
ISN 0016      DATA PI / 3.141592654D+00 /
ISN 0017      DATA TIMMAX, TIMPRT / 24.0D+00, 1.0D+00 /
ISN 0018      DATA GPM / 10.0D+00 /
ISN 0019      DATA TH2O / 40.0D0 /
C
ISN 0020      DATA     RHOF,CPF     / 62.4D+00, 1.0D+00 /
ISN 0021      DATA RK1,RHO1,CP1,H1 / 0.084D+00,27.0D+00,0.24D+00,615.0D+00 /
ISN 0022      DATA RK2,RHO2,CP2 / 0.084D+00,27.0D+00,0.24D+00 /
ISN 0023      DATA H2/30*37.5D0/
ISN 0024      DATA RK3,RHO3,CP3/ 1.880D+00,130.0D+00,0.23D+00 /
ISN 0025      DATA H3/30*37.5D0/
C
ISN 0026      DATA R1,R2,R3,R4 / 5.3D-01,6.56D-01,1.5D+00,1.75D+00 /
ISN 0027      DATA DRSOIL / 1.0, 3.0, 8.0, 12.0, 24.0, 48.0, 3*0.0 /
ISN 0028      DATA DTIME / 2.5D-03 /
ISN 0029      DATA ZMAX / 200.0D+00 /
ISN 0030      DATA TINFIN / 30*62.0D+00 /
ISN 0031      DATA NZ / 20 /, NPIPE / 5 /, NSOIL / 7 /, NPIPE2 / 5 /
```

```
C
C-----------------------------------------------------------------------C
C                                                                       C
C                                                                       C
C      H2O       PIPE        H2O        PIPE                SOIL       C
C   ---------------------------------------------------------------   C
C   I        I          I          I            I                   I   C
C   I        I          I          I            I                   I   C
C   I  U(J)  I T(I,J)   I   V(J)   I   P(I,J)   I         S(I,J)    I   C
C   I        I          I          I            I                   I   C
C   I   X    X     X    X     X    X      X     X   X    X     X    X   C
C   I        I          I          I            I                   I   C
C   I        I          I          I            I                   I   C
C   ---------------------------------------------------------------   C
C                                                                       C
C-----------------------------------------------------------------------C
C
ISN 0032          READ(5,1) TITLE
ISN 0033    1     FORMAT(20A4)
ISN 0034          READ(5,INPUT)
ISN 0035          WRITE(IOUT,2) TITLE
ISN 0036    2     FORMAT(1H1,20A4)
C
ISN 0037          IPCTON = 100*PCTON
ISN 0038          ICPH = CPH
ISN 0039          DZ = ZMAX/NZ
ISN 0040          WRITE(7,1) TITLE
ISN 0041          WRITE(8,1) TITLE
C
ISN 0042          WRITE(7,3) NZ,ICPH,IPCTON,ZMAX,GPM
ISN 0043          WRITE(7,4) R1,R2,R3,R4,RK1,RK2,RK3
ISN 0044          WRITE(7,4) RHO1,RHO2,RHO3,RHOF,CP1,CP2,CP3,CPF
ISN 0045          WRITE(8,3) NZ,ICPH,IPCTON,ZMAX,GPM
ISN 0046          WRITE(8,4) R1,R2,R3,R4,RK1,RK2,RK3
ISN 0047          WRITE(8,4) RHO1,RHO2,RHO3,RHOF,CP1,CP2,CP3,CPF
ISN 0048    3     FORMAT(3I10,F10.0,F10.2)
ISN 0049    4     FORMAT(8F10.4)
C
ISN 0050          NSOIL1 = NSOIL - 1
ISN 0051          NRM1 = NPIPE - 1
ISN 0052          NRM12 = NPIPE2 - 1
ISN 0053          NZM1 = NZ - 1
C
C         INITIALIZE STARTING CONDITIONS
C
ISN 0054          TIME = 0.
ISN 0055          BTUOUT = 0.
ISN 0056          BTUIN = 0.0
ISN 0057          HFLUX = 0.0
ISN 0058          DO 40 K=1,2
ISN 0059          DO 30 J=1,NZ
ISN 0060          DO 10 I=1,NPIPE
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ISN 0061              T(I,J,K) = TINFIN(J)
ISN 0062         10   CONTINUE
ISN 0063              DO 15 I=1,NPIPE2
ISN 0064              P(I,J,K) = TINFIN(J)
ISN 0065         15   CONTINUE
ISN 0066              DO 20 I=1,NSOIL
ISN 0067              S(I,J,K) = TINFIN(J)
ISN 0068         20   CONTINUE
ISN 0069              U(J,K) = TINFIN(J)
ISN 0070      30      V(J,K) = TINFIN(J)
ISN 0071         40   CONTINUE
              C
              C       READ PREVIOUS RESULTS (IF ANY)
              C
ISN 0072              IF (OLDATA) READ(19,2001,END=41) TIME,BTUOUT,BTUIN,HFLUX,
                 &                                     T,S,U,V,P
ISN 0074      41      CONTINUE
              C
              C       CALCULATE DRPIPE FROM NPIPE
              C
ISN 0075              DRPIPE = (R2 - R1)/(NPIPE - 1.)
ISN 0076              DRPIP2 = (R4-R3)/(NPIPE2-1.)
ISN 0077              DZ = 12.0*ZMAX/NZ
              C
              C       SET VELOCITIES IN THE INNER AND OUTER PIPES
              C
ISN 0078              VINNER = 1728.0*(GPM * 0.1337)/(PI*R1*R1)
ISN 0079              VOUTER = 1728.0*(GPM * 0.1337)/(PI*(R3*R3 - R2*R2))
              C
ISN 0080              SOIL(1) = 0.0
ISN 0081              DO 50 ISOIL=2,NSOIL
ISN 0082      50      SOIL(ISOIL) = SOIL(ISOIL-1) + DRSOIL(ISOIL-1)/12.0D+00
ISN 0083              R5 = SOIL(NSOIL)
              C
ISN 0084              ZERO = 0.0
ISN 0085              DO 60 IZ=1,NZ
ISN 0086      60      DEPTH(IZ) = (IZ-0.)*DZ/12.
              C
              C       PRINT DATA FOR THIS RUN
              C
ISN 0087              WRITE(IOUT,1001) R1,R2,R3,R4,R5,ZMAX
ISN 0088      1001    FORMAT('OGEOMETRIC DATA:',/,
                 &       5X,' R1      - INTERNAL RADIUS OF INNER PIPE      ',F7.3,
                 &                                                  ' INCHES',/,
                 &       5X,' R2      - EXTERNAL RADIUS OF INNER PIPE      ',F7.3,
                 &                                                  ' INCHES',/,
                 &       5X,' R3      - INTERNAL RADIUS OF OUTER PIPE      ',F7.3,
                 &                                                  ' INCHES',/,
                 &       5X,' R4      - EXTERNAL RADIUS OF OUTER PIPE      ',F7.3,
                 &                                                  ' INCHES',/,
                 &       5X,' R5      - DISTANCE FROM PIPE TO UNDISTURBED ',/,
                 &       5X,'           SOIL                               ',F7.3,
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                &                                                    ' FEET',/,
                &     5X,' ZMAX   - DEPTH OF WELL                     ',F7.1,
                &                                                  ' FEET')
ISN 0089           R5 = R4 + 12.00+00*R5
          C
ISN 0090           WRITE(IOUT,1002) NPIPE,DRPIPE,NPIPE2,DRPIP2,NSOIL,DRSOIL,NZ,DZ
ISN 0091     1002  FORMAT('OGEOMETRIC GRID:',/,
                &     5X,' NPIPE  - NUMBER OF MESH POINTS IN PIPE      ',I7,/,
                &     5X,' DRPIPE - RADIAL SPACING OF POINTS IN INNER',/,
                &     5X,'          PIPE                               ',F7.3,
                &                                                  ' INCHES',/,
                &     5X,' NPIPE2 - NUMBER OF MESH POINTS IN OUTER PIPE ',I5,/,
                &     5X,' DRPIP2 - RADIAL SPACING OF POINTS IN OUTER',/,
                &     5X,'          PIPE                               ',F7.3,
                &                                              ' INCHES ',/,
                &     5X,' NSOIL  - NUMBER OF MESH POINTS IN SOIL      ',I7,/,
                &     5X,' DRSOIL - RADIAL SPACING OF POINTS IN SOIL   ',9F8.3,
                &                                                  ' INCHES',/,
                &     5X,' NZ     - NUMBER OF VERTICAL MESH POINTS     ',I7,/,
                &     5X,' DZ     - VERTICAL SPACING OF POINTS         ',F7.2,
                &                                                  ' INCHES')
          C
ISN 0092           WRITE(IOUT,1003) TIMMAX,TIMPRT,DTIME
ISN 0093     1003  FORMAT('OTIME 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')
          C
ISN 0094           V1FT = VINNER/12.
ISN 0095           V2FT = VOUTER/12.
ISN 0096           WRITE(IOUT,1004) GPM,V1FT,V2FT
ISN 0097     1004  FORMAT('OPUMPING DATA:',/,
                &     5X,' GPM    - PUMPING RATE                       ',F7.3,
                &                                          ' GALLONS/MINUTE',/,
                &     5X,' VINNER - VELOCITY IN INNER PIPE             ',F7.2,
                &                                          ' FEET/MINUTE',/,
                &     5X,' VOUTER - VELOCITY IN OUTER PIPE             ',F7.2,
                &                                          ' FEET/MINUTE')
          C
ISN 0098           WRITE(IOUT,1005) (TINFIN(J),J=1,NZ)
ISN 0099     1005  FORMAT('OTEMPERATURE DATA:',/,
                &     5X,' TINFIN - AMBIENT SOIL TEMPERATURE           ',10F7.3,
                &                                                  ' F')
          C
          C        CALCULATE ALPHA'S
          C
ISN 0100           ALPHA1 = RK1/(RHO1*CP1)
ISN 0101           ALPHA2 = RK2/(RHO2*CP2)
ISN 0102           ALPHA3 = RK3/(RHO3*CP3)
```

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C
ISN 0103          WRITE(IOUT,1006)
ISN 0104    1006  FORMAT('0MATERIAL PROPERTIES:')
ISN 0105          WRITE(IOUT,1007)
ISN 0106    1007  FORMAT('0INNER PIPE:')
ISN 0107          WRITE(IOUT,1008) RK1,RHO1,CP1,ALPHA1,H1
ISN 0108    1008  FORMAT(
                & 5X,' CONDUCTIVITY                          ',F7.3,
                &                                 ' BTU/HR-FT-F',/,
                & 5X,' DENSITY                               ',F7.3,
                &                                 ' LBM/FT3',/,
                & 5X,' SPECIFIC HEAT                         ',F7.3,
                &                                 ' BTU/LBM-F',/,
                & 5X,' ALPHA                                 ',F7.5,
                &                                 ' FT2/HR',/,
                & 5X,' HEAT TRANSFER RATE                    ',10F7.3,
                &                                 'BTU/HR-FT2-F')
C
ISN 0109          WRITE(IOUT,1009)
ISN 0110    1009  FORMAT('0OUTER PIPE:')
ISN 0111          WRITE(IOUT,1008) RK2,RHO2,CP2,ALPHA2,(H2(J),J=1,NZ)
ISN 0112          WRITE(IOUT,1010)
ISN 0113    1010  FORMAT('0SOIL:')
ISN 0114          WRITE(IOUT,1008) RK3,RHO3,CP3,ALPHA3,(H3(J),J=1,NZ)
C
ISN 0115          WRITE(IOUT,1011) RHOF,CPF
ISN 0116    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
ISN 0117          TIMMAX = 60.0*TIMMAX + TIME
ISN 0118          NPRINT = (60.0D0*TIMPRT + DTIME/2.0D0)/DTIME
ISN 0119          ZMAX = 12.0D+00*ZMAX
ISN 0120          RK1 = RK1/(60.*12.)
ISN 0121          RK2 = RK2/(60.*12.)
ISN 0122          RK3 = RK3/(60.*12.)
C
ISN 0123          H1 = H1/(60.*144.)
ISN 0124          DO 63 J=1,NZ
ISN 0125          H2(J)=H2(J)/(60.*144.)
ISN 0126          H3(J)=H2(J)
ISN 0127    63    CONTINUE
ISN 0128          CALL HXF(V2FT,RHOF,TH2O,R2,R3,ZMAX,H2,H3,NZ)
C
ISN 0129          RHOF = RHOF/1728.
ISN 0130          RHO1 = RHO1/1728.
ISN 0131          RHO2 = RHO2/1728.
ISN 0132          RHO3 = RHO3/1728.
```

```
              C
ISN 0133              ALPHA1 = RK1/(RHO1*CP1)
ISN 0134              ALPHA2 = RK2/(RHO2*CP2)
ISN 0135              ALPHA3 = RK3/(RHO3*CP3)
              C
              C       SET CONSTANTS USED IN THE CALCULATIONS
              C
ISN 0136              DTDZ = DTIME/DZ
ISN 0137              CON1 = 2.0*H1*DTIME/(R1*RHOF*CPF)
ISN 0138              DO 64 J=1,NZ
ISN 0139              CON2(J)=2.0*(R2*H2(J)+R3*H3(J))*DTIME/(RHOF*CPF*(R3*R3-R2*R2))
ISN 0140      64      CONTINUE
ISN 0141              CON3 = 60.0*DTIME*PI*(R3*R3 - R2*R2)*RHOF*CPF
ISN 0142              CONIN = 2.0D+00 * PI * R5 * RK3 * DTIME / DRSOIL(NSOIL1)
              C
ISN 0143              BETA3 = 2.0*H1*DTIME/(RHOF*CPF*R1)
              C
ISN 0144              A1DTDR = ALPHA1 * DTIME / DRPIPE
ISN 0145              GAMMA1 = 1.0 - A1DTDR*(2.0D+00/DRPIPE + 1.0D+00/R1 +
                 &                          2.0D+00*H1/RK1)
ISN 0146              GAMMA2 = A1DTDR*(2.0D+00/DRPIPE + 1.0D+00/R1)
ISN 0147              GAMMA3 = 2.0D+00*A1DTDR*H1/RK1
              C
ISN 0148              DELTA1 = ALPHA1*DTIME/DRPIPE
ISN 0149              DELTA3 = ALPHA1*DTIME/(DRPIPE*DRPIPE)
ISN 0150              DO 70 I=1,NPIPE
ISN 0151              R = R1 + (I-1.0D+00)*DRPIPE
ISN 0152              C1R(I) = DELTA1*(1.0D+00/DRPIPE + 1.0D+00/R)
ISN 0153              C2R(I) = 1.0D+00 - DELTA1*(2.0D+00/DRPIPE + 1.0D+00/R)
ISN 0154      70      CONTINUE
              C
ISN 0155              PSY3 = ALPHA2*DTIME/(DRPIP2*DRPIP2)
ISN 0156              DO 75 I=1,NPIPE2
ISN 0157              R = R3 + (I-1.0D+00)*DRPIP2
ISN 0158              PSY1(I) = ALPHA2*DTIME*(1.0D+00/DRPIP2 + 1.0D+00/R)/DRPIP2
ISN 0159      75      PSY2(I) = 1.0D+00 - PSY1(I) - PSY3
              C
ISN 0160              MU1 = 2.0D+00*(RK3/RK2)*(ALPHA2*DTIME/DRPIP2)/DRSOIL(1)
ISN 0161              MU3 = (ALPHA2*DTIME/DRPIP2)*(2.0D+00/DRPIP2 - 1.0D+00/R4)
ISN 0162              MU2 = 1.0D+00 - MU1 - MU3
              C
ISN 0163              CHI1 = (ALPHA2*DTIME/DRPIP2)*(2.0D+00/DRPIP2 + 1.0D+00/R3)
ISN 0164              DO 77 J=1,NZ
ISN 0165              CHI3(J) = (ALPHA2*DTIME/RK2)*H3(J)*2/DRPIP2
ISN 0166              CHI2(J) = 1.0D+00 - CHI1 - CHI3(J)
ISN 0167              E3(J) = 2.0*DTIME*R2*H2(J)/(RHOF*CPF*(R3*R3-R2*R2))
ISN 0168              E4(J) = 2.0*DTIME*R3*H3(J)/(RHOF*CPF*(R3*R3-R2*R2))
ISN 0169      77      CONTINUE
              C
ISN 0170              A3DTDR = ALPHA3 * DTIME / DRSOIL(1)
```

```
C
      R = R4
      DO 80 I=2,NSOIL1
      R = R + DRSOIL(I-1)
      DRAVG = (DRSOIL(I) + DRSOIL(I-1))/2.0D+00
      OMEGA3(I) = ALPHA3 * DTIME / DRSOIL(I)
      OMEGA4(I) = ALPHA3 * DTIME / (DRSOIL(I-1)*DRAVG)
      C3R(I) = OMEGA3(I) * (1.0D+00/DRAVG + 1.0D+00/R)
      C4R(I) = 1.0D+00 - OMEGA3(I) * (2.0D+00/DRSOIL(I-1) + 1.0D+00/R)
80    CONTINUE
C
      VOL1 = PI * R1 * R1 * DZ
      VOL2 = PI * (R3*R3 - R2*R2) * DZ
      RINNER = R4
      DO 90 I=1,NSOIL1
      ROUTER = RINNER + DRSOIL(I)
      VOL(I) = PI * (ROUTER*ROUTER - RINNER*RINNER) * DZ
      RHALF = DSQRT((ROUTER*ROUTER + RINNER*RINNER)/2.0D+00)
      WEIGHT(I,1) = (ROUTER - RHALF)/DRSOIL(I)
      WEIGHT(I,2) = (RHALF - RINNER)/DRSOIL(I)
      RINNER = ROUTER
90    CONTINUE
C
      ZETA2 = A1DTDR*(2.0D+00/DRPIPE - 1.0D+00/R2)
      DO 91 J=1,NZ
      ZETA1(J) = 1.0 - A1DTDR*(2.0D+00/DRPIPE - 1.0D+00/R2 +
     &                         2.0D+00*H2(J)/RK1)
      ZETA3(J) = A1DTDR*2.0D+00*H2(J)/RK1
91    CONTINUE
C
C     THE FOLLOWING CONSTANTS ARE USED WHEN FLUID VELOCITY IS ZERO
C
      BETA10=2.0D0*RK1/(RHOF*CPF*R1)*DTIME/DRPIPE
      GAMM10=(2.0D0*R1+DRPIPE)*ALPHA1*DTIME/(DRPIPE*DRPIPE*R1)
      GAMM20=ALPHA1*R1*RHOF*CPF/DRPIPE
      E10=2.0D0*R3*RK2*DTIME/(RHOF*CPF*(R3*R3-R2*R2)*DRPIP2)
      E20=2.0D0*R2*RK1*DTIME/(RHOF*CPF*(R3*R3-R2*R2)*DRPIPE)
C
      ITIME = 0
      WRITE(IOUT,2) TITLE
C
      HOURS = (TIME + 0.5/60.0)/60.
      DAYS = HOURS/24
      HOURS = HOURS - 24*DAYS
      MINUTE = TIME - 60*(HOURS + 24.0D+00*DAYS)
      SECOND = 60.*(TIME - 60*(HOURS + 24.0D+00*DAYS) - MINUTE)
C
      TEXIT = 2.0*V(1,1) - V(2,1)
      CALL VELOC(TIME,VINNER,VOUTER,V1,V2,BTUOUT,CPH,PCTON)
C
      CAPACT = 0.
      WRITE(IOUT,998) DAYS,HOURS,MINUTE,SECOND,CAPACT,
     &                (SOIL(ISOIL),ISOIL=2,NSOIL)
      WRITE(IOUT,999) ZERO,TH20,TEXIT
```

```
ISN 0213              DO 99 J=1,NZ
ISN 0214              DO 98 I=1,NSOIL1
ISN 0215      98      SHALF(I) = S(I+1,J,1)*WEIGHT(I,2) + S(I,J,1)*WEIGHT(I,1)
ISN 0216      99      WRITE(IOUT,1901) DEPTH(J),U(J,1),T(1,J,1),T(NPIPE,J,1),V(J,1),
                 &                P(1,J,1),S(1,J,1),(SHALF(I),S(I+1,J,1),I=1,NSOIL1)
ISN 0217              WRITE(IOUT,1902)
              C
              C       INITIALIZE TIMING PARAMETERS FOR SAVING DATA FOR PLOTS
              C
ISN 0218              TIMPLT=TIME
ISN 0219              QPLT=0.
ISN 0220              PLTSTP=1.
ISN 0221              TIMPLT=PLTSTP
ISN 0222              TMPLT2=PLTSP2
ISN 0223              PLTTIM=TIME
              C
ISN 0224              WRITE(7,3001) TIME,QPLT,TH2O,TEXIT,V(NZ,INOW),TINFIN(NZ)
ISN 0225              WRITE(8,3002) TIME,(V(J,INOW),J=1,NZ)
ISN 0226              WRITE(8,3003) (HFLX(J),J=1,NZ)
ISN 0227      3001    FORMAT(2F10.1,4F10.3)
ISN 0228      3002    FORMAT(F7.1,10F7.2,/,(7X,10F7.2,/))
ISN 0229      3003    FORMAT(7X,10F7.2)
              C
              C       COMPUTE OFF TIME IN MINUTES
              C
ISN 0230              OFFTIM=60.*(1.-PCTON)/CPH
              C
              C       BEGIN THE TRANSIENT CALCULATIONS
              C
ISN 0231      100     INOW = MOD(ITIME,2)+1
ISN 0232              ITHEN = MOD(ITIME+1,2)+1
ISN 0233              ITIME=ITIME+1
ISN 0234              TIME = TIME + DTIME
              C
ISN 0235              IF (TIME .GE. TIMMAX) STOP=.TRUE.
ISN 0237              CALL VELOC(TIME,VINNER,VOUTER,V1,V2,BTUOUT,CPH,PCTON)
ISN 0238              IF(V1 .LT. 1.0D-5 .AND. OFFTIM .GT. 30.) GO TO 200
              C
              C
              C
ISN 0240              BETA1 = 1.0 - V1*DTDZ - CON1
ISN 0241              BETA2 = V1*DTDZ
ISN 0242              DO 102 J=1,NZ
ISN 0243              E1(J) = 1.0 - V2*DTDZ - CON2(J)
ISN 0244      102     CONTINUE
ISN 0245              E2 = V2*DTDZ
              C
              C
              C       CALCULATE THE WATER TEMPERATURE INSIDE THE INNER PIPE
              C
ISN 0246              U(1,ITHEN) = BETA1*U(1,INOW) + BETA2*TH2O + BETA3*T(1,1,INOW)
ISN 0247              DO 110 J=2,NZ
ISN 0248              U(J,ITHEN) = BETA1*U(J,INOW) + BETA2*U(J-1,INOW) +
                 &                BETA3*T(1,J,INOW)
```

```
ISN 0249              IF (U(J,ITHEN) .LE. 32.0D+00) STOP=.TRUE.
ISN 0251      110     CONTINUE
              C
              C
              C       CALCULATE THE TEMPERATURE IN THE INNER PIPE
              C
ISN 0252              DO 130 J=1,NZ
ISN 0253              T(1,J,ITHEN) = GAMMA1*T(1,J,INOW) + GAMMA2*T(2,J,INOW) +
                 &                   GAMMA3*U(J,INOW)
ISN 0254              IF (NRM1 .LT. 2) GO TO 130
ISN 0256              DO 120 I=2,NRM1
ISN 0257              T(I,J,ITHEN) = C1R(I)*T(I+1,J,INOW) + C2R(I)*T(I,J,INOW) +
                 &                     DELTA3*T(I-1,J,INOW)
ISN 0258      120     CONTINUE
ISN 0259      130     T(NPIPE,J,ITHEN) = ZETA1(J)*T(NPIPE,J,INOW) +
                 &                     ZETA2*T(NPIPE-1,J,INOW) + ZETA3(J)*V(J,INOW)
              C
              C
              C       CALCULATE THE WATER TEMPERATURE BETWEEN THE TWO PIPES
              C
ISN 0260              DO 140 J=1,NZM1
ISN 0261              V(J,ITHEN) =E1(J)*V(J,INOW)+E2*V(J+1,INOW)+E3(J)*T(NPIPE,J,INOW)
                 &              + E4(J)*P(1,J,INOW)
ISN 0262              IF (V(J,ITHEN) .LE. 32.0D0) STOP = .TRUE.
ISN 0264      140     CONTINUE
ISN 0265              V(NZ,ITHEN) = E1(NZ)*V(NZ,INOW)+ E2*U(NZ,INOW) +
                 &  E3(NZ)*T(NPIPE,NZ,INOW) + E4(NZ)*P(1,NZ,INOW)
ISN 0266              IF (V(NZ,ITHEN) .LE. 32.0D0) STOP=.TRUE.
              C
              C       CALCULATE TEMPERATURES IN THE OUTER PIPE
              C
ISN 0268              DO 160 J=1,NZ
ISN 0269      160     P(1,J,ITHEN) = CHI1*P(2,J,INOW) + CHI2(J)*P(1,J,INOW) +
                 &                   CHI3(J)*V(J,INOW)
ISN 0270              GO TO 162
              C
              C       THE FOLLOWING CALCULATIONS ARE FOR THE CASE WHEN THE
              C       FLUID VELOCITY IS ZERO
              C
              C       CALCULATE THE WATER TEMPERATURE INSIDE THE INNER PIPE
              C
ISN 0271      200     DO 210 J=1,NZ
ISN 0272              U(J,ITHEN) = U(J,INOW) + BETA10*(T(2,J,INOW)-T(1,J,INOW))
ISN 0273              IF (U(J,ITHEN) .LE. 32.0D+00) STOP=.TRUE.
ISN 0275      210     CONTINUE
              C
              C       CALCULATE THE WATER TEMPERATURE BETWEEN THE TWO PIPES
              C
ISN 0276              DO 240 J=1,NZ
ISN 0277              V(J,ITHEN) = V(J,INOW)+E10*(P(2,J,INOW)-P(1,J,INOW)) -
                 &                 E20*(T(NPIPE,J,INOW)-T(NRM1,J,INOW))
ISN 0278              IF (V(J,ITHEN) .LE. 32.0D0) STOP = .TRUE.
```

```
ISN 0280      240      CONTINUE
ISN 0281               IF (V(NZ,ITHEN) .LE. 32.0D0) STOP=.TRUE.
              C
              C
              C        CALCULATE THE TEMPERATURE IN THE INNER PIPE
              C
ISN 0283               DO 230 J=1,NZ
ISN 0284               T(1,J,ITHEN)=U(J,ITHEN)
ISN 0285               IF (NRM1 .LT. 2) GO TO 230
ISN 0287               DO 220 I=2,NRM1
ISN 0288               T(I,J,ITHEN) = C1R(I)*T(I+1,J,INOW) + C2R(I)*T(I,J,INOW) +
                     &                    DELTA3*T(I-1,J,INOW)
ISN 0289      220      CONTINUE
ISN 0290      230      T(NPIPE,J,ITHEN)=V(J,ITHEN)
              C
              C        CALCULATE TEMPERATURES IN THE OUTER PIPE
              C
ISN 0291               DO 260 J=1,NZ
ISN 0292               P(1,J,ITHEN) = V(J,ITHEN)
ISN 0293      260      CONTINUE
ISN 0294      162      DO 165 J=1,NZ
ISN 0295               IF (NRM12 .LT. 2) GO TO 165
ISN 0297               DO 150 I=2,NRM12
ISN 0298               P(I,J,ITHEN) = PSY1(I)*P(I+1,J,INOW) + PSY2(I)*P(I,J,INOW) +
                     &                    PSY3*P(I-1,J,INOW)
ISN 0299      150      CONTINUE
ISN 0300      165      P(NPIPE2,J,ITHEN) = MU1*S(2,J,INOW) + MU2*P(NPIPE2,J,INOW) +
                     &                     MU3*P(NRM12,J,INOW)
              C
              C
              C        CALCULATE THE SOIL TEMPERATURE
              C
ISN 0301               DO 180 J=1,NZ
              C
ISN 0302               HFLX(J)=HFLX(J)+2.0D+00*PI*R3*H3(J)*DTIME*
                     &          (P(1,J,ITHEN)-V(J,ITHEN))
ISN 0303               S(1,J,ITHEN) = P(NPIPE2,J,ITHEN)
ISN 0304               HFLUX = HFLUX + 2.0*PI*R3*H3(J)*DZ*DTIME*(P(1,J,ITHEN)
                     & -V(J,ITHEN))
ISN 0305               DO 170 I=2,NSOIL1
              C
              C        SKIP CALCULATIONS IF ALL SURROUNDING TEMPERATURES ARE UNCHANGED
              C        FROM THE AMBIENT (THERE WON'T BE ANY HEAT FLOW)
              C
ISN 0306               IF (DABS(S(I-1,J,INOW)-TINFIN(J)) .LE. 0.002) GO TO 170
ISN 0308               S(I,J,ITHEN) = C3R(I)*S(I+1,J,INOW) + C4R(I)*S(I,J,INOW) +
                     &                OMEGA4(I)*S(I-1,J,INOW)
ISN 0309      170      CONTINUE
ISN 0310               BTUIN = BTUIN + CONIN*(S(NSOIL,J,ITHEN) - S(NSOIL1,J,ITHEN))
ISN 0311      180      CONTINUE
              C
              C        THE FOLLOWING DETERMINES INLET WATER TEMPERATURE AND MAY
              C        VARY DEPENDING ON THE SYSTEM MODELED.
```

```
              C
ISN 0312              TEXIT = 2.0*V(1,ITHEN) - V(2,ITHEN)
              C
              C       TEMPORARILY REMOVE THE DEPENDENCE OF THE INLET WATER TEMPERATURE ON TIME
              C
              C       TH2O=TINLET(TIME)
              C
ISN 0313              BTUOUT = BTUOUT + V2*CON3*(TEXIT - TH2O)
ISN 0314              IF (STOP) GO TO 190
ISN 0316              IF (ITIME .LT. NPRINT) GO TO 2100
ISN 0318              ITIME = 0
              C
              C       ROUND TIME TO THE NEXT HIGHEST HOUR:MINUTE:SECOND
              C
ISN 0319      190     TIME2 = TIME + 0.5/60.
ISN 0320              HOURS = TIME2/60.
ISN 0321              DAYS = HOURS/24
ISN 0322              HOURS = HOURS - 24*DAYS
ISN 0323              MINUTE = TIME2 - 60.*(HOURS + 24.0D+00*DAYS)
ISN 0324              SECOND = 60.*(TIME2 - 60.*(HOURS + 24.0D+00*DAYS) - MINUTE)
ISN 0325              CAPACT = BTUOUT/TIME
ISN 0326              WRITE(IOUT,998) DAYS,HOURS,MINUTE,SECOND,CAPACT,
                    &                 (SOIL(ISOIL),ISOIL=2,NSOIL)
ISN 0327              WRITE(IOUT,999) ZERO,TH2O,TEXIT
ISN 0328      998     FORMAT(/,1H0,'TIME = ',I3,' DAYS ',I3,' HOURS ',I3,
                    &            ' MINUTES ',I3,' SECONDS',
                    &            5X,'(AVERAGE CAPACITY = ',F8.0,' BTU/HR)',/,
                    &  2X,'DEPTH',3X,'H2O',8X,'PIPE',7X,'H2O',7X,'PIPE',15X,'SOIL',/,
                    &  3X,'FT.',51X,5(F7.3,5X),F7.3)
ISN 0329      999     FORMAT(1X,F5.1,2X,F6.2,16X,F6.2,15X,73(1H-))
ISN 0330              BTUSOL = 0.0D+00
              C
ISN 0331              R312 = DSQRT((R3*R3 + R4*R4)/2.0D+00)
ISN 0332              W1 = (R4 - R312)/(R4 - R3)
ISN 0333              W2 = (R312 - R4)/(R4 - R3)
ISN 0334              DO 2000 J=1,NZ
              C
ISN 0335              T312 = W1*P(1,J,ITHEN) + W2*P(NPIPE2,J,ITHEN)
ISN 0336              BTUSOL = BTUSOL + RHO2*CP2*DZ*(TINFIN(J) - T312)
              C
              C       INTERPOLATE FOR PRINTING HALF-INTERVAL RESULTS AND DO A TRAPEZOIDAL
              C       CALCULATION OF HEAT EXTRACTED FROM THE SOIL.
              C
ISN 0337              FACTOR = RHO3*CP3
ISN 0338              DO 1900 I=1,NSOIL1
ISN 0339              SHALF(I) = WEIGHT(I,1)*S(I,J,ITHEN) + WEIGHT(I,2)*S(I+1,J,ITHEN)
ISN 0340              IF (J .GT. 1) GO TO 1850
ISN 0342              GRND1 = 2.0D+00*S(I,1,ITHEN) - S(I,2,ITHEN)
ISN 0343              GRND2 = 2.0D+00*S(I+1,1,ITHEN) - S(I+1,2,ITHEN)
ISN 0344              GRND = WEIGHT(I,1)*GRND1 + WEIGHT(I,2)*GRND2
ISN 0345              BTUSOL = BTUSOL + 0.5D+00*FACTOR*VOL(I)*(TINFIN(J) - GRND)
              C
ISN 0346      1850    IF (J .EQ. NZ) FACTOR = 0.5D+00*RHO3*CP3
ISN 0348              DELTAT = TINFIN(J) - SHALF(I)
```

```
ISN 0349              BTUSOL = BTUSOL + FACTOR*VOL(I)*DELTAT
ISN 0350      1900    CONTINUE
              C
ISN 0351              WRITE(IOUT,1901) DEPTH(J),U(J,ITHEN),T(1,J,ITHEN),
                 &          T(NPIPE,J,ITHEN),V(J,ITHEN),P(1,J,ITHEN),S(1,J,ITHEN),
                 &          (SHALF(I),S(I+1,J,ITHEN),I=1,NSOIL1)
ISN 0352      1901    FORMAT(1X,F5.1,2X,F6.2,' I',2F6.2,' I',F6.2,' I',2F6.2,
                 &         ' I',13F6.2)
ISN 0353      1902    FORMAT(/,1H0)
ISN 0354      2000    CONTINUE
              C
ISN 0355              BTUWIN = 0.0
ISN 0356              BTUWOU = 0.0
ISN 0357              DO 2050 J=1,NZ
ISN 0358              DELTAT = TINFIN(J) - U(J,ITHEN)
ISN 0359              BTUWIN = BTUWIN + RHOF*CPF*VOL1*DELTAT
              C
ISN 0360              DELTAT = TINFIN(J) - V(J,ITHEN)
ISN 0361              BTUWOU = BTUWOU + RHOF*CPF*VOL2*DELTAT
ISN 0362      2050    CONTINUE
              C
ISN 0363              BTUSUM = BTUIN + BTUWIN + BTUWOU + HFLUX
ISN 0364              BTUAVG = BTUSUM / (TIME/60.)
ISN 0365              PERCNT = 0.0
ISN 0366              IF (CAPACT .NE. 0.) PERCNT = ((CAPACT-BTUAVG)/CAPACT)*100.0
ISN 0368              WRITE(IOUT,2051) BTUWIN, BTUIN,
                 &                     BTUWOU, BTUSOL,
                 &                     BTUSUM, HFLUX,
                 &                     BTUAVG
ISN 0369              WRITE(IOUT,2052) PERCNT
ISN 0370      2052    FORMAT('0PERCENT ERROR IN ENERGY BALANCE = ',F7.4)
ISN 0371      2051    FORMAT(//,'0HEAT EXTRACTED FROM WATER (INNER PIPE) = ',F10.2,5X,
                 &            ' HEAT FROM ACROSS OUTER BOUNDARY = ',F10.2,/,
                 &            ' HEAT EXTRACTED FROM WATER (OUTER PIPE) = ',F10.2,5X,
                 &            ' HEAT EXTRACTED FROM SOIL        = ',F10.2,/,
                 &            ' TOTAL HEAT EXTRACTED FROM SYSTEM       = ',F10.2,5X,
                 &            ' HEAT PASSED FROM SOIL TO WATER  = ',F10.2,/,
                 &            ' RATE OF HEAT EXTRACTION (BTU/HR)       = ',F10.2)
              C
              C       STORE INTERMEDIATE RESULTS ON DISK FOR RESTART
              C
ISN 0372              REWIND 20
ISN 0373              WRITE(20,2001) TIME,BTUOUT,BTUIN,HFLUX,T,S,U,V,P
ISN 0374      2001    FORMAT(7(1PE11.4))
              C
              C
ISN 0375      2100    CONTINUE
ISN 0376              IF (TIME .LT. TIMPLT) GO TO 2150
ISN 0378              QPLT = DABS((BTUOUT-QPLT)/(TIME-PLTTIM))
ISN 0379              WRITE(7,3001) TIME,QPLT,TH2O,TEXIT,V(NZ,ITHEN),TINFIN(NZ)
ISN 0380              TIMPLT=TIMPLT+PLTSTP
ISN 0381              QPLT=BTUOUT
ISN 0382              PLTTIM=TIME
ISN 0383      2150    IF (TIME .LT. TMPLT2) GO TO 2190
```

```
                C
                C       FIND AVERAGE HOURLY HEAT FLUX DURING PERIOD
                C               CHANGE UNITS FROM BTU/HR/IN TO BTU/HR/FT
                C
ISN 0385                DO 2160 J=1,NZ
ISN 0386        2160    HFLX(J)=60.*12.*DABS(HFLX(J))/PLTSP2
ISN 0387                WRITE(8,3002) TIME,(V(J,ITHEN),J=1,NZ)
ISN 0388                WRITE(8,3003) (HFLX(J),J=1,NZ)
ISN 0389                TMPLT2=TMPLT2+PLTSP2
ISN 0390                DO 2170 J=1,NZ
ISN 0391        2170    HFLX(J)=0.
ISN 0392        2190    IF (STOP) GO TO 2200
ISN 0394                IF (TIME .LT. TIMMAX) GO TO 100
                C
ISN 0396        2200    CONTINUE
ISN 0397                STOP
ISN 0398                END
```

```
ISN 0002          SUBROUTINE VELOC(ATIME,VINNER,VOUTER,V1,V2,BTUOUT,CPH,PCTON)
            C   THIS SUBROUTINE IS FOR GROUND HEAT EXCHANGER CYCLIC OPERATION
            C
ISN 0003          IMPLICIT REAL*8(A-H,O-Z)
            C
ISN 0004          DATA IFIRST / 0 /
            C
ISN 0005          IF (IFIRST .EQ. 0) GO TO 500
            C
ISN 0007    1     TMOD = DMOD(ATIME,TPCYCL)
ISN 0008          IF (TMOD .LE. TON) GO TO 200
ISN 0010          IF (V1 .EQ. 0.) RETURN
ISN 0012          V1 = 0.
ISN 0013          V2 = 0.
ISN 0014          BTUAVG = (BTUOUT - BTUSTR)/(ATIME - TIMSTR)
ISN 0015          WRITE(6,1001) BTUAVG
ISN 0016    1001  FORMAT('0***** AVERAGE CAPACITY OVER THE LAST CYCLE: ',
                &          1PE13.6,' BTU/HR *****',/)
ISN 0017          RETURN
            C
ISN 0018    200   IF (V1 .NE. 0.) RETURN
ISN 0020          V1 = VINNER
ISN 0021          V2 = VOUTER
ISN 0022          BTUSTR = BTUOUT
ISN 0023          TIMSTR = ATIME
ISN 0024          RETURN
            C
ISN 0025    500   WRITE(6,501) CPH, PCTON
ISN 0026    501   FORMAT('0***** FLOW RATE CYCLING AT ',F3.0,' CYCLES PER HOUR',
                &          ' RUNNING ',F5.3,' OF THE TIME')
ISN 0027          IFIRST = 1
ISN 0028          TPCYCL = 60./CPH
ISN 0029          TON = TPCYCL*PCTON
            C     TON = 60./(2.*CPH)
ISN 0030          V1=0.
ISN 0031          GO TO 1
ISN 0032          END
```

```
ISN 0002          DOUBLE PRECISION FUNCTION TINLET(TIME)
            C     THIS FUNCTION IS TO INPUT THE FLUID INLET TEMPERATURE
            C     AS A FUNCTION OF TIME
ISN 0003          IMPLICIT REAL*8(A-H,O-Z)
ISN 0004          TINLET = 107.
ISN 0005          RETURN
ISN 0006          END
```

```
ISN 0002              SUBROUTINE HXF(V2FT,RHOF,TMAX,R2,R3,ZMAX,H2,H3,NZ)
            C         THIS SUBROUTINE IS TO CALCULATE THE CONVECTIVE HEAT TRANSFER
            C         COEFFICIENTS IN THE ANNULUS AREA
ISN 0003              IMPLICIT REAL*8(A-H,O-Z)
ISN 0004              DIMENSION H2(NZ),H3(NZ)
            C
ISN 0005              Z=ZMAX/12.
ISN 0006              DZ = Z/NZ
ISN 0007              DE = 2.0*(R3 - R2)/12.
ISN 0008              T = 5.0*(TMAX - 32.)/9.
            C         CALCULATION OF "WATER" VISCOSITY,THERMAL CONDUCTIVITY,
            C         PRANDTL AND REYNOLDS NUMBERS.  WATER TEMPERATURE SHOULD
            C         NOT BE OVER 200F(93C)
ISN 0009              VISCOS = (17318. - 442.77*T + 4.175*T*T)/4130.
ISN 0010              CONDUC = (570.905 + 1.47714*T)/1730.7
ISN 0011              PR = 12.8047 - 0.357054*T + 0.0034982*T*T
ISN 0012              RE = RHOF*V2FT*60.*DE/VISCOS
            C
ISN 0013              WRITE(6,1) V2FT,RHOF,TMAX,R2,R3,Z,NZ
ISN 0014    1         FORMAT('0COMPUTED HEAT TRANSFER COEFFICIENTS:',/,
                 &      '      VELOCITY OF WATER IN THE ANNULUS     ',F7.2,' FT/MIN',/,
                 &     '      DENSITY OF THE WATER                 ',F7.2,' LB/FT3',/,
                 &        '      MAXIMUM WATER TEMPERATURE            ',F7.2,' F',/,
                 &      '      INNER RADIUS OF ANNULUS              ',F7.4,' IN',/,
                 &        '      OUTER RADIUS OF ANNULUS              ',F7.4,' IN',/,
                 &        '      LENGTH OF HEAT EXCHANGER             ',F7.2,' FT',/,
                 &        '      NUMBER OF VERTICAL SEGMENTS          ',I7)
            C
ISN 0015              WRITE(6,2) RE,PR,DE,VISCOS,CONDUC
ISN 0016    2         FORMAT('0COMPUTED PARAMETERS:',/,
                 &          '      REYNOLDS NUMBER                      ',F7.0,/,
                 &          '      PRANDTL NUMBER                       ',F7.2,/,
                 &          '      EQUIVALENT DIAMETER                  ',F7.4,' FT',/,
                 &          '      VISCOSITY OF WATER                   ',F7.5,/,
                 &          '      THERMAL CONDUCTIVITY OF WATER        ',F7.5)
ISN 0017              WRITE(6,3)
ISN 0018    3         FORMAT('OPT.',8X,'X/DE/(RE*PR)',1X,'NUSELT NUMBER',9X,'H')
ISN 0019              DO 100 J=1,NZ
ISN 0020              X = (Z - J*DZ)/12. + 0.35
            C         NUSSULT NUMBER IN ANNULUS REGION IS A FUNCTION OF
            C         ALPHA, WHICH HAS TAKEN INTO ACCOUNT OF ENTRENCE AND
            C         TEMPERATURE PROFILE EFFECTS.  THE CALCULATION IS GOOD
            C         FOR LAMINAR FLOW ONLY (RE < 2200).
ISN 0021              ALPHA = (X/DE)/(RE*PR)
ISN 0022              IF (ALPHA .LT. 0.25) GO TO 50
ISN 0024              RNU = 4.83
ISN 0025              GO TO 99
ISN 0026    50        A = DLOG10(ALPHA)
```

```
ISN 0027              RNU = ((( 0.391721*A + 2.12092)*A + 5.87134)*A + 6.54688)*A +
                  &           7.03786
ISN 0028      99      H2(J) = RNU*CONDUC/DE
ISN 0029              WRITE(6,101) J,ALPHA,RNU,H2(J)
ISN 0030      101     FORMAT(1X,I2,'. ',3F15.4)
ISN 0031              H2(J)=H2(J)/(60.*144.)
ISN 0032              H3(J)=H2(J)
ISN 0033      100     CONTINUE
ISN 0034              RETURN
ISN 0035              END
```

Appendix B

SAMPLE CALCULATION

```
HIGH DENSITY POLYETHYLENE, 400', 1 CPH, 100%, 3" ID, 5 GPM, K3=1.751, 107 F

GEOMETRIC DATA:
     R1     - INTERNAL RADIUS OF INNER PIPE        0.530 INCHES
     R2     - EXTERNAL RADIUS OF INNER PIPE        0.656 INCHES
     R3     - INTERNAL RADIUS OF OUTER PIPE        1.530 INCHES
     R4     - EXTERNAL RADIUS OF OUTER PIPE        1.780 INCHES
     R5     - DISTANCE FROM PIPE TO UNDISTURBED
              SOIL                                 8.000 FEET
     ZMAX   - DEPTH OF WELL                        400.0 FEET

GEOMETRIC GRID:
     NPIPE  - NUMBER OF MESH POINTS IN PIPE            5
     DRPIPE - RADIAL SPACING OF POINTS IN INNER
              PIPE                                 0.032 INCHES
     NPIPE2 - NUMBER OF MESH POINTS IN OUTER PIPE      5
     DRPIP2 - RADIAL SPACING OF POINTS IN OUTER
              PIPE                                 0.063 INCHES
     NSOIL  - NUMBER OF MESH POINTS IN SOIL            7
     DRSOIL - RADIAL SPACING OF POINTS IN SOIL      1.000   3.000   8.000  12.000  24.000  48.000   0.0     0.0     0.0   INCHES
     NZ     - NUMBER OF VERTICAL MESH POINTS          10
     DZ     - VERTICAL SPACING OF POINTS          480.00 INCHES

TIME PARAMETERS:
     TIMMAX - LENGTH OF SIMULATION                  6.00 HOURS
     TIMPRT - TIMING OF PRINTED INFORMATION       1.0000 HOURS
     DTIME  - TIME STEP                          0.00250 MINUTES

PUMPING DATA:
     GPM    - PUMPING RATE                         5.000 GALLONS/MINUTE
     VINNER - VELOCITY IN INNER PIPE              109.08 FEET/MINUTE
     VOUTER - VELOCITY IN OUTER PIPE               16.04 FEET/MINUTE

TEMPERATURE DATA:
     TINFIN - AMBIENT SOIL TEMPERATURE           62.000 62.000 62.000 62.000 62.000 62.000 62.000 62.000 62.000 62.000 F

MATERIAL PROPERTIES:

INNER PIPE:
     CONDUCTIVITY                                 0.101 BTU/HR-FT-F
     DENSITY                                     77.000 LBM/FT3
     SPECIFIC HEAT                               0.300 BTU/LBM-F
     ALPHA                                      0.00437 FT2/HR
     HEAT TRANSFER RATE                         615.000

OUTER PIPE:
     CONDUCTIVITY                                 0.266 BTU/HR-FT-F
     DENSITY                                     60.000 LBM/FT3
     SPECIFIC HEAT                               0.500 BTU/LBM-F
     ALPHA                                      0.00887 FT2/HR
```

SOIL:

CONDUCTIVITY	1.751 BTU/HR-FT-F
DENSITY	168.510 LBM/FT3
SPECIFIC HEAT	0.255 BTU/LBM-F
ALPHA	0.04075 FT2/HR

WORKING FLUID:

RHOF - DENSITY	62.400 LBM/FT3
CPF - SPECIFIC HEAT	1.000 BTU/LBM-F

COMPUTED HEAT TRANSFER COEFFICIENTS:

VELOCITY OF WATER IN THE ANNULUS	16.04 FT/MIN
DENSITY OF THE WATER	62.40 LB/FT3
MAXIMUM WATER TEMPERATURE	107.00 F
INNER RADIUS OF ANNULUS	0.6560 IN
OUTER RADIUS OF ANNULUS	1.5300 IN
LENGTH OF HEAT EXCHANGER	400.00 FT
NUMBER OF VERTICAL SEGMENTS	10

COMPUTED PARAMETERS:

REYNOLDS NUMBER	5905.
PRANDTL NUMBER	4.00
EQUIVALENT DIAMETER	0.1457 FT
VISCOSITY OF WATER	1.48124
THERMAL CONDUCTIVITY OF WATER	0.36543

PT.	X/DE/(RE*PR)	NUSELT NUMBER	H
1.	0.0088	6.9569	17.4526
2.	0.0079	7.1817	18.0166
3.	0.0069	7.4541	18.6999
4.	0.0059	7.7931	19.5504
5.	0.0049	8.2306	20.6479
6.	0.0040	8.8246	22.1380
7.	0.0030	9.6949	24.3214
8.	0.0020	11.1450	27.9592
9.	0.0011	14.3056	35.8883
10.	0.0001	39.0487	97.9607

HIGH DENSITY POLYETHYLENE, 400', 1 CPH, 100%, 3" ID, 5 GPM, K3=1.751, 107 F

***** FLOW RATE CYCLING AT 1. CYCLES PER HOUR RUNNING 0.999 OF THE TIME

TIME = 0 DAYS 0 HOURS 0 MINUTES 0 SECONDS (AVERAGE CAPACITY = 0. BTU/HR)

DEPTH FT.	H2O	PIPE		H2O	PIPE		SOIL 0.083			0.333			1.000			2.000			4.000			8.000		
0.0	107.00			62.00																				
40.0	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00
80.0	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00
120.0	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00
160.0	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00
200.0	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00
240.0	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00
280.0	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00
320.0	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00
360.0	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00
400.0	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00

***** AVERAGE CAPACITY OVER THE LAST CYCLE: -8.087715D 04 BTU/HR *****

TIME = 0 DAYS 1 HOURS 0 MINUTES 0 SECONDS (AVERAGE CAPACITY = -80800. BTU/HR)

DEPTH FT.	H2O	PIPE		H2O	PIPE		SOIL 0.083			0.333			1.000			2.000			4.000			8.000		
0.0	107.00			85.01																				
40.0	106.26	106.04	92.75	86.09	79.59	71.45	68.96	66.95	64.38	62.56	62.23	62.01	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00
80.0	105.68	105.47	93.16	87.18	80.58	72.06	69.44	67.34	64.57	62.62	62.25	62.01	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00
120.0	105.14	104.95	93.65	88.36	81.70	72.75	70.00	67.78	64.80	62.68	62.28	62.01	62.01	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00
160.0	104.65	104.48	94.24	89.65	82.95	73.53	70.63	68.29	65.06	62.76	62.32	62.01	62.01	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00
200.0	104.22	104.07	94.93	91.05	84.36	74.41	71.35	68.88	65.36	62.87	62.36	62.02	62.01	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00
240.0	103.84	103.71	95.74	92.57	85.98	75.43	72.18	69.56	65.72	62.99	62.41	62.02	62.01	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00
280.0	103.52	103.41	96.68	94.24	87.85	76.63	73.16	70.36	66.14	63.14	62.47	62.02	62.01	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00
320.0	103.27	103.18	97.77	96.06	90.11	78.07	74.34	71.34	66.66	63.34	62.55	62.03	62.01	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00
360.0	103.08	103.01	99.06	98.06	93.04	79.94	75.88	72.61	67.34	63.60	62.66	62.04	62.02	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00
400.0	102.97	102.93	100.54	100.30	98.22	83.24	78.58	74.83	68.52	64.05	62.85	62.05	62.02	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00

HEAT EXTRACTED FROM WATER (INNER PIPE) = -6464.71
HEAT EXTRACTED FROM WATER (OUTER PIPE) = -31583.26
TOTAL HEAT EXTRACTED FROM SYSTEM = -77217.64
RATE OF HEAT EXTRACTION (BTU/HR) = -77217.64

HEAT FROM ACROSS OUTER BOUNDARY = 0.0
HEAT EXTRACTED FROM SOIL = -72804.16
HEAT PASSED FROM SOIL TO WATER = -39169.67

PERCENT ERROR IN ENERGY BALANCE = 4.4332

***** AVERAGE CAPACITY OVER THE LAST CYCLE: -5.013156D 04 BTU/HR *****

TIME = 0 DAYS 2 HOURS 0 MINUTES 0 SECONDS (AVERAGE CAPACITY = -65441. BTU/HR)

DEPTH FT.	H2O	PIPE		H2O	PIPE		SOIL 0.083	0.333	1.000	2.000	4.000	8.000					
0.0	107.00			88.15													
40.0	106.37	106.18	94.78	89.06	82.84	74.98	72.53	70.57	66.86	64.23	62.96	62.10	62.05	62.00	62.00	62.00	62.00
80.0	105.87	105.69	95.12	89.97	83.72	75.56	73.03	70.99	67.12	64.37	63.02	62.11	62.05	62.00	62.00	62.00	62.00
120.0	105.41	105.25	95.53	90.97	84.71	76.22	73.58	71.46	67.40	64.53	63.09	62.12	62.05	62.00	62.00	62.00	62.00
160.0	104.99	104.85	96.02	92.06	85.82	76.97	74.21	71.99	67.73	64.71	63.17	62.13	62.06	62.00	62.00	62.00	62.00
200.0	104.62	104.49	96.61	93.26	87.08	77.81	74.92	72.60	68.11	64.93	63.26	62.14	62.06	62.00	62.00	62.00	62.00
240.0	104.30	104.19	97.31	94.57	88.52	78.78	75.75	73.31	68.55	65.18	63.38	62.16	62.07	62.00	62.00	62.00	62.00
280.0	104.03	103.93	98.12	96.00	90.19	79.91	76.71	74.13	69.07	65.49	63.51	62.18	62.08	62.00	62.00	62.00	62.00
320.0	103.81	103.74	99.07	97.58	92.21	81.28	77.87	75.13	69.71	65.86	63.67	62.20	62.09	62.00	62.00	62.00	62.00
360.0	103.66	103.60	100.18	99.32	94.83	83.06	79.39	76.43	70.53	66.34	63.89	62.24	62.10	62.00	62.00	62.00	62.00
400.0	103.57	103.54	101.47	101.26	99.43	86.19	82.05	78.72	71.98	67.20	64.26	62.29	62.13	62.00	62.00	62.00	62.00

HEAT EXTRACTED FROM WATER (INNER PIPE) = -6525.91
HEAT EXTRACTED FROM WATER (OUTER PIPE) = -33714.68
TOTAL HEAT EXTRACTED FROM SYSTEM = -124875.22
RATE OF HEAT EXTRACTION (BTU/HR) = -62437.61

HEAT FROM ACROSS OUTER BOUNDARY = -0.00
HEAT EXTRACTED FROM SOIL = -172583.05
HEAT PASSED FROM SOIL TO WATER = -84634.63

PERCENT ERROR IN ENERGY BALANCE = 4.5888

***** AVERAGE CAPACITY OVER THE LAST CYCLE: -4.5554930 04 BTU/HR *****

TIME = 0 DAYS 3 HOURS 0 MINUTES 0 SECONDS (AVERAGE CAPACITY = -58797. BTU/HR)

DEPTH FT.	H2O	PIPE		H2O	PIPE		SOIL 0.083	0.333	1.000	2.000	4.000	8.000					
0.0	107.00			89.32													
40.0	106.41	106.23	95.55	90.19	84.20	76.62	74.26	72.36	68.52	65.80	63.70	62.30	62.13	62.01	62.00	62.00	62.00
80.0	105.94	105.77	95.87	91.05	85.05	77.21	74.77	72.80	68.82	65.99	63.79	62.31	62.14	62.01	62.00	62.00	62.00
120.0	105.51	105.36	96.26	92.00	86.01	77.87	75.34	73.30	69.15	66.21	63.89	62.34	62.15	62.01	62.00	62.00	62.00
160.0	105.12	104.98	96.74	93.03	87.08	78.61	75.98	73.85	69.53	66.46	64.01	62.36	62.16	62.01	62.00	62.00	62.00
200.0	104.78	104.65	97.30	94.16	88.28	79.45	76.70	74.49	69.96	66.74	64.14	62.39	62.17	62.01	62.00	62.00	62.00
240.0	104.48	104.37	97.95	95.40	89.66	80.42	77.53	75.22	70.45	67.08	64.29	62.42	62.19	62.01	62.00	62.00	62.00
280.0	104.23	104.13	98.72	96.75	91.26	81.54	78.51	76.07	71.04	67.47	64.47	62.46	62.20	62.01	62.00	62.00	62.00
320.0	104.03	103.95	99.61	98.23	93.18	82.89	79.68	77.09	71.74	67.94	64.69	62.51	62.23	62.01	62.01	62.00	62.00
360.0	103.88	103.83	100.66	99.86	95.66	84.63	81.19	78.42	72.66	68.57	64.98	62.58	62.25	62.01	62.01	62.00	62.00
400.0	103.80	103.77	101.86	101.67	99.97	87.69	83.85	80.76	74.26	69.66	65.49	62.69	62.31	62.02	62.01	62.00	62.00

HEAT EXTRACTED FROM WATER (INNER PIPE) = -6549.46
HEAT EXTRACTED FROM WATER (OUTER PIPE) = -34576.29
TOTAL HEAT EXTRACTED FROM SYSTEM = -168192.99
RATE OF HEAT EXTRACTION (BTU/HR) = -56064.33

HEAT FROM ACROSS OUTER BOUNDARY = -0.00
HEAT EXTRACTED FROM SOIL = -268817.06
HEAT PASSED FROM SOIL TO WATER = -127067.24

PERCENT ERROR IN ENERGY BALANCE = 4.6473

***** AVERAGE CAPACITY OVER THE LAST CYCLE: -4.3194170 04 BTU/HR *****

TIME = 0 DAYS 4 HOURS 0 MINUTES 0 SECONDS (AVERAGE CAPACITY = -54885. BTU/HR)

DEPTH FT.	H2O	PIPE		H2O	PIPE		SOIL 0.083	0.333	1.000	2.000	4.000	8.000
0.0	107.00			90.11								
40.0	106.44	106.26	96.07	90.94	85.14	77.78	75.49	73.64	69.80	67.08	64.38	62.56	62.25	62.02	62.01	62.00	62.00	62.00
80.0	105.99	105.83	96.38	91.78	85.98	78.37	76.00	74.10	70.13	67.31	64.48	62.59	62.26	62.02	62.01	62.00	62.00	62.00
120.0	105.58	105.43	96.77	92.70	86.91	79.04	76.58	74.61	70.49	67.57	64.61	62.62	62.28	62.02	62.01	62.00	62.00	62.00
160.0	105.21	105.08	97.23	93.70	87.95	79.78	77.24	75.19	70.90	67.86	64.75	62.66	62.29	62.02	62.01	62.00	62.00	62.00
200.0	104.88	104.76	97.77	94.79	89.13	80.63	77.97	75.84	71.36	68.19	64.91	62.71	62.31	62.02	62.01	62.00	62.00	62.00
240.0	104.60	104.50	98.40	95.97	90.46	81.59	78.82	76.59	71.90	68.58	65.10	62.76	62.34	62.02	62.01	62.00	62.00	62.00
280.0	104.36	104.27	99.14	97.27	92.01	82.70	79.79	77.46	72.52	69.03	65.32	62.82	62.37	62.03	62.01	62.00	62.00	62.00
320.0	104.17	104.10	99.99	98.68	93.86	84.04	80.97	78.50	73.28	69.57	65.58	62.90	62.40	62.03	62.01	62.00	62.00	62.00
360.0	104.03	103.98	100.99	100.23	96.24	85.76	82.49	79.85	74.25	70.28	65.93	63.00	62.45	62.03	62.01	62.00	62.00	62.00
400.0	103.96	103.93	102.13	101.95	100.35	88.75	85.12	82.20	75.96	71.52	66.53	63.18	62.53	62.04	62.02	62.00	62.00	62.00

HEAT EXTRACTED FROM WATER (INNER PIPE) = -6565.41
HEAT EXTRACTED FROM WATER (OUTER PIPE) = -35166.06
TOTAL HEAT EXTRACTED FROM SYSTEM = -209237.63
RATE OF HEAT EXTRACTION (BTU/HR) = -52309.41

HEAT FROM ACROSS OUTER BOUNDARY = -0.00
HEAT EXTRACTED FROM SOIL = -362332.81
HEAT PASSED FROM SOIL TO WATER = -167506.16

PERCENT ERROR IN ENERGY BALANCE = 4.6933

***** AVERAGE CAPACITY OVER THE LAST CYCLE: -4.1476900 04 BTU/HR *****

TIME = 0 DAYS 5 HOURS 0 MINUTES 0 SECONDS (AVERAGE CAPACITY = -52195. BTU/HR)

DEPTH FT.	H2O	PIPE		H2O	PIPE		SOIL 0.083	0.333	1.000	2.000	4.000	8.000
0.0	107.00			90.71								
40.0	106.46	106.29	96.46	91.53	85.87	78.69	76.45	74.64	70.83	68.13	64.98	62.86	62.39	62.04	62.02	62.00	62.00	62.00
80.0	106.03	105.87	96.77	92.34	86.69	79.28	76.97	75.11	71.17	68.38	65.10	62.90	62.41	62.04	62.02	62.00	62.00	62.00
120.0	105.63	105.49	97.15	93.23	87.61	79.95	77.56	75.64	71.56	68.67	65.25	62.95	62.43	62.04	62.02	62.00	62.00	62.00
160.0	105.28	105.15	97.60	94.21	88.63	80.70	78.22	76.23	71.99	68.99	65.41	63.01	62.45	62.04	62.02	62.00	62.00	62.00
200.0	104.96	104.85	98.13	95.26	89.78	81.54	78.96	76.89	72.48	69.35	65.59	63.07	62.48	62.05	62.02	62.00	62.00	62.00
240.0	104.69	104.59	98.74	96.41	91.08	82.49	79.81	77.65	73.04	69.77	65.81	63.14	62.51	62.05	62.02	62.00	62.00	62.00
280.0	104.46	104.38	99.45	97.66	92.59	83.60	80.79	78.53	73.70	70.27	66.06	63.23	62.55	62.05	62.02	62.00	62.00	62.00
320.0	104.28	104.21	100.28	99.02	94.39	84.93	81.97	79.59	74.48	70.86	66.36	63.33	62.60	62.06	62.02	62.00	62.00	62.00
360.0	104.15	104.10	101.24	100.52	96.68	86.62	83.48	80.95	75.49	71.62	66.75	63.47	62.66	62.07	62.03	62.00	62.00	62.00
400.0	104.08	104.05	102.33	102.16	100.63	89.55	86.09	83.30	77.25	72.96	67.43	63.71	62.77	62.08	62.03	62.00	62.00	62.00

HEAT EXTRACTED FROM WATER (INNER PIPE) = -6577.60
HEAT EXTRACTED FROM WATER (OUTER PIPE) = -35617.21
TOTAL HEAT EXTRACTED FROM SYSTEM = -248624.99
RATE OF HEAT EXTRACTION (BTU/HR) = -49725.00

HEAT FROM ACROSS OUTER BOUNDARY = -0.01
HEAT EXTRACTED FROM SOIL = -453785.98
HEAT PASSED FROM SOIL TO WATER = -206430.17

PERCENT ERROR IN ENERGY BALANCE = 4.7329

***** AVERAGE CAPACITY OVER THE LAST CYCLE: -4.0130480 04 BTU/HR *****

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TIME =   0 DAYS    6 HOURS    0 MINUTES    0 SECONDS      (AVERAGE CAPACITY =  -50178. BTU/HR)
 DEPTH   H2O         PIPE        H2O         PIPE                SOIL
  FT.                                                          0.083       0.333       1.000       2.000       4.000       8.000
  0.0  107.00                   91.19                  ----------------------------------------------------------------------------
 40.0  106.47 I106.31 96.78 I 91.99 I 86.45 79.42 I 77.23 75.46 71.68 68.99 65.52 63.19 62.54 62.06 62.03 62.00 62.00 62.00
 80.0  106.06 I105.91 97.08 I 92.79 I 87.26 80.02 I 77.76 75.94 72.03 69.26 65.66 63.24 62.56 62.06 62.03 62.00 62.00 62.00
120.0  105.67 I105.54 97.46 I 93.66 I 88.16 80.69 I 78.35 76.47 72.43 69.57 65.82 63.30 62.59 62.07 62.03 62.00 62.00 62.00
160.0  105.33 I105.21 97.90 I 94.61 I 89.17 81.43 I 79.01 77.07 72.88 69.91 66.00 63.37 62.62 62.07 62.03 62.00 62.00 62.00
200.0  105.03 I104.92 98.41 I 95.64 I 90.30 82.27 I 79.76 77.74 73.39 70.30 66.20 63.45 62.66 62.08 62.03 62.00 62.00 62.00
240.0  104.76 I104.67 99.01 I 96.76 I 91.58 83.22 I 80.61 78.51 73.97 70.75 66.44 63.54 62.70 62.08 62.04 62.00 62.00 62.00
280.0  104.54 I104.46 99.70 I 97.97 I 93.05 84.32 I 81.59 79.40 74.64 71.27 66.71 63.65 62.75 62.09 62.04 62.00 62.00 62.00
320.0  104.37 I104.30100.50 I 99.29 I 94.80 85.63 I 82.76 80.46 75.45 71.89 67.04 63.78 62.82 62.10 62.04 62.00 62.00 62.00
360.0  104.24 I104.20101.43 I100.74 I 97.03 87.30 I 84.26 81.81 76.48 72.70 67.47 63.96 62.89 62.11 62.05 62.00 62.00 62.00
400.0  104.17 I104.15102.49 I102.33 I100.85 90.18 I 86.84 84.16 78.27 74.10 68.21 64.26 63.03 62.13 62.05 62.00 62.00 62.00


HEAT EXTRACTED FROM WATER (INNER PIPE) =   -6587.25      HEAT FROM ACROSS OUTER BOUNDARY =      -0.02
HEAT EXTRACTED FROM WATER (OUTER PIPE) =  -35974.27      HEAT EXTRACTED FROM SOIL        = -543643.69
TOTAL HEAT EXTRACTED FROM SYSTEM       = -286714.18      HEAT PASSED FROM SOIL TO WATER  = -244152.64
RATE OF HEAT EXTRACTION (BTU/HR)       =  -47785.70

PERCENT ERROR IN ENERGY BALANCE =  4.7674


TIME =   0 DAYS    6 HOURS    0 MINUTES    0 SECONDS      (AVERAGE CAPACITY =  -50178. BTU/HR)
 DEPTH   H2O         PIPE        H2O         PIPE                SOIL
  FT.                                                          0.083       0.333       1.000       2.000       4.000       8.000
  0.0  107.00                   91.19                  ----------------------------------------------------------------------------
 40.0  106.47 I106.31 96.78 I 91.99 I 86.45 79.42 I 77.23 75.46 71.68 68.99 65.52 63.19 62.54 62.06 62.03 62.00 62.00 62.00
 80.0  106.06 I105.90 97.08 I 92.79 I 87.26 80.02 I 77.76 75.94 72.03 69.26 65.66 63.24 62.56 62.06 62.03 62.00 62.00 62.00
120.0  105.67 I105.54 97.46 I 93.66 I 88.16 80.69 I 78.35 76.47 72.43 69.57 65.82 63.30 62.59 62.07 62.03 62.00 62.00 62.00
160.0  105.33 I105.21 97.90 I 94.61 I 89.17 81.43 I 79.01 77.07 72.88 69.91 66.00 63.37 62.62 62.07 62.03 62.00 62.00 62.00
200.0  105.03 I104.91 98.41 I 95.64 I 90.30 82.27 I 79.76 77.74 73.39 70.30 66.20 63.45 62.66 62.08 62.03 62.00 62.00 62.00
240.0  104.76 I104.67 99.01 I 96.76 I 91.58 83.22 I 80.61 78.51 73.97 70.75 66.44 63.54 62.70 62.08 62.04 62.00 62.00 62.00
280.0  104.54 I104.46 99.70 I 97.97 I 93.05 84.32 I 81.59 79.40 74.64 71.27 66.71 63.65 62.75 62.09 62.04 62.00 62.00 62.00
320.0  104.37 I104.30100.50 I 99.29 I 94.80 85.63 I 82.76 80.46 75.45 71.89 67.04 63.78 62.82 62.10 62.04 62.00 62.00 62.00
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400.0  104.17 I104.15102.49 I102.33 I100.85 90.18 I 86.84 84.16 78.27 74.10 68.21 64.26 63.03 62.13 62.05 62.00 62.00 62.00


HEAT EXTRACTED FROM WATER (INNER PIPE) =   -6587.27      HEAT FROM ACROSS OUTER BOUNDARY =      -0.02
HEAT EXTRACTED FROM WATER (OUTER PIPE) =  -35974.29      HEAT EXTRACTED FROM SOIL        = -543647.40
TOTAL HEAT EXTRACTED FROM SYSTEM       = -286715.76      HEAT PASSED FROM SOIL TO WATER  = -244154.18
RATE OF HEAT EXTRACTION (BTU/HR)       =  -47785.63

PERCENT ERROR IN ENERGY BALANCE =  4.7674

IHC002I STOP      0
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