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USER'S MANUAL FOR GEOTEMP,
A COMPUTER CODE FOR PREDICTING DOWNHOLE
WELLBORE AND SOIL TEMPERATURES IN
GEOTHERMAL WELLS*

APPENDIX TO PART I REPORT

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Abstract

GEOTEMP is a computer code that calculates downhole temperatures in and surrounding a well. Temperatures are computed as a function of time in a flowing stream, in the wellbore, and in the soil. Flowing options available in the model include the following:

1. Injection/Production
2. Forward/Reverse Circulation
3. Drilling

A special feature for options 2 and 3 is an added secondary production that joins the circulating fluid.

This manual describes how to input data to the code and what results are printed out, provides six examples of both input and output, and supplies a listing of the code. The user's manual is an appendix to the Part I report "Development of Computer Code and Acquisition of Field Temperature Data," for Sandia contract 13-0212 "Wellbore Thermal Simulation for Geothermal Wells."

Although GEOTEMP is designed for applications to geothermal wells, it is a valuable tool for all wells. A few examples are presented, but almost unlimited combinations of well descriptions, casing programs, temperature distributions and fluid types are possible. Flowing options allow accurate modeling of drilling and completion of a well, workovers, injection or production, and even shut-in during or after the life of a well. Furthermore, all these capabilities can be expanded for special applications by adjusting thermal properties or well dimensions, and by making rather simple modifications to the computer code. However, to encourage extensive application of GEOTEMP, input data has been minimized to information commonly available for all wells.

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I Introduction

I-1 Background

Determination of downhole wellbore and soil temperatures is a complex task. Many variables influence the temperatures, which are continuously changing with time. Temperature recording devices have been developed, but these provide only isolated data points for a transient quantity, and furthermore cannot provide sufficient information to establish the relative importance of the variables influencing temperatures. Therefore, a means of predicting downhole temperatures is needed to determine important design criteria such as maximum temperature and time of exposure to high temperatures. Many simplified analytical techniques and some correlations of experimental data have been constructed in the past, each with limited success in predicting downhole temperatures. However, experience has demonstrated that a computer model is needed to account for the complexities of heat transfer in a well.

Computer models have been developed as needs arise for specific heat transfer analyses. For example several models appeared at the time interest in steam stimulation surged in the 1960's, and additional models were introduced in the early 1970's as a result of the interest in arctic completions.

Most existing wellbore thermal simulators have been designed for one of the following four applications.

1. drilling, cementing, circulation
2. single phase injection or production
3. two phase injection or production
4. permafrost thaw

The present model is planned for applications one and two.

There are basically three components of wellbore thermal simulators, flowing stream, well completion, and soil. The relative importance of each component depends on the particular application and the desired result. For predicting surface production temperature in high rate wells, the soil calculation is much less important than in the flowing stream. Conversely, for predicting permafrost thaw around an arctic well the flowing stream is less important than the soil analysis.

Several methods have been used to determine flowing stream temperatures. Many of the early models assumed constant temperatures in the flowing fluid, or used experimentally determined correlations to compute temperatures. Later studies performed a steady state analysis to estimate fluid temperature, followed by models employing a pseudo steady state scheme whereby the temperatures in the flowing stream are assumed to be steady state at each time step. Recent models have included the full transient response of the flowing stream. For short time periods the transient response is very important, such as for drilling and cementing operations.

There is resistance to heat flow between the flowing fluid and the soil. During drilling in an open hole the resistance results simply from the convection coefficient between the drilling fluid and the soil. However, when circulating inside casing, or during production and injection, the heat transfer resistance is more complex. Indeed, arctic well completions use this resistance to advantage with varying methods of insulation.

Figure 1 shows a well completion for an injection or production well. It is clear from this figure that heat must pass through several materials to travel from the fluid stream to the soil. Moreover, the resistance to heat flow varies with depth as casing is set, introducing steel, cement, and annular fluids where there once was soil. Some previous work has neglected the wellbore resistance, but more recent papers have indicated a trend to detailed analyses of the well components.

In the soil heat is transferred both radially and vertically by conduction. Early attempts to model wellbore temperatures assumed a constant undisturbed geothermal temperature in the soil, or employed an analytical solution to the steady state or transient radial heat conduction problem. Later models included numerical solutions to transient radial heat flow, or both radial and vertical conduction.

I-2 Theory

Details of the formulation of GEOTEMP are provided in the part I report "Development of Computer Model and Acquisition of Field Temperature Data". This section summarizes the basis for the program formulation.

Energy is transferred in a flowing stream by various mechanisms. In the radial direction heat conduction transfers energy into and out of each mathematical cell. Fourier's law of heat conduction established the rate of heat flow

$$E^C = - \frac{2 \pi K \Delta z}{\ln \frac{r_2}{r_1}} \Delta T, \quad (I-1)$$

where ΔT denotes the radial temperature difference, r_2 and r_1 are the radii to the temperatures, Δz is a length interval, and K is thermal conductivity.

Energy transport in a flowing stream is more complex than simple conduction. A change in flow energy along a streamline is the sum of the change in enthalpy, potential energy and kinetic energy.

$$\Delta E^f = \Delta H + \Delta PE + \Delta KE, \quad (I-2)$$

where ΔE^f is the rate of change of the flow energy.

In addition to energy being transferred through a cell energy may be accumulated within the cell. The rate at which energy is accumulated, E^a , is the rate at which the sensible heat of the fluid in the cell changes,

$$\Delta E^a = \rho V c \frac{\Delta T}{\Delta t}, \quad (I-3)$$

where V denotes the volume of the cell, ΔT is a change of temperature in the cell with time, and Δt is the time increment. This transient behavior term is a key feature missing in the thermal simulators available for public use.

Radial conduction in the soil is formulated much like that in the flowing stream. Fourier's law for heat conduction in radial coordinates can be written in terms of a conductance U ,

$$E_r^C = \Delta z U \Delta T. \quad (I-4)$$

Fourier's law governs the vertical transfer of energy also. However, the geometry is somewhat different involving rectangular coordinates, or linear flow as opposed to radial,

$$E_v^C = KA \frac{\Delta T}{\Delta z}. \quad (I-5)$$

Another energy form that must be considered is heat generation. Heat may be generated by fluid friction against pipe walls, by chemical reaction such as cement hydration, or by external sources such as bit work during drilling. In the soil a phase change in the pore fluid, evaporation or condensation in geothermal formations, may be modeled with heat generation. Other phenomena such as electric resistance heating in an electrode well may be modeled with a heat generation term. The rate at which heat is generated is denoted Q in the energy balance to follow.

All the energy terms discussed must obey the first law of thermodynamics, an energy balance. An energy balance requires that the sum of the energy flowing into a cell, plus the heat generated in the cell, less the energy flowing out of a cell must equal the energy accumulated in the cell,

$$\Delta E^C + \Delta E^F + \dot{Q} = \Delta E^S \quad (I-6)$$

Substituting the expressions given above for the terms in equation I-6 yields an equation of the form

$$T_{K,i}^{n+1} = A_{k,i} T_{K-1,i}^{n+1} + B_{k,i} T_{k+1,i}^{n+1} + C_{k,i} T_{K,i-1}^{n+1} + D_{k,i} T_{k,i+1}^{n+1} + E_{k,i} T_{k,i}^n + F_{k,i} T_{k-1,i-1}^{n+1} + G_{k,i} T_{k-1,i+1}^{n+1} \quad (I-7)$$

This equation can be written for every position k, i to yield a system of simultaneous linear algebraic equations. The unknowns are the temperatures at each node at time step $n + 1$ and there is one independent equation at each node, for a total of $N_z \times N_r$ equations and unknowns.

II Input Data

II-1 Introduction

A necessary beginning for a thermal simulation is a complete definition of the geometry of the well to be modeled. Casing, tubing, and drill pipe are all defined by specifying the inside and outside diameters and the setting depth. In addition, the cement interval length is specified for each casing. Five strings of pipe are described for each well. For wells with less than five strings, as many of the outer strings as necessary may be shortened in length to zero. For more than five strings the additional annuli are approximated by modifying the thermal properties and geometry of the five available. Borehole pipe are numbered from smallest to largest diameter. Figure 1 illustrates a completed well for injection with five strings of pipe. Here the injection tubing is string number one and the conductor pipe is number five. It is required that the setting depth for each pipe be less than that for the previous pipe, except for the tubing, which is allowed to be shorter than the first casing string.

Fluid properties are specified for the primary flowing fluid, a secondary flowing fluid, and the annular fluid between casings. Each fluid is defined by three properties, density, plastic viscosity, and yield point. The specific heat capacity and thermal conductivity for each fluid are computed from the density. This computation, and the use of the viscosity parameters are discussed in detail in sections IV-3 and IX-5 of the part I report.

Other data defined as input to the computer model are well dimensions, temperatures, and flow rates. The initial and final hole depths are defined, as is the surface bore hole diameter. Of course the initial and final hole depths are identical for production, injection, and circulation. However, for drilling the initial depth may be zero and the total depth thousands of feet. It is possible to analyze resumption of drilling by setting the initial depth at some point downhole and estimating the downhole temperatures at the time of resuming drilling.

An initial temperature distribution in the well and surrounding soil is specified. The geothermal gradients are approximated with two constants, which yields a temperature distribution like that given in figure 2. Two linear

temperature functions are computed from the surface temperature, the bottom hole temperature, and an intermediate temperature and depth. This temperature distribution is used to set the initial distribution, the surface boundary temperatures, the boundary temperatures four hundred feet below the bottom hole depth, and the downhole boundary temperatures at the maximum radius.

Inlet fluid temperatures and flow rates are specified. During circulation it is possible to account for fluid influx at the bottom of the hole. Fluid properties, inlet temperature, and flow rate may all be defined for this secondary fluid independent of the circulation. The parameters for the primary flowing fluid are allowed to change at any time and as often as necessary. A flowing option is specified at each change as one of the following:

1. Injection
2. Production
3. Forward circulation
4. Reverse circulation

Also needed is the inlet temperature and volume flow rate. Each of these variables is held constant through every time step until the next change occurs at a specified time.

Drilling requires additional input information, but uses essentially the same format. In addition to flow direction, inlet temperature, and flow rate, drilling requires the depth to which the well is drilled under these conditions and the number of hours per day that fluid is circulated. All of these variables may be changed at any specified time. Based on this information, a drilling rate is computed for the period during each day that fluid is circulated. Of course, depth does not change with time during the shut-in period of a day.

Thermal properties for all solid materials are defined in the program. The solids that are modeled in the computer code are:

- * cement
- * soil
- * steel.

Although several types of each material exist, the thermal properties are not expected to vary significantly between types and are therefore not part of the input data. Of course, for special applications a user may enter the program to redefine thermal properties for solids. The three thermal properties needed are:

- * density
- * specific heat capacity
- * thermal conductivity

These properties are discussed in more detail in section IV-4 of the part I report. The quantities presently employed by the thermal simulator are listed in table II-1.

II-2 Data Formats

This section describes in detail how to input data to the model. The format for each card is specified and the variables on that card are defined.

TITLE CARD:

This card allows any title to be printed on columns 1-80.
Format (20A4)
Columns 1-80 Title.

CASING SPECIFICATION CARDS:

Each of these five cards defines a string of pipe in the well, the order of presentation is immaterial.
Format (20X,15,4F10.0)

Columns 21-25	Casing identification number
26-35	Inside diameter, inches
36-45	Outside diameter, inches
46-55	Setting depth, feet
56-65	Interval length of cement or annulus fluid outside casing, feet.

BOREHOLE DIMENSIONS CARD:

This card defines the borehole dimensions.
Format (20X,3F10.0)

Columns 21-30	Initial depth, feet, (0 to TD).
31-40	Total depth, feet
41-50	Maximum borehole diameter, inches, (outside casing #5 OD and cement).

Initial and total depths are equal for applications other than drilling.

INITIAL TEMPERATURES CARD:

This card defines the initial and boundary temperatures in the well and soil.
Format (20X,4F10.0)

Columns 21-30	Surface temperature, F.
31-40	Bottom hole temperature, F.
41-50	Intermediate temperature, F.
51-60	Intermediate depth corresponding to temperature in columns 21-30, feet.

PRIMARY FLUID PROPERTIES CARD:

This card has the fluid properties for the primary flowing fluid assumed to be measured at 70 F.

Format (20X,3F10.0, I5)

Columns 21-30	Density, lb_m/ft^3
31-40	Plastic viscosity, centipoise
41-50	Yield point, $\text{lb}_f/100\text{ft}^2$.
51-55	Secondary fluid production indicator,
	0= no secondary fluid flow
	1= secondary fluid flow present

SECONDARY FLUID PROPERTIES CARD:

This card contains the secondary fluid properties and conditions at 70 F. This card is included only if a 1 is in columns 31-35 of the PRIMARY FLUID PROPERTIES CARD.

Format (20X,5F10.0)

Columns 21-30	Density, lb_m/ft^3 .
31-40	Plastic viscosity, centipoise.
41-50	Yield point, $\text{lb}_f/100\text{ft}^2$
51-60	Flow rate, gal/min.
61-70	Bottom hole inlet temperature, F.

ANNULAR FLUID PROPERTIES CARD:

This card describes the properties at 70 F of the annular fluids between casings.

Format (20X,3F10.0)

Columns 21-30	Density, lb_m/ft^3 .
31-40	Plastic viscosity, centipoise.
41-50	Yield point, $\text{lb}_f/100\text{ft}^2$

CHANGING FLOW PARAMETERS CARDS:

These cards contain the flow parameters that are allowed to change at any time during a simulation. As many cards as needed may be used.

Format (20X,I5,5F10.0)

Columns 21-25	Flowing option selector
	1 = injection
	2 = production
	3 = forward circulation
	4 = reverse circulation
	(irrelevant during shut-in)

26-35	Primary fluid inlet temperature, F.
36-45	Primary fluid volume flow rate, gal/min.
46-55	Time to read next card for a change of variables, days
56-65	Hole depth at time to change variables (col.46-55), feet
66-75	Circulation time per day, hours

The hole depth and circulation time per day specified in columns 56-65 and 66-75 serve a purpose for drilling only, for other applications they may be omitted.

II-3 Examples

Although the thermal simulator operates in essentially the same manner for injection, production, forward and reverse circulation, and drilling. The input data varies somewhat to reflect the selection of one of these options. An example of application of the thermal simulator to each of these options is provided.

Injection and production are the simplest modes of operation. Consider the injection system illustrated in figure 1, where fluid is injected in the tubing at the surface at a known temperature. The fluid travels down the well and exits at the bottom of the well. Downhole temperatures of the fluid, wellbore, and soil are computed as a function of time. Table II-2 gives the data required to activate the thermal simulator for injection at 70 F into a 5000 foot deep well. The first card contains the problem title, followed by five CASING SPECIFICATION CARDS. The casing program contains a 4½" injection tubing with 9 5/8", 13 3/8", and 20" casings set at depths of 5000', 3000', and 1000' respectively. The 9 5/8" and 13 3/8" strings are cemented back to inside the next string, or 2200' of cement each. The surface casing is cemented back to the surface, as is a 30" conductor pipe set at 100'. Since no drilling is involved, the initial and total depths are the same at 5000'. A borehole diameter of 40" is used to insert the 30" casing.

A constant geothermal gradient is assumed for the undisturbed initial temperature distribution. For a gradient of 1.5 F/100ft the temperature at a depth of 5000' is 145 F with a surface temperature of 70 F. Of course a much higher gradient is likely for geothermal applications, or two gradients may be more appropriate. Two gradients are defined by using the intermediate temperature at an intermediate depth.

Primary fluid properties are typical of those for drilling fluids. A 10lb_m/gal mud is defined with a plastic viscosity of 15 centipoise and a yield point of 5lb_f/100ft². No secondary fluid is indicated since this option is only available for circulation, and therefore no secondary fluid properties are given. Annular fluid properties are identical to those for the primary fluid.

Injection into the well is continued for 20 days with a change in flow rate occurring at 10 days after start-up. The primary fluid is injected at a surface temperature of 70 F and a flow rate of 10 gal/min, which is increased to 100 gal/min after 10 days.

Production data is very similar to that for injection. Table II-3 lists the input data to activate the thermal simulator for production. The example presented has the same wellbore geometry, casing program, and initial temperature distribution as the previous example for injection. Also, fluid properties and rates of flow are the same as those discussed in the previous example. Two changes in the data from the injection case presented in table II-2 are evident in the CHANGING FLOW PARAMETERS CARDS. In columns 21-25 the flowing option selected is 2 to specify production. And in columns 26-35 the fluid inlet temperature is set at the bottom hole temperature of 145 F. Flow rate is increased at 10 days from 10 to 100 gal/min. The thermal simulation ends after 20 days of production.

Forward circulation is the flow of fluid down the drill pipe or tubing to bottom hole and returning to the surface through the tubing x casing annulus. Table II-4 lists input data for a forward circulation thermal simulation. By comparison with the previous examples it is clear that all the casing, wellbore, and initial temperature data are unchanged. The data describe forward circulation to a depth of 5000' with an inlet temperature of 70 F. The CHANGING FLOW PARAMETERS CARDS show a flowing option selector of 3, corresponding to forward circulation, and the prescribed inlet temperature. Flow rate increases as in the previous examples from the initial rate of 10 gal/min to 100 gal/min at 10 days. Again, the thermal simulation ends at 20 days.

Reverse circulation differs from the previous example only in the direction of flow. Table II-5 contains the data for a thermal simulation of reverse circulation. These data are for the same well and temperature conditions of the other examples. A flowing option of 4 signifies reverse circulation, where fluid enters the well at the surface in the tubing x casing annulus and travels to bottom hole where it returns to the surface through the tubing or drill pipe.

An extra feature that has not been described is secondary flow of fluid into the well at bottom hole during circulation. Table II-6 gives a set of input data for forward circulation with secondary fluid flow. In the PRIMARY FLUID PROPERTIES CARD a secondary fluid production indicator of 1 introduces the added flow. The next card read is the SECONDARY FLUID PROPERTIES CARD, which indicates the same properties and flow rate as the primary fluid and an inlet temperature of 145 F at the bottom hole depth of 5000'. All other data are unchanged from the forward circulation example of table II-4.

Drilling is a special application of the circulation mode for the thermal simulator. Two special features of drilling are a change in depth of circulation with time, and a defined fraction of each day for circulation and for shut-in. For the time period between CHANGING FLOW PARAMETERS CARDS the drilling rate during circulation and the hours per day of circulation are fixed constants. Of course, these constants may be changed as often as necessary to develop a realistic model by simply adding CHANGING FLOW PARAMETERS CARDS. Table II-7 gives input data for a thermal simulation of drilling. A casing program is described for the completed well, except for the tubing which is replaced by drill pipe dimensions. These casings enter the calculations only as the drilling depth passes each casing setting depth. In this example forward circulation is specified with flowing option 3. An initial depth of 0 and a final depth of 5000' are input. The drilling fluid enters the well at 70 F and travels down the drill pipe to the circulation depth defined by the drilling rate. A drilling rate is computed from the initial and final depths during a change period and the time span of the period. Also supplied on each change card is the hours per day that circulation is active. It is assumed that these hours are continuous during the beginning of a day and that a shut-in period follows for the remainder of the day. For the example in table II-7 circulation occurs for 8 hours of each day. During the first ten days of drilling, a depth of 2000' is achieved. During the next ten days the depth is increased from 2000' to 5000'.

It should be emphasized that the applications described in this section are examples only. Almost unlimited combinations of well descriptions, casing programs, temperature distributions and fluid types are possible to describe a particular well. Furthermore, the use of CHANGING FLOW PARAMETERS CARDS allows modeling almost any conceivable flow conditions from drilling a well and circulating during completion, to production or injection, circulating during a workover, and more production until a well is shut-in. Even the shut-in period after the life of a well has expired can be studied.

Of course, even with all the above possibilities, there will be applications where it seems that the model does not have the necessary capability. But many unusual applications may be approximated by employing "fictitious" thermal properties or well dimensions. Furthermore, relatively simple modifications to the internal workings of the thermal simulator can provide an even greater range of capabilities. Such capabilities may include the following:

1. Dual completions.
2. Counter current or parallel independent flows.
3. Closed system circulation in casing annuli with simultaneous production or injection.
4. Fluid influx at any level during drilling.
5. Two or more fluid phases during flow.
6. Unusual casing annulus materials other than fluids or cements.
7. Influence of nearby neighboring wells on temperature distributions.
8. Phase change in the pore space fluid in the soil, such as vaporization or freezing of water.
9. Abnormal undisturbed geothermal gradients.
10. Paraffin or wax build-up in wells.

Many other special needs may be visualized that the thermal simulator can model with some modifications. However, for the sake of simplicity and to promote its widespread use, the simulator input has been realistically minimized at the expense of exotic generalities. Yet, nearly all practical applications can be readily analyzed.

Table II-1

Thermal Properties of Solids

Material	Density, lbm/ft³	Specific Heat Capacity BTU/lbm^oF	Thermal Conductivity BTU/hrft^oF
Cement	104	0.20	0.6
Soil	140	0.30	1.0
Steel	490	0.11	26.2

Table II-2
Input Data For Injection

50 THERMAL SIMULATOR EXAMPLE CASE: INJECTION					
60 CASING CARD	1	3.958	4.500	5000.	5000.
70 CASING CARD	2	8.681	9.625	5000.	2200.
80 CASING CARD	3	12.347	13.375	3000.	2200.
90 CASING CARD	4	19.124	20.000	1000.	1000.
100 CASING CARD	5	29.000	30.000	100.	100.
110 BORE HOLE CARD		5000.	5000.	40.	
120 INITIAL TEMPERATURES		70.	145.	70.	0.
130 PRIMARY FLUID		10.0	15.0	5.0	
140 ANNULAR FLUID		10.0	15.0	5.0	
150 CHANGE CARD	1	70.	10.	10.	
160 CHANGE CARD	1	70.	100.	20.	

Table II-3

Input Data For Production

50	THERMAL SIMULATOR EXAMPLE CASE: PRODUCTION					
60 CASING CARD	1	3.958	4.500	5000.	5000.	
70 CASING CARD	2	8.681	9.625	5000.	2200.	
80 CASING CARD	3	12.347	13.375	3000.	2200.	
90 CASING CARD	4	19.124	20.000	1000.	1000.	
100 CASING CARD	5	29.000	30.000	100.	100.	
110 BORE HOLE CARD		5000.	5000.	40.		
120 INITIAL TEMPERATURES		70.	145.	70.	0.	
130 PRIMARY FLUID		10.0	15.0	5.0		
140 ANNULAR FLUID		10.0	15.0	5.0		
150 CHANGE CARD	2	145.	10.	10.		
160 CHANGE CARD	2	145.	100.	20.		

Table II-4

Input Data For Forward Circulation

50	THERMAL SIMULATOR EXAMPLE CASE: FORWARD CIRCULATION					
60 CASING CARD	1	3.958	4.500	5000.	5000.	
70 CASING CARD	2	8.681	9.625	5000.	2200.	
80 CASING CARD	3	12.347	13.375	3000.	2200.	
90 CASING CARD	4	19.124	20.000	1000.	1000.	
100 CASING CARD	5	29.000	30.000	100.	100.	
110 BORE HOLE CARD		5000.	5000.	40.		
120 INITIAL TEMPERATURES		70.	145.	70.	0.	
130 PRIMARY FLUID		10.0	15.0	5.0		
140 ANNULAR FLUID		10.0	15.0	5.0		
150 CHANGE CARD	3	70.	10.	10.		
160 CHANGE CARD	3	70.	100.	20.		

Table II-5

Input Data For Reverse Circulation

50 THERMAL SIMULATOR EXAMPLE CASE: REVERSE CIRCULATION					
60 CASING CARD	1	3.958	4.500	5000.	5000.
70 CASING CARD	2	8.681	9.625	5000.	2200.
80 CASING CARD	3	12.347	13.375	3000.	2200.
90 CASING CARD	4	19.124	20.000	1000.	1000.
100 CASING CARD	5	29.000	30.000	100.	100.
110 BORE HOLE CARD		5000.	5000.	40.	
120 INITIAL TEMPERATURES		70.	145.	70.	0.
130 PRIMARY FLUID		10.0	15.0	5.0	
140 ANNULAR FLUID		10.0	15.0	5.0	
150 CHANGE CARD	4	70.	10.	10.	
160 CHANGE CARD	4	70.	100.	20.	

Table II-6

Input Data For
Forward Circulation With Secondary Flow

50	THERMAL SIMULATOR EXAMPLE CASE: FORWARD CIRCULATION WITH SECONDARY FLOW					
60 CASING CARD	1	8.958	4.500	5000.	5000.	
70 CASING CARD	2	8.681	9.625	5000.	2200.	
80 CASING CARD	3	12.347	13.375	3000.	2200.	
90 CASING CARD	4	19.124	20.000	1000.	1000.	
100 CASING CARD	5	29.000	30.000	100.	100.	
110 BORE HOLE CARD		5000.	5000.	40.		
120 INITIAL TEMPERATURES		70.	145.	70.	0.	
130 PRIMARY FLUID		10.0	15.0	5.0	1	
131 SECONDARY FLUID		10.0	15.0	5.0	10.0	145.
140 ANNULAR FLUID		10.0	15.0	5.0		
150 CHANGE CARD	3	70.	10.	10.		
160 CHANGE CARD	3	70.	100.	20.		

Table II-7

Input Data For Drilling

50	THERMAL SIMULATOR EXAMPLE CASE: DRILLING					
60 CASING CARD	1	3.958	4.500	5000.	5000.	
70 CASING CARD	2	8.681	9.625	5000.	2200.	
80 CASING CARD	3	12.347	13.375	3000.	2200.	
90 CASING CARD	4	19.124	20.000	1000.	1000.	
100 CASING CARD	5	29.000	30.000	100.	100.	
110 BORE HOLE CARD		0.	5000.	40.		
120 INITIAL TEMPERATURES		70.	145.	70.	0.	
130 PRIMARY FLUID		10.0	15.0	5.0		
140 ANNULAR FLUID		10.0	15.0	5.0		
150 CHANGE CARD	3	70.	100.	10.	2000.	8.0
160 CHANGE CARD	3	70.	100.	20.	5000.	8.0

C

1

1. The first part of the report
describes the general situation
of the country and the
main problems which
are facing it. It also
mentions the main
achievements of the
government in the
last few years.
2. The second part of the
report deals with the
economic situation of the
country. It mentions the
main sectors of the
economy and the
main problems which
are facing them.
3. The third part of the
report deals with the
social situation of the
country. It mentions the
main social problems
which are facing the
country and the
main achievements of
the government in
this field.

C

III Computer Output

This section describes the computer printout for six examples. Results presented correspond to the six cases discussed in section II, computer input. Actual computer printouts are given and the data are plotted on two figures for some cases, temperature versus time and temperature versus depth.

III-1 Injection/Production

Table III-1 contains the computer printout from GEOTEMP for fluid injection into a well. The conditions are those for the input data presented in table II-2. All five strings of pipe are described in the printout after printing the problem title. Injection tubing is $4\frac{1}{2}$ " and casing is $9\frac{5}{8}$ " set at 5000', a $9\frac{5}{8}$ " intermediate casing is set at 3000' and a 20" surface casing is 1000' deep. 30" conductor pipe is driven to a depth of 100'.

Conduction and convection thermal properties are printed for the primary flowing fluid and the annulus fluid. For this example both have the same properties, a 10 lbm/gal density, a plastic viscosity of 15 centipoise, and a yield point of 5 lbf/100 ft². Thermal properties are computed in the simulator from these basic properties as described in section IV-3 of the part I report.

Values set in the CHANGING FLOW PARAMETERS CARDS are listed next. The time at which the variables are set is printed, initially at time zero. Injection is specified with an inlet temperature of 70 F at a rate of 10 gal/min. Also listed is the time at which these variables are to be redefined.

The computed temperature distribution is printed at the end of the first time period for the flow parameters. After ten days of fluid injection the temperatures are displayed. Temperatures are given at six radial positions, the three wellbore temperatures, the first two in the soil, and finally the last radial position with an undisturbed temperature. Figure 3 shows the location of the three temperature nodes in the wellbore, and figure 4 depicts a typical soil grid. These six temperatures are printed at every depth level in 200' increments.

The second column, at a radial position of 0.1 feet, gives the injected fluid temperature as the fluid travels downhole. Fluid enters at 70 F and heats up to 111 F by the time it leaves the well to enter the reservoir at 5000'. As it travels downhole the injected fluid cools the surrounding formation. Figure 5 illustrates the temperature profile from surface to bottom hole in the flowing fluid and in the soil. Three curves are plotted, one is the undisturbed temperature distribution, one gives the injection fluid temperature profile after 10 days with an injection rate of 10 gal/min, and the third curve is the fluid temperature profile at 20 days while injecting at 100 gal/min. Clearly the increased velocity at the higher rate allows less time for the surrounding temperatures to affect the flowing temperature. Bottom hole temperature in the injection fluid is plotted versus time in figure 6. Temperatures change rapidly shortly after flow begins, then approach an equilibrium value. Again the effect of an increased flow rate is clearly illustrated in this figure.

Results from GEOTEMP for a fluid production example are presented in table III-2. These results correspond to the input data presented in table II-3. All conditions are very similar to those for the injection case above, except for the direction of flow. Fluid enters the well at a bottom hole depth of 5000' at a temperature of 145 F. Flow rate begins at 10 gal/min and increases to 100 gal/min after 10 days of production. The second column of table III-2 at a radial position of 0.1 feet gives the production fluid temperature profile. Figure 7 plots the profile at 10 days with a flow rate of 10 gal/min, and at 20 days with a flow rate of 100 gal/min. Also plotted is the undisturbed soil temperatures. The effect of flow rate is evident again as it was for injection. Surface production fluid temperatures are plotted in figure 8. Temperatures quickly build and reach a value of 102 F after 10 days for a flow rate of 10 gal/min, and 138 F after 20 days for 100 gal/min.

III-2 Forward/Reverse Circulation

Results for a forward circulation example are in table III-3. Well completion, depths, and initial temperatures are all unchanged from the injection/production examples. Fluid enters the well at the surface at 70 F and travels down the tubing at temperatures presented in column 2 of the temperature distribution. At a flow rate of 10 gal/min fluid reaches bottom hole at 5000' at 133 F and crosses over to the tubing X casing annulus, column 3 at a radial position of 0.3 ft. Fluid travels up the annulus to reach the surface at 73 F. At 20 days with a flow rate of 100 gal/min the bottom hole circulating temperature is 100 F and the surface return temperature is 74 F. Figure 9 plots the circulating temperature profile

at 20 days. Figure 10 shows the change in bottom hole circulating temperature with time. These figures may be compared to figures 5 and 6 for injection to determine the influence of the returning annulus fluid during circulation.

Table III-4 contains printout for a reverse circulation example. A change in flow direction is the only difference from the forward circulation example. Fluid enters the tubing X casing annulus at 70 F at the surface, travels down the annulus to 5000', and returns to the surface through the tubing. Figure 11 gives the circulating fluid temperature profile at 20 days for a rate of 100 gal/min. For these conditions the bottom hole temperature is 115 F and the surface temperature of the returning fluid in the tubing is 74 F. These results were obtained from the input data of table II-5.

A special application of forward circulation is given in table III-5. Fluid travels down the tubing to 5000' where it is joined by a secondary source of fluid for the return trip to the surface in the tubing X casing annulus. The added fluid accounts for the change in temperature as the circulating fluid crosses from tubing to casing at 5000'. Table II-6 gives the input data for this run and shows a secondary production fluid entering the well at 145 F and 10 gal/min. Figure 12 gives the fluid temperature profiles for a circulating rate of 100 gal/min at 20 days. A bottom hole temperature of 128 F is reached by the circulating fluid, which jumps to 130 F when the secondary fluid joins it in the annulus. The surface return temperature for the 110 gal/min combined fluid is 77 F.

III-3 Drilling

Drilling is modeled as a special application of circulation. The depth of circulation varies with time and each day is divided into a circulating and a shut-in period. Table II-7 contains the input data for a drilling simulation and is discussed in section II of this report. Results from the drilling simulation example are presented in table III-6. The drilling is to proceed from the surface to 2000' in ten days, then from 2000' to 5000' during the next ten days. For each day eight hours is specified as the circulation period and the remaining sixteen hours is the period of shut-in. A drilling rate is computed based on the drilling time, depth, and hours per day of circulation. From the drilling rate the depth of circulation is computed at each time step.

A temperature distribution is printed twice for each day, once at the end of circulation and once after shut-in. The first distribution at the end of the eight hours of circulation shows a drilling depth of 200 ft. Fluid enters at 70.0 F, reaches 70.1 F at 200 ft., and returns to the surface at essentially the same temperature. The next temperature

distribution is printed at one day, after sixteen hours of shut-in. Several printed time steps have been deleted and the temperatures at the end of drilling during the ninth day are given next. A circulation depth of 2000' has been achieved when the well is shut-in, after which the temperatures are printed out at 10 days. Note that at 10 days the drilling rate is increased to get to 5000' after 20 days. Finally, temperature distributions are printed at 19.3 and 20 days when drilling has reached 5000'.

Table III-1

Example Printout For Injection

THERMAL SIMULATOR EXAMPLE CASE: INJECTION

C A S I N G P R O G R A M

CASING	ID, IN	OD, IN	DEPTH, FT	CEMENT INTERVAL, FT
1	3.958	4.500	5000.	5000.
2	8.681	9.625	5000.	2200.
3	12.347	13.375	3000.	2200.
4	19.124	20.000	1000.	1000.
5	29.000	30.000	100.	100.

F L O W I N G F L U I D P R O P E R T I E S

DENSITY = 10.0 LBM/GAL

PLASTIC VISCOSITY = 15. CENTIPOISE

YIELD POINT = 5. LBF/100 FT2

A N N U L A R F L U I D P R O P E R T I E S

DENSITY = 10.0 LBM/GAL

PLASTIC VISCOSITY = 15. CENTIPOISE

YIELD POINT = 5. LBF/100 FT2

Table III-1
(Continued)

SET VARIABLES AT TIME = .000 DAYS
 FLOWING OPTION = INJECTION
 INLET TEMPERATURE = 70. F
 FLOW RATE = 10. GAL/MIN
 TIME TO CHANGE DATA = 10.000 DAYS

TIME = 10.000 DAYS

ITERATIONS = 2

TEMPERATURE DISTRIBUTION

DEPTH, FT	RADIAL POSITIONS, FEET					
	.1	.3	1.7	3.3	5.5	50.0
-0.	70.0	70.0	70.0	70.0	70.0	70.0
200.	70.1	70.8	72.4	72.7	72.9	73.0
400.	70.4	71.8	74.9	75.4	75.8	76.0
600.	70.9	72.9	77.4	78.2	78.7	79.0
800.	71.5	74.1	80.0	81.0	81.6	82.0
1000.	72.3	75.6	82.4	83.7	84.5	85.0
1200.	73.3	77.1	85.0	86.5	87.4	88.0
1400.	74.4	78.7	87.6	89.3	90.3	91.0
1600.	75.6	80.4	90.3	92.1	93.3	94.0
1800.	77.0	82.2	92.9	95.0	96.2	97.0
2000.	78.5	84.0	95.6	97.8	99.1	100.0
2200.	80.0	86.0	98.3	100.7	102.1	103.0
2400.	81.7	88.0	101.1	103.6	105.0	106.0
2600.	83.5	90.1	103.8	106.4	108.0	109.0
2800.	85.3	92.0	106.7	109.4	111.0	112.0
3000.	87.3	94.8	109.1	112.1	113.9	115.0
3200.	89.4	97.1	111.9	115.0	116.8	118.0
3400.	91.5	99.5	114.8	117.9	119.8	121.0
3600.	93.8	101.9	117.6	120.8	122.8	124.0
3800.	96.0	104.4	120.4	123.8	125.7	127.0
4000.	98.4	106.9	123.3	126.7	128.7	130.0
4200.	100.8	109.5	126.2	129.6	131.7	133.0
4400.	103.2	112.1	129.1	132.6	134.7	136.0
4600.	105.7	114.7	132.0	135.5	137.6	139.0
4800.	108.2	117.3	134.9	138.5	140.6	142.0
5000.	110.7	120.0	137.8	141.4	143.6	145.0
5200.	148.0	148.0	148.0	148.0	148.0	148.0
5400.	151.0	151.0	151.0	151.0	151.0	151.0

Table III-1
(Continued)

SET VARIABLES AT TIME = 10.000 DAYS
 FLOWING OPTION = INJECTION
 INLET TEMPERATURE = 70. F
 FLOW RATE = 100. GAL/MIN
 TIME TO CHANGE DATA = 20.000 DAYS

TIME = 20.000 DAYS

ITERATIONS = 3

TEMPERATURE DISTRIBUTION

DEPTH, FT	RADIAL POSITIONS, FEET					
	.1	.3	1.7	3.3	5.5	50.0
-0.	70.0	70.0	70.0	70.0	70.0	70.0
200.	70.0	70.7	72.3	72.6	72.8	73.0
400.	70.0	71.4	74.6	75.2	75.6	76.0
600.	70.1	72.1	76.9	77.8	78.4	79.0
800.	70.2	72.8	79.3	80.5	81.2	82.0
1000.	70.2	73.6	81.6	83.1	84.0	85.0
1200.	70.4	74.4	83.9	85.7	86.9	88.0
1400.	70.5	75.2	86.3	88.3	89.7	91.0
1600.	70.6	76.0	88.6	91.0	92.5	94.0
1800.	70.8	76.8	91.0	93.6	95.4	97.0
2000.	71.0	77.7	93.4	96.3	98.2	100.0
2200.	71.2	78.5	95.7	99.0	101.0	103.0
2400.	71.4	79.4	98.1	101.6	103.9	106.0
2600.	71.7	80.3	100.5	104.3	106.7	109.0
2800.	72.0	81.0	103.1	107.1	109.7	112.0
3000.	72.2	82.7	104.8	109.3	112.3	115.0
3200.	72.6	83.7	107.1	112.0	115.2	118.0
3400.	72.9	84.7	109.5	114.7	118.0	121.0
3600.	73.3	85.7	111.9	117.4	120.9	124.0
3800.	73.7	86.8	114.3	120.1	123.8	127.0
4000.	74.1	87.8	116.8	122.8	126.6	130.0
4200.	74.5	88.9	119.2	125.5	129.5	133.0
4400.	74.9	90.0	121.6	128.2	132.4	136.0
4600.	75.4	91.1	124.0	130.9	135.2	139.0
4800.	75.9	92.2	126.5	133.6	138.1	142.0
5000.	76.4	93.3	128.9	136.3	141.0	145.0
5200.	148.0	148.0	148.0	148.0	148.0	148.0
5400.	151.0	151.0	151.0	151.0	151.0	151.0

Table III-2
Example Printout For Production

THERMAL SIMULATOR EXAMPLE CASE: PRODUCTION

C A S I N G P R O G R A M

CASING	ID, IN	OD, IN	DEPTH, FT	CEMENT INTERVAL, FT
1	3.958	4.500	5000.	5000.
2	8.681	9.625	5000.	2200.
3	12.347	13.375	3000.	2200.
4	19.124	20.000	1000.	1000.
5	29.000	30.000	100.	100.

F L O W I N G F L U I D P R O P E R T I E S

DENSITY = 10.0 LBM/GAL
 PLASTIC VISCOSITY = 15. CENTIPOISE
 YIELD POINT = 5. LBF/100 FT²

A N N U L A R F L U I D P R O P E R T I E S

DENSITY = 10.0 LBM/GAL
 PLASTIC VISCOSITY = 15. CENTIPOISE
 YIELD POINT = 5. LBF/100 FT²

Table III-2
(Continued)

SET VARIABLES AT TIME = .000 DAYS
 FLOWING OPTION = PRODUCTION
 INLET TEMPERATURE = 145. F
 FLOW RATE = 10. GAL/MIN
 TIME TO CHANGE DATA = 10.000 DAYS

TIME = 10.000 DAYS

ITERATIONS = 2

TEMPERATURE DISTRIBUTION

DEPTH, FT	RADIAL POSITIONS, FEET					
	.1	.3	1.7	3.3	5.5	50.0
-0.	102.0	70.0	70.0	70.0	70.0	70.0
200.	107.6	98.7	79.9	76.4	74.3	73.0
400.	110.0	101.3	82.8	79.3	77.3	76.0
600.	112.4	103.8	85.7	82.3	80.3	79.0
800.	114.6	106.6	88.3	85.1	83.2	82.0
1000.	116.9	108.6	91.4	88.2	86.2	85.0
1200.	119.1	111.1	94.3	91.1	89.2	88.0
1400.	121.3	113.5	97.1	94.0	92.2	91.0
1600.	123.4	115.8	99.9	96.9	95.1	94.0
1800.	125.5	118.1	102.8	99.8	98.1	97.0
2000.	127.5	120.4	105.6	102.8	101.1	100.0
2200.	129.4	122.6	108.3	105.6	104.0	103.0
2400.	131.2	124.7	111.1	108.5	107.0	106.0
2600.	133.0	126.8	113.9	111.4	109.9	109.0
2800.	134.6	128.9	116.5	114.2	112.9	112.0
3000.	136.2	130.5	119.5	117.2	115.9	115.0
3200.	137.7	132.4	122.2	120.1	118.8	118.0
3400.	139.1	134.2	124.9	122.9	121.8	121.0
3600.	140.4	136.0	127.5	125.7	124.7	124.0
3800.	141.5	137.6	130.1	128.5	127.6	127.0
4000.	142.5	139.2	132.7	131.3	130.5	130.0
4200.	143.4	140.6	135.2	134.1	133.4	133.0
4400.	144.1	141.9	137.7	136.9	136.3	136.0
4600.	144.6	143.1	140.2	139.6	139.2	139.0
4800.	144.9	144.1	142.6	142.3	142.1	142.0
5000.	145.0	145.0	145.0	145.0	145.0	145.0
5200.	148.0	148.0	148.0	148.0	148.0	148.0
5400.	151.0	151.0	151.0	151.0	151.0	151.0

Table III-2
(Continued)

SET VARIABLES AT TIME = 10.000 DAYS
 FLOWING OPTION = PRODUCTION
 INLET TEMPERATURE = 145. F
 FLOW RATE = 100. GAL/MIN
 TIME TO CHANGE DATA = 20.000 DAYS

TIME = 20.000 DAYS

ITERATIONS = 3

TEMPERATURE DISTRIBUTION

DEPTH, FT	RADIAL POSITIONS, FEET					
	.1	.3	1.7	3.3	5.5	50.0
-0.	138.0	70.0	70.0	70.0	70.0	70.0
200.	139.2	123.4	88.1	81.2	76.8	73.0
400.	139.7	124.5	90.5	83.9	79.6	76.0
600.	140.1	125.5	93.0	86.6	82.5	79.0
800.	140.6	126.9	95.1	89.1	85.3	82.0
1000.	141.0	127.9	97.6	91.9	88.2	85.0
1200.	141.3	128.9	100.0	94.6	91.1	88.0
1400.	141.7	129.9	102.4	97.3	93.9	91.0
1600.	142.1	130.9	104.8	100.0	96.8	94.0
1800.	142.4	131.9	107.3	102.6	99.7	97.0
2000.	142.7	132.8	109.7	105.3	102.5	100.0
2200.	143.0	133.7	112.1	108.0	105.4	103.0
2400.	143.2	134.6	114.5	110.7	108.3	106.0
2600.	143.5	135.5	116.8	113.4	111.1	109.0
2800.	143.7	136.6	119.1	115.9	113.9	112.0
3000.	143.9	136.9	122.0	118.9	116.9	115.0
3200.	144.1	137.8	124.4	121.6	119.7	118.0
3400.	144.3	138.6	126.7	124.2	122.6	121.0
3600.	144.5	139.5	129.0	126.8	125.4	124.0
3800.	144.6	140.3	131.3	129.4	128.2	127.0
4000.	144.7	141.2	133.6	132.1	131.0	130.0
4200.	144.8	142.0	135.9	134.7	133.8	133.0
4400.	144.9	142.7	138.2	137.3	136.6	136.0
4600.	145.0	143.5	140.5	139.9	139.4	139.0
4800.	145.0	144.3	142.7	142.4	142.2	142.0
5000.	145.0	145.0	145.0	145.0	145.0	145.0
5200.	148.0	148.0	148.0	148.0	148.0	148.0
5400.	151.0	151.0	151.0	151.0	151.0	151.0

Table III-3

Example Printout For Forward Circulation

THERMAL SIMULATOR EXAMPLE CASE: FORWARD CIRCULATION

C A S I N G P R O G R A M

CASING	ID, IN	OD, IN	DEPTH, FT	CEMENT INTERVAL, FT
1	3.958	4.500	5000.	5000.
2	8.681	9.625	5000.	2200.
3	12.347	13.375	3000.	2200.
4	19.124	20.000	1000.	1000.
5	29.000	30.000	100.	100.

F L O W I N G F L U I D P R O P E R T I E S

DENSITY = 10.0 LBM/GAL
PLASTIC VISCOSITY = 15. CENTIPOISE
YIELD POINT = 5. LBF/100 FT2

A N N U L A R F L U I D P R O P E R T I E S

DENSITY = 10.0 LBM/GAL
PLASTIC VISCOSITY = 15. CENTIPOISE
YIELD POINT = 5. LBF/100 FT2

Table III-3
(Continued)

SET VARIABLES AT TIME = .000 DAYS
 FLOWING OPTION = FORWARD CIRCULATION
 INLET TEMPERATURE = 70. F
 FLOW RATE = 10. GAL/MIN
 TIME TO CHANGE DATA = 10.000 DAYS

TIME = 10.000 DAYS

ITERATIONS = 1

TEMPERATURE DISTRIBUTION

DEPTH, FT	RADIAL POSITIONS, FEET					
	.1	.3	1.7	3.3	5.5	50.0
-0.	70.0	72.7	70.0	70.0	70.0	70.0
200.	72.1	75.1	73.7	73.3	73.1	73.0
400.	74.4	77.7	76.5	76.3	76.1	76.0
600.	76.9	80.3	79.4	79.2	79.1	79.0
800.	79.5	83.0	82.3	82.1	82.1	82.0
1000.	82.1	85.8	85.3	85.1	85.0	85.0
1200.	84.9	88.6	88.2	88.1	88.0	88.0
1400.	87.7	91.4	91.1	91.1	91.0	91.0
1600.	90.5	94.3	94.1	94.1	94.0	94.0
1800.	93.4	97.3	97.1	97.0	97.0	97.0
2000.	96.3	100.2	100.1	100.0	100.0	100.0
2200.	99.2	103.1	103.0	103.0	103.0	103.0
2400.	102.2	106.1	106.0	106.0	106.0	106.0
2600.	105.1	109.0	109.0	109.0	109.0	109.0
2800.	108.0	111.9	112.0	112.0	112.0	112.0
3000.	111.0	114.8	115.0	115.0	115.0	115.0
3200.	113.9	117.7	117.9	118.0	118.0	118.0
3400.	116.8	120.6	120.9	120.9	121.0	121.0
3600.	119.6	123.3	123.8	123.9	124.0	124.0
3800.	122.4	126.0	126.7	126.8	126.9	127.0
4000.	125.0	128.4	129.5	129.7	129.9	130.0
4200.	127.5	130.6	132.2	132.6	132.9	133.0
4400.	129.8	132.5	134.8	135.4	135.8	136.0
4600.	131.6	133.7	137.2	138.1	138.7	139.0
4800.	132.9	134.2	139.3	140.7	141.5	142.0
5000.	133.4	133.4	140.9	143.0	144.2	145.0
5200.	148.0	148.0	148.0	148.0	148.0	148.0
5400.	151.0	151.0	151.0	151.0	151.0	151.0

Table III-3
(Continued)

SET VARIABLES AT TIME = 10.000 DAYS
 FLOWING OPTION = FORWARD CIRCULATION
 INLET TEMPERATURE = 70. F
 FLOW RATE = 100. GAL/MIN
 TIME TO CHANGE DATA = 20.000 DAYS

TIME = 20.000 DAYS

ITERATIONS = 3

TEMPERATURE DISTRIBUTION

DEPTH, FT	RADIAL POSITIONS, FEET					
	.1	.3	1.7	3.3	5.5	50.0
-0.	70.0	74.0	70.0	70.0	70.0	70.0
200.	72.1	76.1	74.1	73.6	73.3	73.0
400.	74.2	78.2	76.8	76.5	76.2	76.0
600.	76.3	80.3	79.5	79.3	79.2	79.0
800.	78.4	82.4	82.2	82.1	82.1	82.0
1000.	80.5	84.5	84.9	85.0	85.0	85.0
1200.	82.6	86.6	87.6	87.9	88.0	88.0
1400.	84.7	88.7	90.3	90.7	90.9	91.0
1600.	86.8	90.7	93.0	93.6	93.8	94.0
1800.	88.8	92.7	95.7	96.4	96.8	97.0
2000.	90.9	94.6	98.4	99.2	99.7	100.0
2200.	92.9	96.5	101.1	102.1	102.7	103.0
2400.	94.8	98.4	103.8	104.9	105.6	106.0
2600.	96.7	100.2	106.6	107.9	108.6	109.0
2800.	98.5	101.9	109.0	110.6	111.4	112.0
3000.	100.3	103.5	110.7	112.9	114.2	115.0
3200.	102.0	104.9	113.1	115.6	117.1	118.0
3400.	103.5	106.3	115.5	118.3	119.9	121.0
3600.	105.0	107.5	117.8	120.9	122.8	124.0
3800.	106.3	108.5	120.0	123.5	125.6	127.0
4000.	107.4	109.4	122.2	126.1	128.4	130.0
4200.	108.4	110.1	124.2	128.6	131.2	133.0
4400.	109.3	110.5	126.2	131.1	134.0	136.0
4600.	109.9	110.8	128.1	133.4	136.7	139.0
4800.	110.3	110.7	129.8	135.7	139.3	142.0
5000.	110.4	110.4	131.4	137.9	141.9	145.0
5200.	148.0	148.0	148.0	148.0	148.0	148.0
5400.	151.0	151.0	151.0	151.0	151.0	151.0

Table III-4

Example Printout For Reverse Circulation

THERMAL SIMULATOR EXAMPLE CASE: REVERSE CIRCULATION

C A S I N G P R O G R A M

CASING	ID, IN	OD, IN	DEPTH, FT	CEMENT INTERVAL, FT
1	3.958	4.500	5000.	5000.
2	8.681	9.625	5000.	2200.
3	12.347	13.375	3000.	2200.
4	19.124	20.000	1000.	1000.
5	29.000	30.000	100.	100.

F L O W I N G F L U I D P R O P E R T I E S

DENSITY = 10.0 LBM/GAL
PLASTIC VISCOSITY = 15. CENTIPOISE
YIELD POINT = 5. LBF/100 FT²

A N N U L A R F L U I D P R O P E R T I E S

DENSITY = 10.0 LBM/GAL
PLASTIC VISCOSITY = 15. CENTIPOISE
YIELD POINT = 5. LBF/100 FT²

Table III-4
(Continued)

SET VARIABLES AT TIME = .000 DAYS
 FLOWING OPTION = REVERSE CIRCULATION
 INLET TEMPERATURE = 70. F
 FLOW RATE = 10. GAL/MIN
 TIME TO CHANGE DATA = 10.000 DAYS

TIME = 10.000 DAYS

ITERATIONS = 1

TEMPERATURE DISTRIBUTION

DEPTH, FT	RADIAL POSITIONS, FEET					
	.1	.3	1.7	3.3	5.5	50.0
-0.	74.0	70.0	70.0	70.0	70.0	70.0
200.	77.0	73.0	73.0	73.0	73.0	73.0
400.	80.0	76.0	76.0	76.0	76.0	76.0
600.	82.9	78.9	79.0	79.0	79.0	79.0
800.	85.9	81.9	82.0	82.0	82.0	82.0
1000.	88.9	84.9	85.0	85.0	85.0	85.0
1200.	91.9	87.9	88.0	88.0	88.0	88.0
1400.	94.9	90.9	91.0	91.0	91.0	91.0
1600.	97.8	93.9	94.0	94.0	94.0	94.0
1800.	100.8	96.9	97.0	97.0	97.0	97.0
2000.	103.7	99.8	99.9	100.0	100.0	100.0
2200.	106.7	102.8	102.9	103.0	103.0	103.0
2400.	109.6	105.7	105.9	106.0	106.0	106.0
2600.	112.5	108.7	108.9	108.9	109.0	109.0
2800.	115.4	111.6	111.9	111.9	112.0	112.0
3000.	118.2	114.5	114.8	114.9	115.0	115.0
3200.	120.9	117.3	117.8	117.9	118.0	118.0
3400.	123.6	120.1	120.7	120.9	120.9	121.0
3600.	126.2	122.8	123.6	123.8	123.9	124.0
3800.	128.6	125.5	126.5	126.8	126.9	127.0
4000.	130.9	128.0	129.3	129.7	129.9	130.0
4200.	133.0	130.4	132.1	132.6	132.8	133.0
4400.	134.8	132.6	134.8	135.4	135.8	136.0
4600.	136.2	134.6	137.5	138.3	138.7	139.0
4800.	137.2	136.2	140.0	141.0	141.6	142.0
5000.	137.5	137.5	142.4	143.7	144.5	145.0
5200.	148.0	148.0	148.0	148.0	148.0	148.0
5400.	151.0	151.0	151.0	151.0	151.0	151.0

Table III-4
(Continued)

SET VARIABLES AT TIME = 10.000 DAYS
 FLOWING OPTION = REVERSE CIRCULATION
 INLET TEMPERATURE = 70. F
 FLOW RATE = 100. GAL/MIN
 TIME TO CHANGE DATA = 20.000 DAYS

TIME = 20.000 DAYS

ITERATIONS = 3

TEMPERATURE DISTRIBUTION

DEPTH, FT	RADIAL POSITIONS, FEET					
	.1	.3	1.7	3.3	5.5	50.0
-0.	74.3	70.0	70.0	70.0	70.0	70.0
200.	76.6	72.3	72.8	72.9	73.0	73.0
400.	78.8	74.5	75.6	75.8	75.9	76.0
600.	81.1	76.8	78.4	78.7	78.9	79.0
800.	83.3	79.0	81.2	81.6	81.9	82.0
1000.	85.5	81.3	83.9	84.5	84.8	85.0
1200.	87.7	83.5	86.7	87.3	87.7	88.0
1400.	89.9	85.8	89.4	90.2	90.7	91.0
1600.	92.0	88.0	92.2	93.1	93.7	94.0
1800.	94.1	90.1	94.9	96.0	96.6	97.0
2000.	96.1	92.3	97.6	98.8	99.6	100.0
2200.	98.1	94.4	100.3	101.7	102.5	103.0
2400.	100.0	96.4	103.0	104.5	105.4	106.0
2600.	101.8	98.4	105.7	107.4	108.4	109.0
2800.	103.6	100.3	108.4	110.2	111.3	112.0
3000.	105.3	102.2	110.2	112.6	114.1	115.0
3200.	106.9	104.0	112.7	115.4	117.0	118.0
3400.	108.4	105.6	115.2	118.1	119.9	121.0
3600.	109.7	107.2	117.6	120.8	122.7	124.0
3800.	110.9	108.7	120.0	123.5	125.6	127.0
4000.	112.0	110.0	122.4	126.2	128.5	130.0
4200.	112.8	111.3	124.7	128.8	131.3	133.0
4400.	113.6	112.3	126.9	131.4	134.1	136.0
4600.	114.1	113.2	129.1	134.0	136.9	139.0
4800.	114.4	113.9	131.1	136.5	139.7	142.0
5000.	114.5	114.5	133.1	138.9	142.4	145.0
5200.	148.0	148.0	148.0	148.0	148.0	148.0
5400.	151.0	151.0	151.0	151.0	151.0	151.0

Table III-5
Example Printout For
Forward Circulation With Secondary Production

THERMAL SIMULATOR EXAMPLE CASE: FORWARD CIRCULATION WITH SECONDARY FLOW

C A S I N G P R O G R A M

CASING	ID, IN	OD, IN	DEPTH, FT	CEMENT INTERVAL, FT
1	3.958	4.500	5000.	5000.
2	8.681	9.625	5000.	2200.
3	12.347	13.375	3000.	2200.
4	19.124	20.000	1000.	1000.
5	29.000	30.000	100.	100.

F L O W I N G F L U I D P R O P E R T I E S

DENSITY = 10.0 LBM/GAL
PLASTIC VISCOSITY = 15. CENTIPOISE
YIELD POINT = 5. LBF/100 FT2

S E C O N D A R Y F L O W I N G F L U I D P R O P E R T I E S

INLET TEMPERATURE = 145. F
FLOW RATE = 10. GAL/MIN
DENSITY = 10.0 LBM/GAL
PLASTIC VISCOSITY = 15. CENTIPOISE
YIELD POINT = 5. LBF/100 FT2

A N N U L A R F L U I D P R O P E R T I E S

DENSITY = 10.0 LBM/GAL
PLASTIC VISCOSITY = 15. CENTIPOISE
YIELD POINT = 5. LBF/100 FT2

Table III-5
(Continued)

SET VARIABLES AT TIME = .000 DAYS
 FLOWING OPTION = FORWARD CIRCULATION
 INLET TEMPERATURE = 70. F
 FLOW RATE = 10. GAL/MIN
 TIME TO CHANGE DATA = 10.000 DAYS

TIME = 10.000 DAYS

ITERATIONS = 2

TEMPERATURE DISTRIBUTION

DEPTH, FT	RADIAL POSITIONS, FEET					
	.1	.3	1.7	3.3	5.5	50.0
-0.	70.0	84.9	70.0	70.0	70.0	70.0
200.	79.6	90.7	78.8	75.9	74.1	73.0
400.	86.9	95.4	82.3	79.1	77.2	76.0
600.	92.6	99.4	85.6	82.3	80.3	79.0
800.	97.2	102.9	88.4	85.2	83.2	82.0
1000.	101.2	106.1	92.0	88.4	86.3	85.0
1200.	104.6	109.1	95.0	91.4	89.3	88.0
1400.	107.8	111.9	97.9	94.4	92.3	91.0
1600.	110.7	114.6	100.8	97.4	95.3	94.0
1800.	113.5	117.1	103.7	100.3	98.3	97.0
2000.	116.2	119.6	106.5	103.2	101.3	100.0
2200.	118.7	122.1	109.3	106.1	104.2	103.0
2400.	121.2	124.4	112.1	109.0	107.2	106.0
2600.	123.5	126.6	114.9	111.9	110.1	109.0
2800.	125.8	128.8	117.4	114.7	113.0	112.0
3000.	128.0	130.8	120.7	117.8	116.1	115.0
3200.	130.1	132.8	123.3	120.7	119.1	118.0
3400.	132.1	134.8	126.0	123.5	122.0	121.0
3600.	134.1	136.6	128.5	126.3	124.9	124.0
3800.	135.9	138.2	131.1	129.0	127.8	127.0
4000.	137.6	139.7	133.5	131.8	130.7	130.0
4200.	139.1	141.1	135.9	134.5	133.6	133.0
4400.	140.5	142.2	138.2	137.1	136.4	136.0
4600.	141.7	143.1	140.5	139.7	139.3	139.0
4800.	142.7	143.8	142.6	142.3	142.1	142.0
5000.	143.4	144.2	144.7	144.8	144.9	145.0
5200.	148.0	148.0	148.0	148.0	148.0	148.0
5400.	151.0	151.0	151.0	151.0	151.0	151.0

Table III-5
(Continued)

SET VARIABLES AT TIME = 10.000 DAYS
 FLOWING OPTION = FORWARD CIRCULATION
 INLET TEMPERATURE = 70. F
 FLOW RATE = 100. GAL/MIN
 TIME TO CHANGE DATA = 20.000 DAYS

TIME = 20.000 DAYS

ITERATIONS = 1

TEMPERATURE DISTRIBUTION

DEPTH, FT	RADIAL POSITIONS, FEET					
	.1	.3	1.7	3.3	5.5	50.0
-0.	70.0	77.2	70.0	70.0	70.0	70.0
200.	73.7	80.6	76.4	75.2	74.3	73.0
400.	77.3	83.9	79.6	78.4	77.4	76.0
600.	80.7	87.2	82.7	81.5	80.5	79.0
800.	84.1	90.3	85.6	84.4	83.5	82.0
1000.	87.3	93.2	88.7	87.5	86.5	85.0
1200.	90.4	96.1	91.7	90.5	89.5	88.0
1400.	93.4	98.9	94.6	93.5	92.5	91.0
1600.	96.3	101.6	97.5	96.4	95.5	94.0
1800.	99.0	104.1	100.3	99.3	98.4	97.0
2000.	101.7	106.6	103.1	102.2	101.4	100.0
2200.	104.3	108.9	105.9	105.1	104.3	103.0
2400.	106.7	111.2	108.6	107.9	107.2	106.0
2600.	109.1	113.3	111.3	110.7	110.2	109.0
2800.	111.3	115.4	113.9	113.5	113.0	112.0
3000.	113.5	117.3	116.6	116.4	116.0	115.0
3200.	115.5	119.2	119.2	119.1	118.9	118.0
3400.	117.4	120.9	121.6	121.8	121.7	121.0
3600.	119.2	122.5	124.0	124.5	124.6	124.0
3800.	120.9	123.9	126.4	127.1	127.4	127.0
4000.	122.5	125.3	128.7	129.7	130.2	130.0
4200.	124.0	126.5	131.0	132.3	133.0	133.0
4400.	125.3	127.6	133.2	134.8	135.7	136.0
4600.	126.5	128.5	135.3	137.3	138.5	139.0
4800.	127.5	129.3	137.3	139.7	141.2	142.0
5000.	128.4	129.9	139.3	142.1	143.8	145.0
5200.	148.0	148.0	148.0	148.0	148.0	148.0
5400.	151.0	151.0	151.0	151.0	151.0	151.0

Table III-6
Example Printout For Drilling

THERMAL SIMULATOR EXAMPLE CASE: DRILLING

C A S I N G P R O G R A M

CASING	ID, IN	OD, IN	DEPTH, FT	CEMENT INTERVAL, FT
1	3.958	4.500	5000.	5000.
2	8.681	9.625	5000.	2200.
3	12.347	13.375	3000.	2200.
4	19.124	20.000	1000.	1000.
5	29.000	30.000	100.	100.

F L O W I N G F L U I D P R O P E R T I E S

DENSITY = 10.0 LBM/GAL
PLASTIC VISCOSITY = 15. CENTIPOISE
YIELD POINT = 5. LBF/100 FT2

A N N U L A R F L U I D P R O P E R T I E S

DENSITY = 10.0 LBM/GAL
PLASTIC VISCOSITY = 15. CENTIPOISE
YIELD POINT = 5. LBF/100 FT2

S E T V A R I A B L E S A T T I M E = .000 DAYS

FLOWING OPTION = FORWARD CIRCULATION
INLET TEMPERATURE = 70. F
FLOW RATE = 100. GAL/MIN
TIME TO CHANGE DATA = 10.000 DAYS
DEPTH TO CHANGE DATA = 2000. FT
CIRCULATION TIME PER DAY = 8.0 HRS

Table III-6
(Continued)

ITERATIONS = 3

CONDITIONS SINCE LAST TIME STEP:

CIRCULATION DEPTH = 200. FT

TEMPERATURE DISTRIBUTION

DEPTH, FT	RADIAL POSITIONS, FEET					
	.1	.3	1.7	3.3	5.5	50.0
-0.	70.0	70.1	70.0	70.0	70.0	70.0
200.	70.1	70.1	70.3	72.8	73.0	73.0
400.	76.0	76.0	76.0	76.0	76.0	76.0
600.	79.0	79.0	79.0	79.0	79.0	79.0
800.	82.0	82.0	82.0	82.0	82.0	82.0
1000.	85.0	85.0	85.0	85.0	85.0	85.0
1200.	88.0	88.0	88.0	88.0	88.0	88.0
1400.	91.0	91.0	91.0	91.0	91.0	91.0
1600.	94.0	94.0	94.0	94.0	94.0	94.0
1800.	97.0	97.0	97.0	97.0	97.0	97.0
2000.	100.0	100.0	100.0	100.0	100.0	100.0
2200.	103.0	103.0	103.0	103.0	103.0	103.0
2400.	106.0	106.0	106.0	106.0	106.0	106.0
2600.	109.0	109.0	109.0	109.0	109.0	109.0
2800.	112.0	112.0	112.0	112.0	112.0	112.0
3000.	115.0	115.0	115.0	115.0	115.0	115.0
3200.	118.0	118.0	118.0	118.0	118.0	118.0
3400.	121.0	121.0	121.0	121.0	121.0	121.0
3600.	124.0	124.0	124.0	124.0	124.0	124.0
3800.	127.0	127.0	127.0	127.0	127.0	127.0
4000.	130.0	130.0	130.0	130.0	130.0	130.0
4200.	133.0	133.0	133.0	133.0	133.0	133.0
4400.	136.0	136.0	136.0	136.0	136.0	136.0
4600.	139.0	139.0	139.0	139.0	139.0	139.0
4800.	142.0	142.0	142.0	142.0	142.0	142.0
5000.	145.0	145.0	145.0	145.0	145.0	145.0
5200.	148.0	148.0	148.0	148.0	148.0	148.0
5400.	151.0	151.0	151.0	151.0	151.0	151.0

Table III-6
(Continued)

TIME = 1.000 DAYS

ITERATIONS = 4

CONDITIONS SINCE LAST TIME STEP:

FLOW RATE = 0. GAL/MIN

CIRCULATION DEPTH = 200. FT

TEMPERATURE DISTRIBUTION

DEPTH, FT	RADIAL POSITIONS, FEET					
	.1	.3	1.7	3.3	5.5	50.0
-0.	70.0	70.0	70.0	70.0	70.0	70.0
200.	70.7	70.8	70.9	72.6	73.0	73.0
400.	76.0	76.0	76.0	76.0	76.0	76.0
600.	79.0	79.0	79.0	79.0	79.0	79.0
800.	82.0	82.0	82.0	82.0	82.0	82.0
1000.	85.0	85.0	85.0	85.0	85.0	85.0
1200.	88.0	88.0	88.0	88.0	88.0	88.0
1400.	91.0	91.0	91.0	91.0	91.0	91.0
1600.	94.0	94.0	94.0	94.0	94.0	94.0
1800.	97.0	97.0	97.0	97.0	97.0	97.0
2000.	100.0	100.0	100.0	100.0	100.0	100.0
2200.	103.0	103.0	103.0	103.0	103.0	103.0
2400.	106.0	106.0	106.0	106.0	106.0	106.0
2600.	109.0	109.0	109.0	109.0	109.0	109.0
2800.	112.0	112.0	112.0	112.0	112.0	112.0
3000.	115.0	115.0	115.0	115.0	115.0	115.0
3200.	118.0	118.0	118.0	118.0	118.0	118.0
3400.	121.0	121.0	121.0	121.0	121.0	121.0
3600.	124.0	124.0	124.0	124.0	124.0	124.0
3800.	127.0	127.0	127.0	127.0	127.0	127.0
4000.	130.0	130.0	130.0	130.0	130.0	130.0
4200.	133.0	133.0	133.0	133.0	133.0	133.0
4400.	136.0	136.0	136.0	136.0	136.0	136.0
4600.	139.0	139.0	139.0	139.0	139.0	139.0
4800.	142.0	142.0	142.0	142.0	142.0	142.0
5000.	145.0	145.0	145.0	145.0	145.0	145.0
5200.	148.0	148.0	148.0	148.0	148.0	148.0
5400.	151.0	151.0	151.0	151.0	151.0	151.0

Table III-6
(Continued)

TIME = 9.333 DAYS

ITERATIONS = 12

CONDITIONS SINCE LAST TIME STEP:

FLOW RATE = 100. GAL/MIN

CIRCULATION DEPTH = 2000. FT

TEMPERATURE DISTRIBUTION

DEPTH, FT	RADIAL POSITIONS, FEET					
	.1	.3	1.7	3.3	5.5	50.0
-0.	70.0	73.1	70.0	70.0	70.0	70.0
200.	71.6	74.8	73.4	72.9	72.9	73.0
400.	73.3	76.6	75.9	75.7	75.8	76.0
600.	75.0	78.3	78.4	78.4	78.7	79.0
800.	76.7	79.9	80.9	81.2	81.7	82.0
1000.	78.4	81.4	83.0	84.0	84.6	85.0
1200.	79.9	82.7	85.0	86.8	87.6	88.0
1400.	81.3	83.6	87.0	89.7	90.7	91.0
1600.	82.4	84.2	88.9	92.7	93.8	94.0
1800.	83.2	84.4	90.8	96.0	96.9	97.0
2000.	83.6	83.6	92.9	99.6	100.0	100.0
2200.	103.0	103.0	103.0	103.0	103.0	103.0
2400.	106.0	106.0	106.0	106.0	106.0	106.0
2600.	109.0	109.0	109.0	109.0	109.0	109.0
2800.	112.0	112.0	112.0	112.0	112.0	112.0
3000.	115.0	115.0	115.0	115.0	115.0	115.0
3200.	118.0	118.0	118.0	118.0	118.0	118.0
3400.	121.0	121.0	121.0	121.0	121.0	121.0
3600.	124.0	124.0	124.0	124.0	124.0	124.0
3800.	127.0	127.0	127.0	127.0	127.0	127.0
4000.	130.0	130.0	130.0	130.0	130.0	130.0
4200.	133.0	133.0	133.0	133.0	133.0	133.0
4400.	136.0	136.0	136.0	136.0	136.0	136.0
4600.	139.0	139.0	139.0	139.0	139.0	139.0
4800.	142.0	142.0	142.0	142.0	142.0	142.0
5000.	145.0	145.0	145.0	145.0	145.0	145.0
5200.	148.0	148.0	148.0	148.0	148.0	148.0
5400.	151.0	151.0	151.0	151.0	151.0	151.0

Table III-6
(Continued)

TIME = 10.000 DAYS ITERATIONS = 29
CONDITIONS SINCE LAST TIME STEP:
FLOW RATE = 0. GAL/MIN CIRCULATION DEPTH = 2000. FT

TEMPERATURE DISTRIBUTION

DEPTH, FT	RADIAL POSITIONS, FEET					
	.1	.3	1.7	3.3	5.5	50.0
-0.	71.1	71.1	70.0	70.0	70.0	70.0
200.	73.5	73.5	73.1	73.0	72.9	73.0
400.	75.8	75.8	75.7	75.7	75.8	76.0
600.	78.1	78.1	78.4	78.5	78.7	79.0
800.	80.4	80.4	81.0	81.3	81.6	82.0
1000.	83.0	83.0	83.6	84.0	84.6	85.0
1200.	85.5	85.6	86.2	86.8	87.6	88.0
1400.	87.9	88.0	88.8	89.7	90.6	91.0
1600.	90.3	90.4	91.5	92.7	93.7	94.0
1800.	92.7	92.8	94.2	95.9	96.8	97.0
2000.	95.0	95.1	97.1	99.3	99.9	100.0
2200.	103.0	103.0	103.0	103.0	103.0	103.0
2400.	106.0	106.0	106.0	106.0	106.0	106.0
2600.	109.0	109.0	109.0	109.0	109.0	109.0
2800.	112.0	112.0	112.0	112.0	112.0	112.0
3000.	115.0	115.0	115.0	115.0	115.0	115.0
3200.	118.0	118.0	118.0	118.0	118.0	118.0
3400.	121.0	121.0	121.0	121.0	121.0	121.0
3600.	124.0	124.0	124.0	124.0	124.0	124.0
3800.	127.0	127.0	127.0	127.0	127.0	127.0
4000.	130.0	130.0	130.0	130.0	130.0	130.0
4200.	133.0	133.0	133.0	133.0	133.0	133.0
4400.	136.0	136.0	136.0	136.0	136.0	136.0
4600.	139.0	139.0	139.0	139.0	139.0	139.0
4800.	142.0	142.0	142.0	142.0	142.0	142.0
5000.	145.0	145.0	145.0	145.0	145.0	145.0
5200.	148.0	148.0	148.0	148.0	148.0	148.0
5400.	151.0	151.0	151.0	151.0	151.0	151.0

SET VARIABLES AT TIME = 10.000 DAYS
FLOWING OPTION = FORWARD CIRCULATION
INLET TEMPERATURE = 70. F
FLOW RATE = 100. GAL/MIN
TIME TO CHANGE DATA = 20.000 DAYS
DEPTH TO CHANGE DATA = 5000. FT
CIRCULATION TIME PER DAY = 8.0 HRS

Table III-6
(Continued)

TIME = 19.333 DAYS

ITERATIONS = 29

CONDITIONS SINCE LAST TIME STEP:

FLOW RATE = 100. GAL/MIN

CIRCULATION DEPTH = 5000. FT

TEMPERATURE DISTRIBUTION

DEPTH, FT	RADIAL POSITIONS, FEET					
	.1	.3	1.7	3.3	5.5	50.0
-0.	70.0	74.3	70.0	70.0	70.0	70.0
200.	72.3	76.7	73.9	73.3	73.1	73.0
400.	74.6	79.0	76.6	76.1	76.0	76.0
600.	76.9	81.4	79.4	79.0	78.9	79.0
800.	79.3	83.8	82.1	81.8	81.8	82.0
1000.	81.6	86.2	84.9	84.7	84.7	85.0
1200.	84.0	88.6	87.7	87.5	87.6	88.0
1400.	86.4	91.0	90.5	90.4	90.6	91.0
1600.	88.8	93.4	93.3	93.3	93.5	94.0
1800.	91.2	95.7	96.2	96.3	96.5	97.0
2000.	93.6	98.1	99.0	99.2	99.5	100.0
2200.	96.0	100.4	101.9	102.2	102.6	103.0
2400.	98.3	102.6	104.6	105.0	105.5	106.0
2600.	100.6	104.8	107.4	108.0	108.5	109.0
2800.	102.8	106.9	110.3	111.0	111.6	112.0
3000.	105.0	108.9	112.8	113.7	114.4	115.0
3200.	107.1	110.8	115.4	116.6	117.4	118.0
3400.	109.0	112.6	118.1	119.7	120.5	121.0
3600.	110.9	114.2	120.7	122.4	123.5	124.0
3800.	112.6	115.6	123.4	125.5	126.6	127.0
4000.	114.2	116.8	126.1	128.7	129.7	130.0
4200.	115.6	117.8	128.5	131.4	132.6	133.0
4400.	116.7	118.5	131.1	134.7	135.8	136.0
4600.	117.6	118.9	133.9	138.1	138.9	139.0
4800.	118.2	119.0	136.0	140.9	141.9	142.0
5000.	118.6	118.6	139.5	144.7	145.0	145.0
5200.	148.0	148.0	148.0	148.0	148.0	148.0
5400.	151.0	151.0	151.0	151.0	151.0	151.0

Table III-6
(Continued)

ITERATIONS = 45

ITERATIONS = 45

CIRCULATION DEPTH = 5000. FT

TEMPERATURE DISTRIBUTION

DEPTH, FT	RADIAL POSITIONS, FEET					
	.1	.3	1.7	3.3	5.5	50.0
-0.	71.6	71.6	70.0	70.0	70.0	70.0
200.	74.5	74.5	73.6	73.3	73.1	73.0
400.	77.1	77.1	76.3	76.1	76.0	76.0
600.	79.7	79.7	79.1	79.0	78.9	79.0
800.	82.4	82.4	81.9	81.8	81.8	82.0
1000.	85.0	85.0	84.7	84.7	84.7	85.0
1200.	87.6	87.6	87.6	87.6	87.6	88.0
1400.	90.3	90.3	90.4	90.5	90.6	91.0
1600.	93.0	93.0	93.3	93.4	93.6	94.0
1800.	95.7	95.7	96.2	96.3	96.5	97.0
2000.	98.3	98.4	99.1	99.3	99.5	100.0
2200.	101.0	101.0	102.0	102.2	102.6	103.0
2400.	103.6	103.6	104.8	105.1	105.5	106.0
2600.	106.2	106.3	107.7	108.0	108.5	109.0
2800.	108.8	108.8	110.6	111.1	111.6	112.0
3000.	111.4	111.4	113.2	113.8	114.4	115.0
3200.	114.1	114.1	116.0	116.7	117.4	118.0
3400.	116.7	116.7	118.9	119.7	120.5	121.0
3600.	119.0	119.0	121.6	122.5	123.4	124.0
3800.	121.4	121.5	124.5	125.5	126.5	127.0
4000.	123.8	123.9	127.4	128.7	129.6	130.0
4200.	125.9	126.0	130.0	131.4	132.6	133.0
4400.	128.2	128.3	133.0	134.6	135.7	136.0
4600.	130.4	130.5	136.0	138.0	138.8	139.0
4800.	132.2	132.3	138.6	140.8	141.8	142.0
5000.	134.3	134.4	141.8	144.3	144.9	145.0
5200.	148.0	148.0	148.0	148.0	148.0	148.0
5400.	151.0	151.0	151.0	151.0	151.0	151.0

IV Description of Subprograms

This section provides a brief description of the operation and purpose of each subroutine and function in GEOTEMP. For details of the calculations the reader is referred to the part I report that describes the thermal simulator development.

IV-1 MAIN

All calculations are executed and organized from MAIN. Actual computations are performed in other subprograms called from MAIN. Subroutines are called to read the input data, define material properties and generate the mathematical grid. An initial temperature distribution is established from input data. Next a loop is entered for reading CHANGING FLOW PARAMETERS CARDS at specified times, after which well-bore conductances and equation coefficients are computed by calling subroutines. An inner loop is entered for incrementing time then solving for temperatures at the new time step. Finally, a check is made for printing results, followed by a check for ending the loop on time or reading a new CHANGING FLOW PARAMETERS CARD.

IV-2 READ

Input data is read into GEOTEMP through this subroutine. The data is described in detail in section II of this report. As the data is read it is written on file 6 to describe the conditions of a simulation. All the data described in section II are read in this subroutine in the order presented except the CHANGING FLOW PARAMETERS CARDS, which are read in MAIN.

IV-3 PROP

Thermal properties that are defined within GEOTEMP appear in PROP. Density, specific heat capacity, and thermal conductivity are set for the soil, cement, and steel. Soil properties are fixed as a constant, but are stored in a one dimensional array to allow for variations in layers when that data is available. For the primary, secondary, and annular fluids the specific heat capacity and thermal conductivity are computed based on the fluid density. The specifics of these correlations appear in section IV-3 and IV-4 of the part I report describing the details of the calculations.

IV-4 GRID

GRID generates the location of the mathematical nodes and cells used to establish the energy balance equations. Radial positions are selected from the number of radial nodes and a maximum radius specified, presently 50'. An exponential distribution concentrates temperature nodes near the well where a high gradient may occur. Cross sectional areas are computed for vertical heat conduction calculations. Finally, the vertical distribution of nodes is set with a constant increment, presently chosen as 200'.

IV-5 COND

This subroutine computes thermal conductances in the radial direction between adjacent nodes. First, a set of thermal resistances are computed based on well geometry and material properties. The appropriate resistances are summed at each depth to obtain a resistance between nodes. Surface convection resistances are added in for flowing streams and natural convection. Next, the total resistances are converted to an overall thermal conductance between nodes in the wellbore. Cells splitting an interval are averaged. Finally, a similar but less complex formulation is performed for the soil nodes. For details see sections IV-1 of the part I report.

IV-6 COEF

This subroutine establishes the coefficients of the system of algebraic equations resulting from an energy balance, see sections III,V, and IX-3 of the part I report for details. Coefficients are computed for flowing conditions and shut-in for the first three radial positions comprising the wellbore. And coefficients are established for the remainder of the cells located in the soil.

IV-7 WELL

Temperature computations are performed in WELL. The iteration scheme described in sections III-4 and V-4 is applied to each node in the mathematical grid. Wellbore temperatures are computed first by traveling up or down the grid in the direction of flow. Soil temperatures are computed subsequently, and the new values are checked for convergence.

IV-8 VISC

This function subprogram determines the effective viscosity of fluids in the well. A power law fluid model is applied as described in section IX-5 of the part I report. Either forced or free convection are considered to establish

the shear strain rate and the shear stress, from which an effective viscosity is computed. Finally, the sensitivity of water viscosity to temperature is used to account for a change in viscosity from the properties specified at 70 F.

IV-9 CA

CA is a function subprogram that locates the vertical interface between cement and casing fluids in annular spaces. It sets the thermal conductivity depending on the depth being above or below the interface, or an average in the cell containing the interface.

IV-10 CONVN

CONVN is a function that computes the overall thermal conductivity across a naturally convecting annular space. The effective conductivity is based on correlations supplied in section IV-2 of the part I report.

IV-11 CONV

This function performs a calculation of the surface convection coefficient in a pipe or an annular region. Only forced convection is considered in this function. Two correlations are used, one for high and one for low Prandtl Number fluids, see section IV-2 of the part I report.

IV-12 CONAN

This subroutine establishes the effective thermal conductivity of each of the annular regions in a well. The conductivity is based on the calculations in CONVN.

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V Figures

Figure 1

COMPUTER MODEL OF WELLBORE COMPLETION FOR PRODUCTION AND INJECTION

Figure 2

Initial and Boundary Temperature Profiles

Figure 3

MATHEMATICAL CELLS IN WELLBORE

Figure 4

MATHEMATICAL GRID FOR SOIL NODES

WELLBORE

GROUND LEVEL

FIXED TEMPERATURES

Figure 5
Flowing Stream Temperature Profiles
For Injection

Figure 6
Bottom Hole Temperature versus Time
For Injection

Figure 7
Flowing Stream Temperature Profiles
For Production

Figure 8
Surface Temperature versus Time
For Production

Figure 9
Flowing Stream Temperature Profiles
For Forward Circulation

Figure 10
Bottom Hole Temperature versus Time
For Forward Circulation

Figure 11
Flowing Stream Temperature Profiles
For Reverse Circulation

Figure 12

Flowing Stream Temperature Profiles
For Forward Circulation with Secondary Flow

VI GEOTEMP
Code Listing

C

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30 C
40 C THIS PROGRAM COMPUTES THE TEMPERATURES IN AND SURROUNDING A WELL.
50 C   CONSTRUCTED UNDER A CONTRACT WITH DOE THROUGH SANDIA FOR
60 C   APPLICATION TO GEOTHERMAL WELL COMPLETIONS.
70 C   JUNE 1978 TO JUNE 1979
80 C
90     COMMON /BLK1/ TW(101,20),TWJ(101,21)
100    COMMON /BLK3/ KDR,NZ,NZP1,DEPTH,TD,Z(101),ZC(5),DZ(5)
110    COMMON /BLK8/ NR,RMAX,R(21),DR(21),AR(20),RI(5),RO(5)
120    COMMON /BLK4/ U(101,20),Q(101,2)
130    COMMON /BLK6/ IFLOW,PI,DT,TIN1,TIN2,FR1,FR2,FR3,NIT
140    COMMON /BLK11/ VFR,DENF,PVF,YPF,SHF,CONF
150    COMMON /BLK14/ TSUR,BHT,TDEPTH,DEPTHT
160    DATA PI/3.1415927/
170    DATA TIME/0.,DTMAX/24./
180 C
190 C READ IN VARIABLES
200 C
210     CALL READ
220 C
230 C MATERIAL PROPERTIES
240 C
250     CALL PROP
260 C
270 C DEFINE GRID
280 C
290     CALL GRID
300 C
310 C INITIALIZE TEMPERATURES
320 C
330     NR1 = NR + 1
340     DO 28 K=1,NZP1
350       IF (Z(K) .GT. (DEPTHT + 1.) .AND. ABS(DEPTHT - TD) .GT. 1.)
360         & GO TO 30
370       TT = TSUR + Z(K)*(TDEPTH - TSUR)/DEPTH
380       GO TO 32
390     30 TT = TDEPTH + (Z(K) - DEPTHT)*(BHT - TDEPTH)/(TD - DEPTHT)
400     32 DO 28 I=1,NR1
410       TWJ(K,I) = TT
420     28 TW(K,I) = TT

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430 C
440 C READ AND WRITE NEW FLOWING DATA
450 C
460 C IFLOW = FLOWING STREAM OPTION
470 C 1 = INJECTION
480 C 2 = PRODUCTION
490 C 3 = FORWARD CIRCULATION
500 C 4 = REVERSE CIRCULATION
510 C TIN = INLET TEMPERATURE OF FLOWING FLUID, F
520 C VFR = VOLUME FLOW RATE OF FLUID, GPM
530 C
540 6 READ (5,202) IFLOW,TIN1,VFR,DAYCH,DDCHG,HRC
550 202 FORMAT (20X,I5,5F10.0)
560 TCHG = DAYCH*24.
570 WRITE (6,104) DAYS
580 104 FORMAT (//2X,'S E T V A R I A B L E S AT TIME =',
590 & F10.3,' DAYS')
600 IF (IFLOW.EQ. 1) WRITE (6,108)
610 IF (IFLOW.EQ. 2) WRITE (6,110)
620 IF (IFLOW.EQ. 3) WRITE (6,112)
630 IF (IFLOW.EQ. 4) WRITE (6,114)
640 108 FORMAT (10X,'FLOWING OPTION = INJECTION')
650 110 FORMAT (10X,'FLOWING OPTION = PRODUCTION')
660 112 FORMAT (10X,'FLOWING OPTION = FORWARD CIRCULATION')
670 114 FORMAT (10X,'FLOWING OPTION = REVERSE CIRCULATION')
680 IF (IFLOW.LT. 1 .OR. IFLOW.GT. 4) WRITE (6,115)
690 115 FORMAT (//10X,'FLOWING OPTION INCORRECTLY DEFINED'//)
700 WRITE (6,116) TIN1,VFR,DAYCH
710 116 FORMAT (10X,'INLET TEMPERATURE =',F6.0,' F'//
720 & 10X,'FLOW RATE =',F6.0,' GAL/MIN'//
730 & 10X,'TIME TO CHANGE DATA =',F10.3,' DAYS')
740 IF (DDCHG.GT. 0.1) WRITE (6,206) DDCHG,HRC
750 206 FORMAT (10X,'DEPTH TO CHANGE DATA =',F6.0,' FT'//
760 & 10X,'CIRCULATION TIME PER DAY =',F6.1,' HRS'//)
770 C
780 C CONVERT UNITS ON FLOW RATE, GAL/MIN TO FT3/HR
790 C 60 MIN/HR AND 7.4805 GAL/FT3
800 C
810 VFR = VFR*60./7.4805
820 IF (HRC.GT. 0.) DRT = 24.*(DDCHG - DEPTH)/(TCHG - TIME)*HRC
830 VFRC = VFR
840 C
850 C FORM WELLBORE CONDUCTANCES
860 C
870 DELT = 0.01
880 DT = DELT*DTMAX
890 CALL COND

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900 C
910 C FORM COEFFICIENTS
920 C
930     IF (DDCHG .LT. 0.1) GO TO 22
940     DT = 1.0
950     IF (HRC .LT. 1.0) DT = HRC
960     CALL COEF
970     DT = 0.
980     VFR = 0.
990     GO TO 4
1000    22 CALL COEF
1010 C
1020 C INCREMENT TIME
1030 C
1040     4 CONTINUE
1050     DTD = DT
1060     IF (DDCHG .LT. 0.1) GO TO 8
1070     IF (VFR .GT. 0.01) GO TO 10
1080     IF (ABS(DT - 1.0) .GT. 0.001) GO TO 24
1090 C SHUT-IN 2ND PART
1100     DT = 24. - HRC - 1.
1110     GO TO 12
1120 C FLOWING 1ST PART
1130     24 VFR = VFR0
1140     DT = 1.0
1150     IF (HRC .LT. 1.0) DT = HRC
1160     GO TO 12
1170     10 IF (ABS(DT - 1.0) .GT. 0.001) GO TO 16
1180 C FLOWING 2ND PART
1190     DT = HRC - 1.0
1200     IF (ABS(DT - 1.0) .LT. 0.001) DT = 0.99
1210     GO TO 12
1220 C SHUT-IN 1ST PART
1230     16 VFR = 0.
1240     DT = 1.0
1250     IF (HRC .GT. 22.9) DT = 24. - HRC
1260     GO TO 12
1270     8 DT = DELT*DTMAX
1280     12 TIME = TIME + DT
1290     IF (TIME .GT. TCHG) DT = TCHG - TIME + DT
1300     IF (TIME .GT. TCHG) TIME = TCHG
1310     DAYS = TIME/24.
1320     DELT = 5.*DELT
1330     IF (DELT .GT. 1.) DELT = 1.
1340     IF (DDCHG .LT. 0.1) GO TO 14
1350     DRLRT = DRT
1360     IF (VFR .LT. 0.1) DRLRT = 0.
1370     DEPTH = DEPTH + DT*DRLRT
1380     KDRO = KDR
1390     DO 18 K=2,NZ
1400     18 IF (DEPTH .LT. (Z(K) + Z(K+1))/2.) GO TO 20
1410     20 KDR = K
1420     IF (KDR .NE. KDRO) CALL COND

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1430 C
1440 C COMPUTE WELLBORE TEMPERATURES
1450 C
1460 14 IF (ABS(DT0 - DT) .GT. 1.E-3) CALL COEF
1470 CALL WELL
1480 IF (TIME .LT. (TCHG-1.E-3) .AND. DDCHG .LT. 0.1) GO TO 4
1490 IF (ABS(DT-1.0) .LT. 0.001) GO TO 4
1500 C
1510 C PRINT OPTION
1520 C
1530 GPM = VFR*7.4805/60.
1540 WRITE (6,101) DAYS,NIT
1550 101 FORMAT (///1X,'TIME =',F10.3,' DAYS',30X,'ITERATIONS =',I3)
1560 IF (DDCHG .GT. 0.1) WRITE (6,122) GPM,DEPTH
1570 122 FORMAT (1X,'CONDITIONS SINCE LAST TIME STEP:/'
1580 & 5X,'FLOW RATE =',F5.0,' GAL/MIN',
1590 & 5X,'CIRCULATION DEPTH =',F6.0,' FT')
1600 WRITE (6,118) (R(I),I=1,5),R(NR1)
1610 118 FORMAT (/17X,'T E M P E R A T U R E ',
1620 & 'D I S T R I B U T I O N'//30X,'RADIAL POSITIONS, FEET'//
1630 & 4X,'DEPTH, FT',1X,5F9.1,4X,F9.1)
1640 WRITE (6,106) (Z(K),(TWJ(K,I),I=1,5),TWJ(K,NR1),K=1,NZP1)
1650 106 FORMAT (3X,F8.0,3X,5F9.1,4X,F9.1)
1660 IF (ABS((TIME - TCHG)/TIME) .LT. 0.001) GO TO 6
1670 GO TO 4
1680 END

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1700      SUBROUTINE READ
1710 C
1720 C   THIS SUBROUTINE READS THE PROBLEM PARAMETERS
1730 C
1740      COMMON /BLK3/ KDR,NZ,NZP1,DEPTH,TD,Z(101),ZC(5),DZ(5)
1750      COMMON /BLK8/ NR,RMAX,R(21),DR(21),AR(20),RI(5),RO(5)
1760      COMMON /BLK6/ IFLOW,PI,DT,TIN1,TIN2,FR1,FR2,FR3,NIT
1770      COMMON /BLK11/ VFR,DENF,PVF,YPF,SHF,CONF
1780      COMMON /BLK12/ VFR2,DENF2,PVF2,YPF2,SHF2,CONF2
1790      COMMON /BLK13/ DENAF,PVAF,YPAF,SHAF,CONAF
1800      COMMON /BLK14/ TSUR,BHT,TDEPTH,DEPTHT
1810      DIMENSION TITLE(20)
1820 C
1830 C   READ AND WRITE PROBLEM TITLE
1840 C
1850      READ (5,212) TITLE
1860      212 FORMAT (20A4)
1870      WRITE (6,124) TITLE
1880      124 FORMAT ('1'///20A4//)
1890 C
1900 C   READ CASING PARAMETERS
1910 C      RI(J) = ID OF CASING, IN
1920 C      RO(J) = OD OF CASING, IN
1930 C      ZC(J) = SETTING DEPTH OF CASING, FT
1940 C      DZ(J) = CEMENT INTERVAL LENGTH ON CASING J, FT
1950 C
1960      READ (5,202) (J,RI(J),RO(J),ZC(J),DZ(J),I=1,5)
1970      202 FORMAT (20X,I5,4F10.0)
1980      WRITE (6,102)
1990      102 FORMAT (///1X,'C A S I N G   P R O G R A M'//
2000      & 8X,'CASING',6X,'ID, IN',4X,'OD, IN',
2010      & 6X,'DEPTH, FT',2X,'CEMENT INTERVAL, FT')
2020      WRITE (6,104) (J,RI(J),RO(J),ZC(J),DZ(J),J=1,5)
2030      104 FORMAT (1X,I10,5X,2F10.3,2X,F10.0,7X,F10.0)
2040 C
2050 C   READ INITIAL AND FINAL DEPTH, FT AND BOREHOLE DIAMETER, IN
2060 C
2070      READ (5,210) DEPTH,TD,R(3)
2080      210 FORMAT (20X,3F10.0)
2090 C
2100 C   READ INITIAL TEMPERATURES
2110 C
2120      READ (5,214) TSUR,BHT,TDEPTH,DEPTHT
2130      214 FORMAT (20X,4F10.0)
2140 C
2150 C   READ PRIMARY FLOWING FLUID PROPERTIES
2160 C      DENF = DENSITY OF FLUID, LB/GAL
2170 C      PVF = PLASTIC VISCOSITY OF PRIMARY FLOWING FLUID, CENTIPOISE
2180 C      YPF = YIELD POINT OF PRIMARY FLOWING FLUID, LBF/100 FT2
2190 C      TIN2 = INLET TEMPERATURE OF SECONDARY FLUID PRODUCTION, F
2200 C      VFR2 = VOLUME FLOW RATE OF SECONDARY FLUID, GPM
2210 C      DENF2 = DENSITY OF SECONDARY FLUID, LB/GAL
2220 C      PVF2 = PLASTIC VISCOSITY OF SECONDARY FLOWING FLUID, CENTIPOISE
2230 C      YPF2 = YIELD POINT OF SECONDARY FLOWING FLUID, LBF/100 FT2

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2240 C      ISEC DENOTES THE EXISTENCE OF SECONDARY FLOW
2250 C      ISEC = 0  NO FLOW
2260 C      ISEC = 1  SECONDARY PRODUCTION DURING CIRCULATION
2270 C
2280      READ (5,204) DENF,PVF,YPF,ISEC
2290      204 FORMAT (20X,3F10.0,I5)
2300      WRITE (6,107)
2310      107 FORMAT (///1X,'F L O W I N G   F L U I D   P R O P E R T I E S')
2320      WRITE (6,116) DENF,PVF,YPF
2330      116 FORMAT (10X,'DENSITY =',F6.1,' LBM/GAL'//
2340      & 10X,'PLASTIC VISCOSITY =',F5.0,' CENTIPOISE'//
2350      & 10X,'YIELD POINT =',F4.0,' LBF/100 FT2'//
2360      IF (DENF .LT. 8.32 .OR. DENF .GT. 21.) WRITE (6,106) DENF
2370      106 FORMAT (/1X,10('♦'),2X,'CAUTION FLUID DENSITY =',
2380      & F6.1,' LBM/GAL',2X,10('♦')//
2390      IF (ISEC .EQ. 0) GO TO 4
2400      READ (5,208) DENF2,PVF2,YPF2,VFR2,TIN2
2410      208 FORMAT (20X,5F10.0)
2420      WRITE (6,120)
2430      120 FORMAT (//1X,'S E C O N D A R Y   F L O W I N G   ',
2440      & 'F L U I D   P R O P E R T I E S')
2450      WRITE (6,118) TIN2,VFR2
2460      118 FORMAT (10X,'INLET TEMPERATURE =',F6.0,' F'//
2470      & 10X,'FLOW RATE =',F6.0,' GAL/MIN')
2480      WRITE (6,116) DENF2,PVF2,YPF2
2490      IF (DENF2 .LT. 8.32 .OR. DENF2 .GT. 21.) WRITE (6,106) DENF2
2500 C
2510 C      CONVERT UNITS ON FLOW RATE, GAL/MIN TO FT3/HR
2520 C      60 MIN/HR AND 7.4805 GAL/FT3
2530 C
2540      4 VFR = VFR*60./7.4805
2550      VFR2 = VFR2*60./7.4805
2560 C
2570 C      ANNULAR FLUID PROPERTIES
2580 C
2590      READ (5,218) DENAF,PVAF,YPAF
2600      218 FORMAT (20X,3F10.0)
2610      WRITE (6,122) DENAF,PVAF,YPAF
2620      122 FORMAT (//1X,'A N N U L A R   F L U I D   P R O P E R T I E S'//
2630      & 10X,'DENSITY =',F6.1,' LBM/GAL'//
2640      & 10X,'PLASTIC VISCOSITY =',F5.0,' CENTIPOISE'//
2650      & 10X,'YIELD POINT =',F4.0,' LBF/100 FT2'//
2660      RETURN
2670      END

```



```

2690      SUBROUTINE PROP
2700 C
2710 C      THIS SUBROUTINE DEFINES PROPERTIES OF THE FOLLOWING MATERIALS:
2720 C      STEEL, CEMENT, PRIMARY FLOWING FLUID, SECONDARY FLOWING FLUID,
2730 C      ANNULUS FLUID, SOIL.
2740 C
2750      COMMON /BLK9/  DENS(100),SHS(100),CONS(100)
2760      COMMON /BLK10/ DENST,SHST,CONST,DENC,SHC,CONC
2770      COMMON /BLK11/ VFR,DENF,PVF,YPF,SHF,CONF
2780      COMMON /BLK12/ VFR2,DENF2,PVF2,YPF2,SHF2,CONF2
2790      COMMON /BLK13/ DENAF,PVAF,YPAF,SHAF,CONAF
2800 C
2810 C      SOIL PROPERTIES
2820 C
2830 C      DENS = DENSITY OF SOIL, LBM/FT3
2840 C      SHS = SPECIFIC HEAT CAPACITY OF SOIL, BTU/LBM-F
2850 C      CONS = THERMAL CONDUCTIVITY OF SOIL, BTU/HR-FT-F
2860 C
2870      DATA DENS/100*140./,SHS/100*0.30/,CONS/100*2.0/
2880 C
2890 C      STEEL AND CEMENT PROPERTIES
2900 C
2910 C      DENST = DENSITY OF STEEL, LBM/FT3
2920 C      SHST = SPECIFIC HEAT CAPACITY OF STEEL, BTU/LBM-F
2930 C      CONST = THERMAL CONDUCTIVITY OF STEEL, BTU/HR-FT-F
2940 C      DENC = DENSITY OF CEMENT, LBM/FT3
2950 C      SHC = SPECIFIC HEAT CAPACITY OF CEMENT, BTU/LBM-F
2960 C      CONC = THERMAL CONDUCTIVITY OF CEMENT, BTU/HR-FT-F
2970 C
2980      DATA DENST/490./,SHST/0.11/,CONST/26.2/
2990      DATA DENC/104./,SHC/0.20/CONC/0.50/
3000 C
3010 C      FLUID PROPERTIES
3020 C
3030 C      DENF = DENSITY OF PRIMARY FLOWING FLUID, LBM/GAL TO LBM/FT3
3040 C      SHF = SPECIFIC HEAT CAPACITY OF PRIMARY FLOWING FLUID, BTU/LBM-F
3050 C      CONF = THERMAL CONDUCTIVITY OF PRIMARY FLOWING FLUID, BTU/HR-FT-F
3060 C      THE F2 AND AF SUFFIXES DENOTE THE SECONDARY FLOWING FLUID AND
3070 C      ANNULAR FLUID RESPECTIVELY.
3080 C
3090 C      PRIMARY FLOWING FLUID
3100 C
3110      IF (DENF .GT. 8.32) GO TO 2
3120      WRITE (6,102) DENF
3130 102 FORMAT (/2X,10('♦')/5X,'PRIMARY FLUID FLUID DENSITY =',
3140      & F8.3,' LBM/GAL'/9X,'COMPARED TO 8.33 FOR WATER'/2X,10('♦')/)
3150      STOP
3160      2 IF (DENF .GT. 10.3) GO TO 4
3170      SF = 0.0798*(DENF - 8.33)
3180      GO TO 6
3190      4 SF = 0.0318*(DENF - 10.3) + 0.162
3200      6 DENF = DENF*7.4805
3210      SHF = 1. - 0.777*SF
3220      CONF = 0.399 + 9.6*SF

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3230 C
3240 C SECONDARY FLOWING FLUID
3250 C
3260     IF (VFR2 .LT. 0.1) GO TO 13
3270     IF (DENF2 .GT. 10.3) GO TO 10
3280     SF = 0.0798*(DENF2 - 8.33)
3290     GO TO 12
3300     10 SF = 0.0318*(DENF2 - 10.3) + 0.162
3310     12 DENF2 = DENF2*7.4805
3320     SHF2 = 1. - 0.777*SF
3330     CONF2 = 0.399 + 9.6*SF
3340 C
3350 C ANNULAR FLUID
3360 C
3370     13 IF (DENAF .GT. 8.32) GO TO 14
3380     WRITE (6,106) DENAF
3390     106 FORMAT (/2X,10('♦')/5X,'ANNULAR FLUID DENSITY =',
3400     & F8.3,' LBM/GAL'/5X,'COMPARED TO 8.33 FOR WATER'/2X,10('♦')/)
3410     STOP
3420     14 IF (DENAF .GT. 10.3) GO TO 16
3430     SF = 0.0798*(DENAF - 8.33)
3440     GO TO 18
3450     16 SF = 0.0318*(DENAF - 10.3) + 0.162
3460     18 DENAF = DENAF*7.4805
3470     SHAF = 1. - 0.777*SF
3480     CONAF = 0.399 + 9.6*SF
3490     RETURN
3500     END

```

```

3520      SUBROUTINE GRID
3530 C
3540 C THIS SUBROUTINE FORMS THE R-Z GRID.
3550 C
3560      COMMON /BLK3/ KDR,NZ,NZP1,DEPTH,TD,Z(101),ZC(5),DZ(5)
3570      COMMON /BLK6/ IFLOW,PI,DT,TIN1,TIN2,FR1,FR2,FR3,NIT
3580      COMMON /BLK8/ NR,RMAX,R(21),DR(21),AR(20),RI(5),RD(5)
3590      DATA NR/10/,RMAX/50.0/,DDEPTH/200./
3600 C
3610 C DEFINE WELLBORE RADII AND CONVERT TO INCHES
3620 C
3630      DO 2 I=1,5
3640      RI(I) = RI(I)/24.
3650      2 RD(I) = RD(I)/24.
3660 C
3670 C SOIL RADII
3680 C
3690      R(1) = RI(1)/2.
3700      R(2) = (RI(2) + RD(1))/2.
3710      R(3) = R(3)/24.
3720      DR(3) = R(3) - R(2)
3730      CR = 0.1
3740      DCR = 1.0
3750      NR1 = NR + 1
3760      NIT = 0
3770      6 CR = CR + DCR
3780      NIT = NIT + 1
3790      DO 8 I=4,NR1
3800      8 DR(I) = DR(I-1)*CR
3810      DO 10 I=4,NR1
3820      10 R(I) = R(I-1) + (DR(I) + DR(I-1))/2.
3830      IF (RMAX .GT. R(NR1)) GO TO 6
3840      CR = CR - DCR
3850      DCR = DCR/10.
3860      IF (ABS(R(NR1) - RMAX)/RMAX .LT. 1.E-3) GO TO 12
3870      IF (NIT .LT. 50) GO TO 6
3880      WRITE (6,102)
3890      102 FORMAT (/2X,10('♦'),2X,'RADIAL COORDINATES NOT CONVERGED',2X,
3900      & 10('♦')/)
3910      12 CONTINUE

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3920 C
3930 C  COMPUTE AREAS
3940 C
3950     DO 14 I=1,NR
3960     R1 = (R(I) + R(I+1))/2.
3970     RR = 0.
3980     IF (I .GT. 1) RR = R(I-1)
3990     R2 = (RR + R(I))/2.
4000     14 AR(I) = PI*(R1*R1 - R2*R2)
4010 C
4020 C  DEFINE VERTICAL SECTIONS
4030 C
4040     KDR = 1.5 + (TD + 1.)/DDEPTH
4050     NZ = KDR + 1
4060     NZP1 = NZ + 1
4070     DO 4 K=1,NZP1
4080     4 Z(K) = (K-1)*DDEPTH
4090     RETURN
4100     END

```

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4120      SUBROUTINE COND
4130 C
4140 C      THIS SUBROUTINE DEFINES THE CONDUCTANCES BETWEEN CELLS.
4150 C
4160      COMMON /BLK1/ TW(101,20),TWJ(101,21)
4170      COMMON /BLK3/ KDR,NZ,NZP1,DEPTH,TD,Z(101),ZC(5),DZ(5)
4180      COMMON /BLK8/ NR,RMAX,R(21),DR(21),AR(20),RI(5),RO(5)
4190      COMMON /BLK4/ U(101,20),Q(101,2)
4200      COMMON /BLK6/ IFLOW,PI,DT,TIN1,TIN2,FR1,FR2,FR3,NIT
4210      COMMON /BLK9/ DENS(100),SHS(100),CONS(100)
4220      COMMON /BLK10/ DENST,SHST,CONST,DENC,SHC,CONC
4230      COMMON /BLK11/ VFR,DENF,PVF,YPF,SHF,CONF
4240      COMMON /BLK5/ CAN(5)
4250      DATA FF/0.003/
4260 C
4270 C      RESISTANCE TERMS
4280 C
4290      RT1 = ALOG(RO(1)/RI(1))/CONST
4300      RT2 = ALOG((RO(1) + RI(2))/(2.*RO(1)))
4310      RT3 = ALOG(2.*RI(2)/(RO(1) + RI(2)))
4320      RT4 = ALOG(RO(2)/RI(2))/CONST
4330      RT5 = ALOG(RI(3)/RO(2))
4340      RT6 = ALOG(RO(3)/RI(3))/CONST
4350      RT7 = ALOG(RI(4)/RO(3))
4360      RT8 = ALOG(RO(4)/RI(4))/CONST
4370      RT9 = ALOG(RI(5)/RO(4))
4380      RT10 = ALOG(RO(5)/RI(5))/CONST
4390      RT11 = ALOG(R(3)/RO(5))
4400      RT12 = ALOG(R(3)/RI(5))
4410      RT13 = ALOG(R(3)/RI(4))
4420      RT14 = ALOG(R(3)/RI(3))
4430 C
4440 C      COMPUTE WELLBORE CONDUCTANCES
4450 C
4460      DO 22 K=1,KDR
4470      ZKP = Z(KDR)
4480      IF (K .LT. KDR) ZKP = (Z(K) + Z(K+1))/2.
4490      ZKM = Z(1)
4500      IF (K .GT. 1) ZKM = (Z(K) + Z(K-1))/2.
4510 C
4520 C      DETERMINE CASING STRINGS THROUGH CELL AT Z(K)
4530 C
4540      DO 26 JJ=1,5
4550      J = 6 - JJ
4560      26 IF (ZKP .LT. ZC(J)+0.1) GO TO 28
4570      28 II = 0

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4580 C
4590 C SUM RESISTANCES
4600 C
4610 36 R12 = RT1
4620 GO TO (10,12,14,16,18),J
4630 10 CALL CONAN(2,K,ZKP,ZKM)
4640 IF (DEPTH .GT. ZC(1)) R23 = RT14/CONS(K)
4650 GO TO 20
4660 12 CALL CONAN(2,K,ZKP,ZKM)
4670 IF (DEPTH .GT. ZC(3)) R23 = RT14/CONS(K)
4680 GO TO 20
4690 14 CALL CONAN(3,K,ZKP,ZKM)
4700 IF (DEPTH .GT. ZC(4)) R23 = RT13/CONS(K)
4710 IF (DEPTH .GT. ZC(3)) R23 = R23 + RT7/CAN(3) + RT6
4720 GO TO 20
4730 16 CALL CONAN(4,K,ZKP,ZKM)
4740 IF (DEPTH .GT. ZC(5)) R23 = RT12/CONS(K)
4750 IF (DEPTH .GT. ZC(4)) R23 = R23 + RT9/CAN(4) + RT8
4760 IF (DEPTH .GT. ZC(3)) R23 = R23 + RT7/CAN(3) + RT6
4770 GO TO 20
4780 18 CALL CONAN(5,K,ZKP,ZKM)
4790 R23 = 1.E-20
4800 IF (DEPTH .GT. ZC(5)) R23 = RT11/CAN(5) + RT10
4810 IF (DEPTH .GT. ZC(4)) R23 = R23 + RT9/CAN(4) + RT8
4820 IF (DEPTH .GT. ZC(3)) R23 = R23 + RT7/CAN(3) + RT6
4830 20 IF (DEPTH .GT. ZC(2)-1.) R23 = R23 + RT5/CAN(2) + RT4
4840 IF (ZC(1) .GT. ZC(2) .AND. J .EQ. 1)
4850 % R23 = ALOG(R(3)/RI(2))/CONS(K)
4860 R2 = RT2/CAN(1)
4870 R3 = RT3/CAN(1)
4880 IF (VFR .GT. 1.) GO TO 40
4890 C
4900 C SHUT-IN CONDITIONS
4910 C
4920 TO = (TW(K,1) + TW(K,2))/2.
4930 VIS = VISC(TW(K,1),TO,0.,RI(1),DENF,PVF,YPF)
4940 CN = CONVN(VIS,DENF,SHF,CONF,0.,RI(1),TW(K,1),TO)
4950 R12 = R12 + ALOG(2)/CN
4960 GO TO 44
4970 C
4980 C ANNULAR CONVECTION, CIRCULATION
4990 C
5000 40 IF (IFLOW .LE. 2) GO TO 42
5010 VIS = VISC(TW(K,2),0.,RO(1),RI(2),VFR,PVF,YPF)
5020 H = CONV(VFR,VIS,DENF,SHF,CONF,RO(1),RI(2))
5030 R2 = 1./(H*RO(1))
5040 R3 = 1./(H*RI(2))
5050 C
5060 C TUBING CONVECTION
5070 C
5080 42 VIS = VISC(TW(K,1),0.,0.,RI(1),VFR,PVF,YPF)
5090 H = CONV(VFR,VIS,DENF,SHF,CONF,0.,RI(1))
5100 R2 = R2 + 1./(H*RI(1))

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5110 C
5120 C TOTAL RESISTANCES
5130 C
5140 44 R12 = R12 + R2
5150 R23 = R23 + R3
5160 C
5170 C CONDUCTANCES
5180 C
5190 46 U(K,1) = 2.*PI/R12
5200 U(K,2) = 2.*PI/R23
5210 C
5220 C CHECK FOR SPLIT CELL
5230 C
5240 IF (II .EQ. 1) GO TO 38
5250 JD = J
5260 DO 32 JJ=1,5
5270 J = 6 - JJ
5280 32 IF (ZKM .LT. ZC(J)+0.1) GO TO 34
5290 34 IF (JD .EQ. J) GO TO 22
5300 II = 1
5310 UK1 = U(K,1)
5320 UK2 = U(K,2)
5330 GO TO 36
5340 38 UT = UK1*(ZKP - ZC(J)) + U(K,1)*(ZC(J) - ZKM)
5350 U(K,1) = UT/(ZKP - ZKM)
5360 UT = UK2*(ZKP - ZC(J)) + U(K,2)*(ZC(J) - ZKM)
5370 U(K,2) = UT/(ZKP - ZKM)
5380 22 CONTINUE
5390 C
5400 C SOIL CONDUCTANCES
5410 C
5420 R1 = 2.*PI/ALOG(R(2)/R(1))
5430 R2 = 2.*PI/ALOG(R(3)/R(2))
5440 K1 = KDR + 1
5450 DO 30 K=K1,NZP1
5460 U(K,1) = R1*CONS(K)
5470 30 U(K,2) = R2*CONS(K)
5480 DO 8 I=3,NR
5490 RR = 2.*PI/ALOG(R(I+1)/R(I))
5500 DO 8 K=1,NZP1
5510 8 U(K,I) = RR*CONS(K)
5520 RETURN
5530 END

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5550      SUBROUTINE COEF
5560 C
5570 C THIS SUBROUTINE COMPUTES THE COEFFICIENTS.
5580 C
5590      COMMON /BLK2/ A(101,20),B(101,20),C(101,20),D(101,20),E(101,20)
5600      COMMON /BLK3/ KDR,NZ,NZP1,DEPTH,TD,Z(101),ZC(5),DZ(5)
5610      COMMON /BLK8/ NR,RMAX,R(21),DR(21),AR(20),RI(5),RO(5)
5620      COMMON /BLK4/ U(101,20),Q(101,2)
5630      COMMON /BLK6/ IFLOW,PI,DT,TIN1,TIN2,FR1,FR2,FR3,NIT
5640      COMMON /BLK7/ F(101,3),G(101,3)
5650      COMMON /BLK9/ DENS(100),SHS(100),CONS(100)
5660      COMMON /BLK10/ DENST,SHST,CONST,DENC,SHC,CONC
5670      COMMON /BLK11/ VFR,DENF,PVF,YPF,SHF,CONF
5680      COMMON /BLK12/ VFR2,DENF2,PVF2,YPF2,SHF2,CONF2
5690 C
5700      FR1 = 2.*VFR*DENF*SHF
5710      FR2 = 2.*VFR2*DENF2*SHF2
5720      FR3 = FR1 + FR2
5730      FFR = 0.
5740 C
5750 C WELLBORE COEFFICIENTS
5760 C
5770      DO 3 I=1,3
5780      ROIM1 = 0.
5790      IF (I.NE. 1) ROIM1 = RO(I-1)
5800      AF = PI*(RI(I)**2 - ROIM1**2)
5810      AP = PI*(RO(I)**2 - RI(I)**2)
5820      HH = (DENF*SHF*AF + DENST*SHST*AP)/DT
5830      IFL = 0
5840      IF (I.EQ. 2 .AND. IFLOW.LE. 2) IFL = 1
5850      IF (FR1.GT. 1. .AND. I.NE. 3 .AND. IFL.EQ. 0) GO TO 20
5860 C
5870 C NO FLOW CONDITIONS
5880 C
5890      UKIM1 = 0.
5900      KK = 2
5910      IF (I.LE. 2) KK = 1
5920      DO 22 K=KK,KDR
5930      IF (I.NE. 1) UKIM1 = U(K,I-1)
5940      H = U(K,I) + UKIM1 + HH
5950      C(K,I) = UKIM1/H
5960      D(K,I) = U(K,I)/H
5970      22 E(K,I) = HH/H
5980      GO TO 3
5990 C
6000 C FLOWING CONDITIONS
6010 C
6020      20 IF (I.EQ. 2) GO TO 4
6030      FFR = FR1
6040      IF (IFLOW.EQ. 2) FFR = - FR1
6050      IF (IFLOW.EQ. 4) FFR = - FR1 - FR2
6060      UKIM1 = 0.
6070      UK1IM1 = 0.
6080      GO TO 12

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6090      4 FFR = FR1
6100      IF (IFLOW .EQ. 3) FFR = - FR1 - FR2
6110      IF (KDR .EQ. (NZ - 1)) GO TO 12
6120      JJ = 0
6130      IF (DEPTH .GT. ZC(5)) JJ = 5
6140      IF (DEPTH .GT. ZC(4)) JJ = 4
6150      IF (DEPTH .GT. ZC(3)) JJ = 3
6160      RR = R(3)
6170      IF (JJ .NE. 0) RR = RI(JJ)
6180      AF = PI*(RR**2 - RD(1)**2)
6190      AP = 0.
6200      IF (JJ .NE. 0) AP = PI*(RD(JJ)**2 - RI(JJ)**2)
6210      HH = (DENF*SHF*AF + DENST*SHST*AP)/DT
6220      12 DO 2 K=2,KDR
6230      FR = FFR/(Z(K) - Z(K-1))
6240      IF (I .EQ. 1) GO TO 6
6250      UKIM1 = U(K,I-1)
6260      UK1IM1 = U(K-1,I-1)
6270      6 H = FR + U(K,I) + UKIM1 + HH
6280      A(K,I) = (FR - U(K-1,I) - UK1IM1 - HH)/H
6290      C(K,I) = UKIM1/H
6300      D(K,I) = U(K,I)/H
6310      E(K,I) = HH/H
6320      F(K,I) = UK1IM1/H
6330      2 G(K,I) = U(K-1,I)/H
6340      3 CONTINUE
6350 C
6360 C SOIL COEFFICIENTS
6370 C
6380      DO 8 I=1,NR
6390      AREA = AR(I)
6400      UKIM1 = 0.
6410      KK = 2
6420      IF (I .LT. 4) KK = KDR + 1
6430      DO 8 K=KK,NZ
6440      HH = DENS(K)*SHS(K)*AREA/DT
6450      DDZ = Z(K+1) - Z(K)
6460      CON1 = AREA*(CONS(K-1) + CONS(K))/(4.*(Z(K) - Z(K-1))**2)
6470      CON2 = AREA*(CONS(K) + CONS(K+1))/(4.*DDZ*DDZ)
6480      IF (I .GT. 1) UKIM1 = U(K,I-1)
6490      H = CON1 + CON2 + UKIM1 + U(K,I) + HH
6500      A(K,I) = CON1/H
6510      B(K,I) = CON2/H
6520      C(K,I) = UKIM1/H
6530      D(K,I) = U(K,I)/H
6540      8 E(K,I) = HH/H
6550 C
6560      RETURN
6570      END

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6590      SUBROUTINE WELL
6600 C
6610 C THIS SUBROUTINE COMPUTES THE TEMPERATURES IN THE WELLBORE
6620 C
6630      COMMON /BLK1/ TW(101,20),TWJ(101,21)
6640      COMMON /BLK2/ A(101,20),B(101,20),C(101,20),D(101,20),E(101,20)
6650      COMMON /BLK3/ KDR,NZ,NZP1,DEPTH,TD,Z(101),ZC(5),DZ(5)
6660      COMMON /BLK8/ NR,RMAX,R(21),DR(21),AR(20),RI(5),RO(5)
6670      COMMON /BLK4/ U(101,20),Q(101,2)
6680      COMMON /BLK7/ F(101,3),G(101,3)
6690      COMMON /BLK6/ IFLOW,PI,DT,TIN1,TIN2,FR1,FR2,FR3,NIT
6700 C
6710 C INITIALIZE
6720 C
6730      NIT = 0
6740      DO 10 I=1,NR
6750      DO 10 K=1,NZP1
6760      10 TW(K,I) = TWJ(K,I)
6770 C
6780 C ITERATE
6790 C
6800      8 NIT = NIT + 1
6810 C
6820 C COMPUTE NEW TEMPERATURES
6830 C
6840      BIG = 0.
6850      DO 20 I=1,3
6860 C
6870 C CHECK FOR FLOWING STREAM
6880 C
6890      IFL = 0
6900      IF (I .EQ. 2 .AND. IFLOW .LE. 2) IFL = 1
6910      IF (FR1 .GT. 1. .AND. I .NE. 3 .AND. IFL .EQ. 0) GO TO 26
6920 C
6930 C NO FLOW CONDITIONS
6940 C
6950      KK = 2
6960      IF (IFLOW .LE. 2 .AND. I .EQ. 1) KK = 1
6970      IF (IFLOW .GE. 3 .AND. I .LE. 2) KK = 1
6980      DO 29 K=KK,KDR
6990      TKIM1 = 0.
7000      IF (I .GT. 1) TKIM1 = TWJ(K,I-1)
7010      TOLD = TWJ(K,I)
7020      TWJ(K,I) = C(K,I)*TKIM1 + D(K,I)*TWJ(K,I+1) + E(K,I)*TW(K,I)
7030      DIFF = ABS(TOLD - TWJ(K,I))
7040      28 IF (DIFF .GT. BIG) BIG = DIFF
7050      GO TO 20

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7060 C
7070 C FLOWING STREAM CALCULATIONS
7080 C
7090 26 JFLOW = 0
7100 IF (I .EQ. 2) GO TO 2
7110 IF (IFLOW .EQ. 2 .OR. IFLOW .EQ. 4) JFLOW = 1
7120 GO TO 4
7130 2 IF (IFLOW .EQ. 3) JFLOW = 1
7140 4 CONTINUE
7150 IF (JFLOW .EQ. 0) GO TO 6
7160 C
7170 C COMPUTE UP FROM BOTTOM
7180 C
7190 IF (I .EQ. 2) GO TO 30
7200 TWJ(KDR,1) = TIN1
7210 IF (IFLOW .EQ. 4) TWJ(KDR,1) = (TWJ(KDR,2)*FR1 + TIN2*FR2)/FR3
7220 GO TO 32
7230 30 TWJ(KDR,2) = (TWJ(KDR,1)*FR1 + TIN2*FR2)/FR3
7240 32 CONTINUE
7250 DO 14 M=2,KDR
7260 K = KDR - M + 2
7270 TKIM1 = 0.
7280 TT = G(K,I)*TWJ(K-1,I+1)
7290 IF (I .EQ. 1) GO TO 5
7300 TKIM1 = TWJ(K,I-1)*C(K,I)
7310 TT = TT + F(K,I)*TWJ(K-1,I-1)
7320 5 TOLD = TWJ(K-1,I)
7330 IF (I .EQ. 1) GO TO 60
7340 TDIF = TWJ(K,I) - TKIM1
7350 IF (ABS(TDIF/TKIM1) .LT. 0.001) TDIF = 0.
7360 TDIFF = TDIF - D(K,I)*TWJ(K,I+1)
7370 GO TO 62
7380 60 TDIF = TWJ(K,I) - D(K,I)*TWJ(K,I+1)
7390 IF (ABS(TDIF/TWJ(K,I)) .LT. 0.001) TDIF = 0.
7400 TDIFF = TDIF - TKIM1
7410 62 AT = TDIFF - E(K,I)*(TWJ(K-1,I) + TWJ(K,I)) - TT
7420 TWJ(K-1,I) = AT/A(K,I)
7430 DIFF = ABS(TOLD - TWJ(K-1,I))
7440 14 IF (DIFF .GT. BIG) BIG = DIFF
7450 GO TO 20

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7460 C
7470 C COMPUTE DOWN FROM TOP
7480 C
7490 6 IF (I .EQ. 1) TWJ(1,1) = TIN1
7500 IF (I .EQ. 2) TWJ(1,2) = TIN1
7510 DO 12 K=2,KDR
7520 TKP1I = TWJ(K,I)
7530 TKIM1 = 0.
7540 TT = G(K,I)+TWJ(K-1,I+1)
7550 IF (I .EQ. 1) GO TO 22
7560 TKIM1 = TWJ(K,I-1)+C(K,I)
7570 TT = TT + F(K,I)+TWJ(K-1,I-1)
7580 22 TOLD = TWJ(K,I)
7590 TWJ(K,I) = A(K,I)+TWJ(K-1,I)
7600 & + TKIM1 + D(K,I)+TWJ(K,I+1)
7610 & + E(K,I)+(TW(K-1,I) + TW(K,I)) + TT
7620 DIFF = ABS(TOLD - TWJ(K,I))
7630 12 IF (DIFF .GT. BIG) BIG = DIFF
7640 20 CONTINUE
7650 C
7660 C SOIL CALCULATION
7670 C
7680 DO 3 I=1,NR
7690 KK = 2
7700 IF (I .LT. 4) KK = KDR + 1
7710 DO 3 K=KK,NZ
7720 TT = 0.
7730 IF (I .GT. 1) TT = C(K,I)+TWJ(K,I-1)
7740 TOLD = TWJ(K,I)
7750 TWJ(K,I) = A(K,I)+TWJ(K-1,I) + B(K,I)+TWJ(K+1,I)
7760 & + TT + D(K,I)+TWJ(K,I+1) + E(K,I)+TW(K,I)
7770 DIFF = ABS(TOLD - TWJ(K,I))
7780 3 IF (DIFF .GT. BIG) BIG = DIFF
7790 C
7800 C CHECK FOR CONVERGENCE
7810 C
7820 IF (NIT .LT. 50) GO TO 16
7830 WRITE (6,100) NIT,BIG
7840 100 FORMAT (/2X,10(' '),2X,' TEMPERATURES NOT CONVERGED ',
7850 & 2X,10(' ')//20X,'NIT =',I3.5X,'BIG =',E12.4/)
7860 GO TO 18
7870 16 IF (BIG .GT. 0.1) GO TO 8
7880 18 CONTINUE
7890 RETURN
7900 END

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7920      FUNCTION VISC(TEM1,TEM2,R1,R2,FRD,PV,YP)
7930 C
7940 C      THIS FUNCTION COMPUTES THE VISCOSITY OF A FLUID.
7950 C      TEM1 = FLUID TEMPERATURE, OR TEMPERATURE AT R1
7960 C      TEM2 = 0, OR TEMPERATURE AT R2
7970 C      R1 = INSIDE RADIUS OF ANNULUS, FT. R1 = 0 FOR INSIDE A PIPE.
7980 C      R2 = OUTSIDE RADIUS OF ANNULUS, FT.
7990 C      PV = PLASTIC VISCOSITY, CENTIPOISE.
8000 C      YP = YIELD POINT, LBF/100FT2.
8010 C      FRD = FLOW RATE, FT3/HR. OR DENSITY, LBM/FT3
8020 C      THE FIRST OPTIONS ARE FOR FORCED CONVECTION,
8030 C      AND THE SECOND OPTIONS ARE FOR NATURAL CONVECTION.
8040 C      GRAY = GRAVITY ACCELERATION, FT/HR2
8050 C      BETA = VOLUMETIC COEFFICIENT OF THERMAL EXPANSION, 1/F
8060 C      VISM = VISCOSITY OF WATER FROM 30 F TO 300 F, LBM/FT-HR
8070 C
8080      DIMENSION VISM(28)
8090      DATA GRAY/4.17E+8/,BETA/0.0001/
8100      DATA VISM/4.464,3.741,3.168,2.733,2.375,2.084,1.848,
8110      & 1.650,1.487,1.353,1.238,1.136,1.048,0.9708,0.9036,
8120      & 0.8411,0.7854,0.7390,0.6955,0.6532,0.6193,0.5854,
8130      & 0.5564,0.5274,0.5044,0.4814,0.4645,0.4476/
8140 C
8150 C      POWER LAW EXPONENT AND COEFFICIENT
8160 C
8170      R600 = YP + 2.*PV
8180      R300 = YP + PV
8190      EXP = 3.322*ALOG10(R600/R300)
8200      CDEF = 5.109*R300/(510.9*EXP)
8210      A = (3.*EXP + 1.)/(EXP*R2)
8220      IF (R1 .GT. 0.01) A = 2.*(2.*EXP + 1.)/(EXP*(R2 - R1))
8230 C
8240 C      NATURAL CONVECTION
8250 C
8260      IF (TEM2 .LT. 0.1) GO TO 12
8270 C
8280 C      APPROXIMATE FLUID VELOCITY TIMES VISCOSITY, LBM/HR2
8290 C      VTV = 8550. CORRESPONDS TO WATER AT 1 FT/SEC
8300 C
8310 C      VTV = GRAY*FRD*BETA*ABS(TEM2 - TEM1)*(R2 - R1)**2
8320      VTV = 8550.
8330 C
8340 C      SHEAR RATE TIMES VISCOSITY, POISE/SEC
8350 C
8360      SRTV = 1.148E-6*A*VTV
8370 C
8380 C      VISCOSITY OF FLUID AT 70 F
8390 C      NOTE (241.92 LBM/FT-HR)/POISE
8400 C
8410      VISC = CDEF*(SRTV**(EXP - 1.))
8420      VISC = 241.92*(VISC**(1./EXP))
8430      GO TO 10

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8440 C
8450 C FORCED CONVECTION
8460 C
8470 12 CONTINUE
8480 C
8490 C FLUID VELOCITY, FT/HR
8500 C
8510 AREA = 3.1415927*(R2*R2 - R1*R1)
8520 VEL = FRD/AREA,
8530 C
8540 C SHEAR RATE
8550 C
8560 SR = VEL/A
8570 C
8580 C VISCOSITY OF FLUID AT 70 F
8590 C NOTE (241.92 LBM/FT-HR)/POISE
8600 C
8610 VISC = CDEF*(SR**(EXP - 1.))
8620 VISC = 241.92/VISC
8630 C
8640 C WATER VISCOSITY AT TEMPERATURE TEM
8650 C
8660 10 TEM = TEM1
8670 IF (TEM2 .GT. 0.1) TEM = (TEM1 + TEM2)/2.
8680 DO 2 I=1,28
8690 TEMP = 20. + 10.*I
8700 2 IF (TEMP .GT. TEM) GO TO 4
8710 4 IF (I .GT. 1) GO TO 6
8720 DV = VISC(1) - VISC(2)
8730 GO TO 8
8740 6 DV = VISC(I-1) - VISC(I)
8750 8 VISMTR = VISC(I) + DV*(TEMP - TEM)/10.
8760 C
8770 C VISCOSITY OF FLUID AT TEMPERATURE TEM.
8780 C
8790 VISC = VISC + VISMTR - VISC(5)
8800 RETURN
8810 END

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8930      FUNCTION CA(CAU,CAL,ZC,DZ,ZKP,ZKM)
8940 C
8950 C  THIS FUNCTION CHECKS FOR THE TYPE MATERIAL IN AN ANNULUS AND
8960 C  AVERAGES THE CONDUCTIVITY FOR A CELL IF AN INTERFACE IS FOUND.
8970 C
8980      IF ((ZC - DZ) .LT. ZKP) GO TO 2
8990      CA = CAU
9000      RETURN
9010  2 IF ((ZC - DZ) .GT. ZKM) GO TO 4
9020      CA = CAL
9030      RETURN
9040  4 CC = CAU*(ZC - DZ - ZKM) + CAL*(ZKP - ZC + DZ)
9050      CA = CC/(ZKP - ZKM)
9060      RETURN
9070      END

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9990      FUNCTION CONVN(VIS,DEN,SH,CON,RI,RO,TI,TD)
9000 C
9010 C      THIS FUNCTION COMPUTES AN OVERALL CONDUCTIVITY OF A NATURALLY
9020 C      CONVECTING FLUID INCLUDING EFFECTIVE CONDUCTIVITY OF FLUID
9030 C      AND SURFACE CONVECTION COEFFICIENT.
9040 C
9050      DATA GRAV/4.17E+8/,BETA/0.0005/
9060 C      GRAV = ACCELERATION OF GRAVITY, FT3/HR
9070 C      BETA = VOLUME COEFFICIENT OF THERMAL EXPANSION
9080 C
9090 C      PRANDTL NUMBER
9100 C
9110      PR = SH*VIS/CON
9120 C
9130 C      GRASHOF NUMBER
9140 C
9150      GR = ABS(TD - TI)*GRAV*BETA*DEN*DEN
9160      GR = GR*((RO - RI)**3)/(VIS*VIS)
9170 C
9180 C      EFFECTIVE FLUID CONDUCTIVITY
9190 C
9200      CONEFF = 0.049*CON*((GR*PR)**0.333)*(PR**0.074)
9210      IF (CONEFF .LT. CON) CONEFF = CON
9220 C
9230 C      SURFACE CONVECTION COEFFICIENT
9240 C
9250      GR = 8.*GR
9260      H = CON*0.59*((GR*PR)**0.25)/(2.*(RO - RI))
9270 C
9280 C      OVERALL CONDUCTIVITY
9290 C
9300      IF (RI .LT. 0.01) RI = RO/2.
9310      AA = 1./(H*RI) + ALOG(RO/RI)/CONEFF + 1./(H*RO)
9320      CONVN = ALOG(RO/RI)/AA
9330      RETURN
9340      END

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9360      FUNCTION CONV(VFR,VIS,DEN,SH,CON,RI,RO)
9370 C
9380 C      THIS FUNCTION COMPUTES A SURFACE COEFFICIENT FOR FORCED CONVECTION
9390 C
9400 C      VFR = VOLUME FLOW RATE, FT3/HR
9410 C      VIS = FLUID VISCOSITY, LBM/FT-HR
9420 C      DEN = DENSITY, LBM/FT3
9430 C      SH = SPECIFIC HEAT CAPACITY, BTU/LBM-F
9440 C      CON = THERMAL CONDUCTIVITY, BTU/HR-FT-F
9450 C      RI, RO = INNER AND OUTER RADII OF ANNULUS, FT
9460 C      CONV = SURFACE CONVECTION COEFFICIENT, BTU/HR-FT2-F
9470 C
9480 C      PRANDL NUMBER
9490 C
9500      PR = SH*VIS/CON
9510 C
9520 C      REYNOLDS NUMBER
9530 C
9540      AREA = 3.1415927*(RO*RO - RI*RI)
9550      VEL = VFR/AREA
9560      RE = 2.*(RO - RI)*DEN*VEL/VIS
9570 C
9580 C      LOW PRANDTL NUMBER CONVECTION COEFFICIENT
9590 C
9600      IF (PR .GT. 50.) GO TO 2
9610      CONV = CON*0.023*(RE**0.8)*(PR**0.35)/(2.*(RO - RI))
9620      RETURN
9630
9640 C      HIGH PRANDTL NUMBER CONVECTION COEFFICIENT
9650 C
9660      2 F = 64./RE
9670      IF (RE .LT. 2000.) GO TO 6
9680      IF (RE .GT. 4000.) GO TO 4
9690      F = 0.0077349
9700      F = (64. + F*(RE - 2000.))/2000.
9710      GO TO 6
9720      4 F = 0.013
9730      IF (RE .LT. 349120.) F = 0.316/(RE**0.25)
9740      6 H = 1.2 + 11.8*(PR - 1)*SQRT(F/8.)/(PR**0.333)
9750      H = F*RE*PR/(8.*H)
9760      CONV = CON*H/(2.*(RO - RI))
9770      RETURN
9780      END

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9900      SUBROUTINE CONAN(J,K,ZKP,ZKM)
9910 C
9920 C      THIS SUBROUTINE COMPUTES THE CONDUCTIVITY OF ALL THE ANNULI
9930 C      NEEDED TO DETERMINE AN OVERALL CONDUCTANCE AT DEPTH LEVEL K.
9940 C
9950      COMMON /BLK5/ CAN(5)
9960      COMMON /BLK3/ KDR,NZ,NZP1,DEPTH,TD,Z(101),ZC(5),DZ(5)
9970      COMMON /BLK1/ T(101,20),TWJ(101,21)
9980      COMMON /BLK8/ NR,RMAX,R(21),DR(21),AR(20),RI(5),RO(5)
9990      COMMON /BLK10/ DENST,SHST,CONST,DENC,SHC,CONC
9900      COMMON /BLK13/ DENAF,PVAF,YPAF,SHAF,CONAF
9910 C
9920 C      FACTORS FOR LINEAR INTERPOLATION OF TEMPERATURES FROM T(K,2) TO T(K,3)
9930 C
9940      TA = T(K,2)
9950      TB = (T(K,3) - T(K,2))/(R(3) - R(2))
9960 C
9970 C      LOOP ON THE NUMBER OF ANNULI NEEDED, J, AT LEVEL K.
9980 C
9990      DO 2 I=1,J
10000 C
10010 C      INTERIOR AND EXTERIOR ANNULI TEMPERATURES.
10020 C
10030      TI = TA + TB*(RO(I) - R(2))
10040      IF (I .EQ. 1) TI = (T(K,1) + T(K,2))/2.
10050      TO = T(K,3)
10060      IF (I .LT. 5) TO = TA + TB*(RI(I+1) - R(2))
10070 C
10080 C      VISCOSITY OF ANNULUS FLUID
10090 C
10100      RR = R(3)
10110      IF (I .LT. 5) RR = RI(I+1)
10120      VIS = VISC(TI,TO,RO(I),RR,DENAF,PVAF,YPAF)
10130 C
10140 C      CONDUCTIVITY OF ANNULUS FLUID AND OF CELL AT LEVEL K
10150 C
10160      CAU = CONVN(VIS,DENAF,SHAF,CONAF,RO(I),RR,TI,TO)
10170      2 CAN(I) = CA(CAU,CONC,ZC(I),DZ(I),ZKP,ZKM)
10180      RETURN
10190      END

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