Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

GEOTRANS: A COMPUTER CODE FOR ESTIMATING TRANSIENT TEMPERATURES IN THE COMPLETION OF GEOTHERMAL WELLS WITH DRILLING FLUID LOSSES

Alfonso Garcia[1], Gilberto Espinosa[2], Edgar Santoyo[3], Pedro Mendoza[1] & Isaias Hernandez[4]
[1]Instituto de Investigaciones Electricas, Ap. Postal 1-475, Cuernavaca, Morelos, Mexico
[2]Universidad Autonoma Metopolitana, Depto. de IPH, Av. Michoacana y La Purisima s/n, Col. Vicentina, Mexico
[3]Universidad Nacional Autonoma de Mexico, Centro de Inv. en Energia, Priv. Xochicalco s/n, Temixco, Morelos, Mexico
[4]Instituto Tecnologico y de Estudios Superiores de Monterrey, Eugenio Garza Sada 2501, Monterrey, Nuevo Leon, Mexico

Key Words. Geothermal wells, drilling, completion, transient temperatures, drilling fluid losses

ABSTRACT

The GEOTRANS computer code is described. It consists of a numerical simulator and a user interface for data input and analysis of results. The equations governing the dynamic heat transfer processes in a geothermal well under construction in the presence of lost circulation are solved. They describe flow of fluid in the drilling pipe and annulus, heat transfer in the drilling pipe metal wall and conductive and convective heat flow in the formation. Solution allows estimation of temperatures in and around a well as function of time and vertical and radial position. The model is closed using heat transfer and fluid friction correlations. Physical properties of drilling fluids (muds and water/air mixtures), cements, rocks and pipes, implemented via numerical routines or as databases complement the model. Numerical solution follows implicit finite differences and the Thomas algorithm is used for their solution Heat transfer in the formation is 2D and is solved via an ADI scheme. A unique feature of GEOTRANS is that it simulates drilling fluid losses at any position along the uncased wellbore and its effect is accounted for as thermal convection in the formation. GEOTRANS operates under Windows and data input can be done from a file, interactively or from the databases implemented. Program execution is controlled from the user interface. Data post-processing includes automated plotting of simulated temperatures as function of depth and time for the circulation and shut-in periods. Previous code validation was performed by comparison against data from the literature and analytical solutions. Results of application to the Mexican well H-26 from the Los Humeros geothermal field are presented. The shut-in logged temperatures were reproduced in the presence of lost circulation. GEOTRANS can be used to estimate formation temperatures and formation porosity by trial and error.

1. INTRODUCTION

Loss of drilling fluid to surrounding formations is normally encountered during drilling of geothermal wells, and these losses provide a good indication about productive horizons in geothermal reservoirs. However, from the point of view of well drilling, lost circulation normally increases the time and cost for well completion and may be considered as an unwanted phenomenon. Yet, the information obtained during well drilling may be analyzed to extract valuable information about the geothermal reservoir such as formation temperatures and formation porosity or permeability. Drilling fluid losses are associated with permeable horizons in the reservoir. Temperature logs are used to obtain unperturbed formation temperatures and for the analysis of thermal gradients and temperature inversions and their relation to the presence of production zones, etc. (e.g., Grant et al., 1982). Also, temperature logs are helpful in locating places where heat is lost to the formation (Garcia et al., 1998a,b). Simulating the dynamic and shut-in processes occurring in the well facilitates this task.

Methods to estimate unperturbed formation temperatures focus on the bottom part of the well where temperatures are measured. Accurate knowledge of such temperatures is one of the problems that the geothermal industry needs to solve (Takahashi et al., 1997). Such methods are normally referred to as analytical or type-curve methods (e.g., Santoyo et al., 1999). For a series of drilling stages in a well, estimation of unperturbed temperatures is called stage testing (Grant et al., 1982). A review of such methods is given in detail elsewhere (e.g., Ascencio et al., 1994; Garcia et al., 1998b; Santoyo et al., 1999). Of these, five are considered as the most commonly used in the geothermal industry (Santoyo et al., 1999). They include the Horner (Dowdle and Cobb, 1975), the improved Horner (Roux et al., 1979), the Two-point (Kritikos and Kutasov, 1988), the Spherical (Ascencio et al., 1994) and the Hasan and Kabir, (1994) methods. The present code has been used for estimating formation temperatures and formation porosity

Numerical simulation of the whole thermal history of the drilling fluid column and the surrounding formation has been studied. The simulators employed include models ranging from pseudo-steady (Raymond, 1969; Garcia et al., 1998a) to fully transient, with constant or variable properties (Mondy and Duda, 1984; Beirute, 1991), and drilling fluid losses (Takahashi et al., 1997; Garcia et al., 1998b). These tools require an extensive amount of information about the well drilling history such as the fluid composition, inlet and outlet mud temperatures, fluid circulation rate, well geometric characteristics and the thermophysical properties of drilling fluids, cements, casings, pipes and surrounding rocks. Studies that account for drilling fluid losses are scarce. Luhesi (1983) proposed a formation/fluid model based on a simplified radial heat transfer equation that includes radial fluid motion and heat flow to the surrounding rock. Luhesi's model is applicable to the bottom 10-20 m of the borehole. Takahashi et al., (1997) modeled fluid losses as a mass and energy source in the reservoir. Fluid motion is assumed to follow Darcy's law. This model considers the drilling fluid inlet and outlet temperatures to obtain the fluid and formation temperatures.

A model for estimating the transient temperature field in and around a geothermal well during fluid circulation and shut-in was developed by Garcia et al. (1998b). This model is applicable to the uncased part of the well and constitutes the mathematical code of GEOTRANS. Thus, in this work the model is described briefly and the details are given there. Attention is then focused on the code's computational user interfaces for pre- and post-processing. Finally, results are presented for well H-26 from the Los Humeros field.

2. MATHEMATICAL MODEL

Fig. 1 shows the physical model of drilling fluid circulation and lost circulation. Fluid enters the drill pipe at the top, exits at the bottom and flows up in the annulus. If lost circulation exists, some fluid flows into the formation and the amount of fluid exiting the well depends on the amount of circulation losses. The problem consists of a set of heat transfer partial differential equations describing the 2D transient temperature field T(z,r,t). Mass conservation considers incompressible flow in the axial and radial directions. The solution considers the heat transfer convective effects (boundary conditions). The well-formation interface is considered as a porous medium through which fluid may be lost or gained by the well. The mathematical formulation is generic and versatile since any vertical well can be studied and fluid loss or gain can be simulated at any point in the well. The model also considers the possibility of the drilling fluid being a mixture of air and mud or water. Use of the air fraction enables calculation of the effective mixture properties and porosity is used to estimate the formation effective properties. The heat transfer coefficients are corrected with the porosity. For shut-in conditions, it is assumed that heat conduction dominates.

2.1 Generic formulation

The fundamental assumptions of the model are:

(1) Axis-symmetric heat
(2) Isotropic rock formation with homogeneous porosity
(3) Formation, cement and pipe metal constant properties
(4) Negligible viscous dissipation effects
(5) No natural convection exists after shut-in

Assumption one considers symmetry of the well and formation about the well axis. This may no be quite true for a faulted formation. However it is used as a working hypothesis. Assumption two is necessary since the variation of formation thermal properties with depth and temperature is unknown for Mexican wells and work in that direction is underway. Homogeneous formation porosity is used in the radial direction, however it varies along the vertical direction (as inferred form lost circulation data), and is thus heterogeneous in that direction. In the present work, formation vertical porosity is found by trial an error and represents an average formation porosity.

The energy and continuity equations reduce to:

$$\rho C_p\left(\frac{\partial T}{\partial t}+v_r\frac{\partial T}{\partial r}+v_z\frac{\partial T}{\partial z}\right)=k\left(\frac{1}{r}\frac{\partial T}{\partial t}+\frac{\partial^2 T}{\partial r^2}+\frac{\partial^2 T}{\partial z^2}\right) \quad (1)$$

$$\frac{1}{r}\frac{\partial(r\,v_r)}{\partial r}+\frac{\partial v_z}{\partial z}=0 \quad (2)$$

where *r,z* are radial and axial coordinates, T is temperature, v is velocity, ρ is density, Cp is specific heat and k is thermal conductivity. The initial and boundary conditions are:

I. C.: $T(r, z, t{=}0) = f(r, z)$ (3)

BC1: $-k\left(\frac{\partial T}{\partial r}\right)_i = h\left(T_s - T_f\right)\ on\ A_i\ \ for\ all\ t$ (4)

BC2: $\left(\frac{\partial T}{\partial r}\right)_{r=0} = 0\ \ at\ r=0\ \ for\ all\ t$ (5)

B. C. 3: $v_z = W/\rho A_f\ \ at\ z=0\ \ for\ all\ t$ (6)

B. C. 4: $v_r = f(\phi, W, \rho, A_l)\ on\ A_i\ \ for\ all\ t$ (7)

where T_s is the solid temperature, T_f is the fluid temperature, A_i is the interfacial area between the rock formation and the fluid, W is the drilling fluid inlet mass flowrate, A_f is the cross sectional area for flow, ϕ is the formation porosity and A_l is the lateral flow area. Equations (1)-(7) define in generic form the problem posed. The functionality of T(t=0), the heat transfer coefficient h and B.C.4 are addressed later on.

2.2 Lost circulation modeling

Circulation losses are given by (Garcia et al., 1998b):

$$W_{fu} = W\varphi \quad (8)$$

where φ is a multiplier which takes values between 0 and 1. If φ=0 no losses occur and if φ=1 all the drilling fluid is lost to the formation. Knowing φ, the axial velocity can be calculated from equation (2). The annulus heat transfer coefficient h at r = r_2 requires knowledge of the fluid velocity in the annulus v_z.

3. COMPUTER CODE

Application of equations (1-7) follows a simplified scheme of the physical well drilling system. Fig. 2 shows schematically an axial region of length Δz, the location and spacing of the radial mesh. The radii of this figure correspond to each physical region in which the well is divided (see Table 1). Five regions were identified as indispensable to be considered: (1) the drill pipe; (2) the drill pipe wall; (3) the annulus; (4) the well wall/annulus interface, and (5) the formation. Using this configuration, a computer code was developed. It consists of eleven subroutines of which eight are related to the mathematics of each region. A detailed description of the computer code is given by García et al. (1998b).

3.1 Drill pipe formulation, Region 1, Module TINTUB

The drill pipe temperature distribution is computed here.

3.2 Drill pipe wall formulation, Region 2, Module TMET

The temperature distribution in the drill pipe wall is computed here. Boundary the heat transfer coefficients are calculated in modules COEFCON and COEFCONA for the fluid in the drill pipe and in the annulus, respectively. If lost circulation is present, the annulus fluid velocity and the heat transfer coefficient are affected. These effects are properly considered in the present model, as described in Garcia et al. (1998b).

3.3 Annulus formulation, Region 3, Module TANU

This module estimates the temperature distribution of the annular region. The effective heat transfer coefficient h_{ef} considers the effect of porosity and is given by:

$$h_{ef} = h_{imp}\left(1-\phi\right) \tag{9}$$

where h_{imp} is the heat transfer coefficient for an impermeable wall and ϕ is the formation porosity.

3.4 Well wall/annulus interface formulation, Region 4, Module TINTER

The temperature distribution at the well wall/annulus interface This interface mathematically couples the formation and the flow in the annulus and should guarantee continuity of the heat flux during circulation and shut-in conditions.

3.5 Formation formulation, Region 5, Module TROCA

The axial and radial temperature distribution in the formation is computed here. The physical properties for this region are:

$$k_{ef} = k_a^{\phi}\, k_f^{(1-\phi)} \tag{10}$$

$$\left(\rho C_p\right)_{ef} = \left(\rho C_p\right)_f \left(1-\phi\right) + \left(\rho C_p\right)_a \phi \tag{11}$$

where f and a correspond to the formation and annulus fluid, respectively. If $\phi = 0$, the original equations are recovered.

3.6 Convective heat transfer coefficients

The heat transfer coefficient for laminar flow (Re < 2300) is calculated using the Seider and Tate correlation for flow inside the drill pipe and the annulus. For transitional and turbulent flow (Re > 2300) in the drill pipe and the annulus, Gnielinsky's (1976) correlation is used.

4. USER INTERFACE

GEOTRANS has a user interface for data input, program execution and analysis of results. It was developed using Visual Basic v4.0.

4.1 Sequential execution

Fig. 3 shows a block diagram of the main steps to be followed when executing a run. The underlined parts define program usage as: **[main window menu]:[menu option].** The steps of the left column are normally followed. However, if previous files exist, they can be read to start a session. **Save** and **Configure** can be accessed at any time. The **Print** option is accessible in each graphical window. Under **Session,** files may be read or saved. Under **Simulator**, data are input on: (1) the well geometric characteristics (drilling stages, diameters, lengths, etc.), (2) the thermophysical and transport properties of rock, cement, drilling fluid and pipes or casings (thermal conductivity, density, specific heat and viscosity), and (3) the data required to model circulation losses (depth, porosity and the loss factor φ). These data are obtained from the well drilling records. If a non-linear formation temperature profile is known, it is input here too. Once these data are input, access is gained to executing the code. Data required for program execution are drilling fluid mass flowrate, inlet temperature and the initial temperature profile (linear – geothermal gradient and surface temperature, non-linear or a new profile). Simulation parameters include simulation time and integration time step. The process to be simulated (**Circulation or Shut-in)** is also selected here. Once these data are input, the code may be executed.

Fig. 4 shows the main window of GEOTRANS. **Session** options are **Read, Save** and **Save as. Simulator** options are **Geometric data, Thermophysical properties, Modeling fluid losses** and **Execution.** Figure 5 shows the GEOTRANS window for geothermal cement thermophysical data input. Other folders refer to the properties of mud, casing and rock. An important feature is **Access to Database**. These bases contain the thermophysical properties of drilling cores of the four main geothermal Mexican fields. Extension to include databases on other rocks, drilling fluids, etc. is straightforward. Figure 6 shows the window for data input to model fluid losses. The first column indicates the drilling stage and the axial numerical node number. Other data are input at each node. Fig. 7 shows the window for feeding the executing parameters and for program execution. The execution mode is chosen here. Once the code is executed, the results may be saved from this window.

In the **Plot** menu, the **Read file** and **Plotting** options exist for **Circulation, Shut-in or Combined Plot.** The **Read file** option allows file selection for loading and plotting. If the file does not have the specified format, an error message is displayed. When a file is read (**Circulation or Shut-in)** the corresponding plotting option is enabled. If files are read for both the **Circulation or Shut-in** periods, then a **Combined Plot** may be displayed at any vertical position.

Figure 8 shows an example of the plotting capabilities of GEOTRANS. The window displays three sets of temperature profiles during shut-in for a well 2000 m deep and with three drilling stages. The left-hand side upper part displays the well termination including stage diameters and depths. **This kind of figure is automatically displayed with the data for each particular well.** Also shown are temperatures T1, T2 and T3. The profile number refers to the radial position or region (see Fig. 2) in which the well and formation are divided. A feature of GEOTRANS is that the user may select which profiles he wants to display. This is done from the **Configure** menu. The graphs shown in Fig. 8 refer to the temperature profiles in the drilling pipe, the drill pipe metal wall and the annulus. If the drill pipe is not in the well the T1 and T2 are identical. On the lower left part of the window one can see the number of the step time into which the simulation was divided and the total number of time steps. Thus, **Profile at time 1 (2/4)** means that there are four time steps (four profiles). The first profile is the initial profile and that the first simulated profile is being displayed. The left- and right-pointing arrows allow one to click there to change forwards or backwards the profile being displayed. These profiles may be displayed either manually or automatically at a frequency that is set by the user from the **Mode** menu. Thus, GEOTRANS allows the user to graphically display the simulated temperature profiles at every time step in automatic form.

5. GEOTRANS VALIDATION AND APPLICATIONS

Use of GEOTRANS

GEOTRANS can be used to simulate the dynamic heat transfer processes occurring in a geothermal well under construction in the presence of lost circulation. Formation temperature and average porosity (or permeability for a given fracture geometry) can be obtained by a trial and error procedure. The treatment of permeability is out of the scope of the present work since the present code does not consider Darcian flow. As a first guess, the initial temperature profile can be assumed based on the last temperature log or on static temperatures obtained via the Ascencio et al., (1994) method since this method has proven to give temperatures which are closer to the formation temperatures than the Horner method. Formation porosity is treated as homogeneous along the radial direction but heterogeneous on the axial direction. Its magnitude may be initially guessed form the lost circulation records or from measurements on drill cores. Approximated.

The results shown in Fig. 8 originate from a validation test using data of well AZ-28 from the Los Azufres geothermal field, Mexico (Garcia et al., 1998a). Further applications of GEOTRANS to wells EAZ-1 and EAZ-2 from the Los Azufres geothermal field and to well LV-3 from the Las Tres Virgenes geothermal field, Mexico, are described in detail by Garcia et al. (1998b). Those results demonstrate that the effect of lost circulation on the shut-in temperature profiles can be modeled satisfactorily.

Fig. 9 compares measured and simulated shut-in temperature profiles for well H-26 from The Los Humeros geothermal field, Mexico. Also shown are static temperatures obtained with the Horner and Ascencio et al. (1994) methods and the initial temperature profile. On the left side, the circulation losses are also shown. It is seen that fluid losses affect the temperature recovery below 2000 m depth. Simulation results reproduce satisfactorily the logged temperatures for 0 and 12 hours shut-in times and are greater than logged temperatures at further times, especially between the 2000 and 2250 m depth range. This may be due to the thermophysical formation properties used since these are unknown adequately, i.e., the values for the rock volume invaded by drilling fluid, or to neglecting natural convection after shut-in. The initial temperature profile was unknown at the beginning of the simulation. It was assumed and changed until simulated and logged temperatures matched. The final temperature profile obtained with GEOTRANS is closer in value to the static temperatures obtained with the Ascencio method than with the Horner method

6. CONCLUSIONS

The development and application of the GEOTRANS computer code were described. The mathematical model is described in generic form and each of the five regions into which the physical model was divided are described briefly. The various user interfaces of the code and the user execution mode are described in some detail. Finally, results of validation and previous applications tests mentioned, and new applications are described. The satisfactory results demonstrate that the effect of lost circulation on the shut-in temperature profiles can be modeled. Further modifications on the code are underway.

7. ACKNOWLEDGEMENTS

Thanks are due to Comision Federal de Electricidad and Inst. de Investigaciones Electricas, Mexico for their support.

8. REFERENCES

Ascencio, F., Garcia, A., Rivera J. and Arellano, V. (1994). Estimation of undisturbed formation temperatures under spherical radial heat flow conditions. *Geothermics*, Vol. 23(4), pp. 317-326.

Beirute, P. M. (1991). A circulating and shut-in well-temperature-profile simulator. *Journal of Petroleum Technology,* September, pp. 1140-1146.

Dowdle, W. L. and Cobb, W. M. (1975). Static formation temperature from well logs - an empirical method. *Journal of Petroleum Technology*, November, pp. 1326-1330.

Garcia, A., Hernandez, I, Espinosa, G., Santoyo, E., (1998a). TEMLOPI: A thermal simulator for estimation of drilling mud and formation temperatures during drilling of geothermal wells. *Computers & Geosciences,* Vol. 24 (5), pp. 465-477.

Garcia, A., Santoyo, E., Espinosa, G., Hernandez, I. and Gutierrez, H. (1998b). Estimation of temperatures in geothermal wells during drilling and shut-in in the presence of lost circulation. *Journal of Transport in Porous Media*, Vol. 33(1-2), pp. 103-127.

Gnielinsky, V. (1976). New equations for heat and mass transfer in turbulent pipe and channel flow. *International Chemical Engineering,* Vol. 1, No. 2, pp. 359-367

Grant, M. A., Donaldson, I. G. and Bixley, P. F. (1982). Geothermal Reservoir Engineering. Academic Press, New York, 369 pp.

Hasan, A. R. and Kabir, C. S. (1994). Static reservoir temperature determination from transient data after mud circulation. *SPE Drilling & Completion,* March, 17-24

Kritikos, W. R. and Kutasov, I. M. (1988). Two-point method for determination of undisturbed reservoir temperature. *SPE Formation Evaluation Journal*, March, pp. 222-226.

Luhesi, M. N. (1983). Estimation of formation temperature from borehole measurements. Geophysics Journal of the Royal Astronomical Society, Vol. 74, pp. 747-776.

Mondy, L. A. and Duda, L. E. (1984). Advanced wellbore thermal simulator GEOTEMP2 - User Manual. Sandia Labs. Technical Report SAND-84-0857, 147 pp.

Raymond, L. R. (1969). Temperature distribution in a circulating drilling fluid. *Journal of Petroleum Technology*, March, pp. 333-341.

Roux, B., Sanyal, S. Y. and Brown, S. L., (1979). An improved approach to estimating true reservoir temperature from transient temperature data. In: *Proceedings Fifth Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, CA, USA, pp.343-354.

Santoyo, E., Garcia, A., Espinosa, G., Hernandez, I. and Santoyo, S. (1999). STATIC TEMP: a useful computer code for calculating static formation temperatures in geothermal wells. *Computers and Geosciences*, in press.

Takahashi, W., Osato, Y., Takasugi, S. and White, S. P. (1997). Estimation of the formation temperature from inlet and outlet mud temperatures while drilling. In: *Proceedings 22nd. Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, CA, USA, 8 pp.

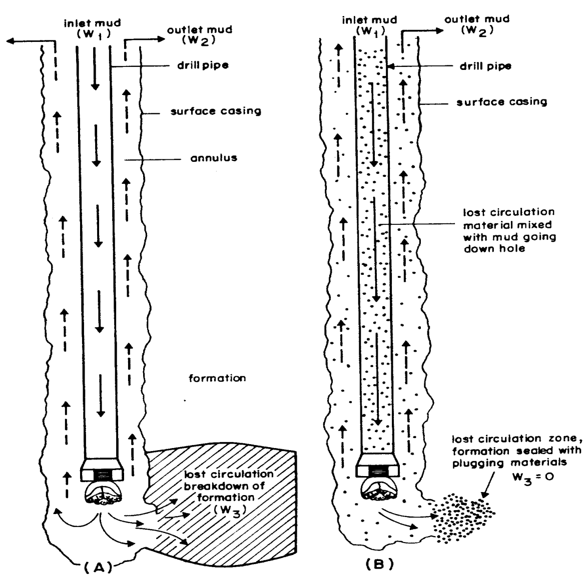


Fig. 1 Physical model of fluid circulation and lost circulation during drilling of a geothermal well.

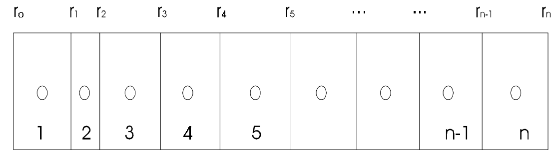


Fig. 2 Radial node distribution. r indicates the boundaries of each radial region of the well and "o" indicates the cell where the computations are performed. The node height is Δz. Table 1 defines the regions.

Region name	Region number	Radial domain	Flow velocity [Eq. (2)]
Drill pipe	1	$r_0 \le r \le r_1$	$v_{z,1} \neq 0$
Drill pipe wall	2	$r_1 \le r \le r_2$	$v_{z,2} = 0$
Annulus	3	$r_2 \le r \le r_3$	$v_{z,3} \neq 0$
Interface between the well and annulus	4	$r = r_3$	$v_{z,4} = 0$
Formation	5	$r > r_3$	$v_{z,5} = 0$

Table 1. Regions defined by the nodes of Figure 2

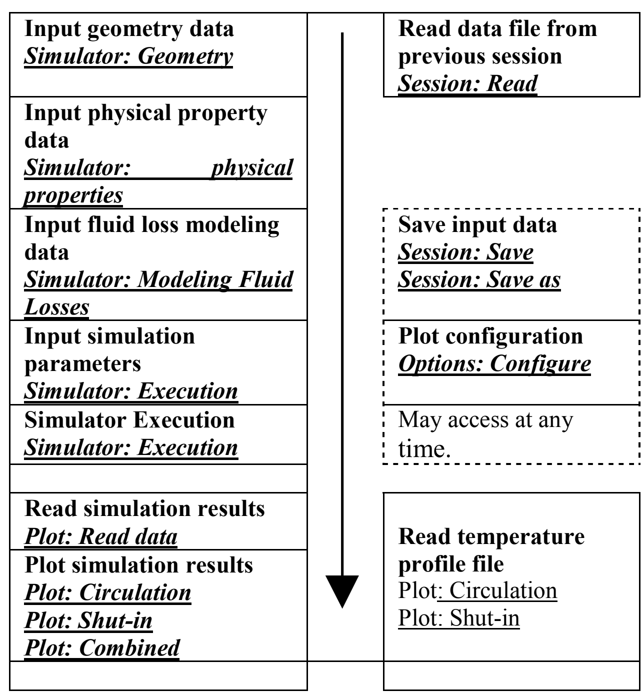


Fig. 3 GEOTRANS step-by-step sequential execution.

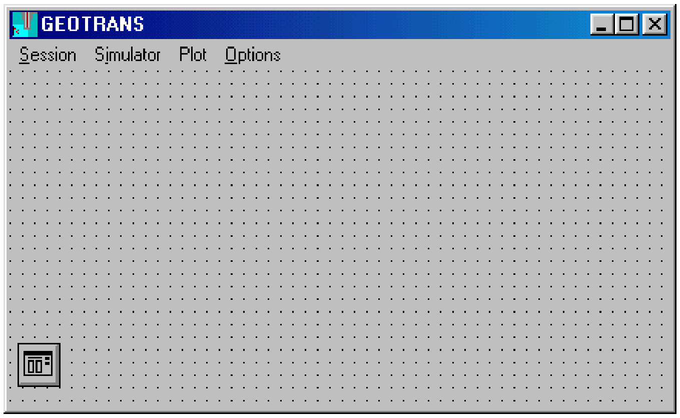


Fig. 4 GEOTRANS main window for data input,

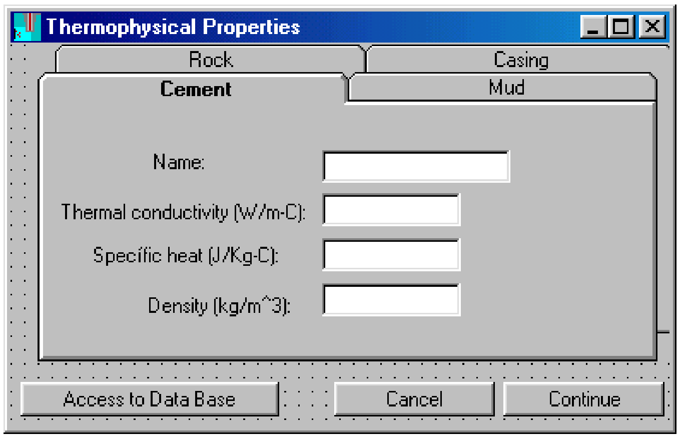


Fig. 5 Thermophysical property input window showing required cement properties. Rock, mud and casings data is input here

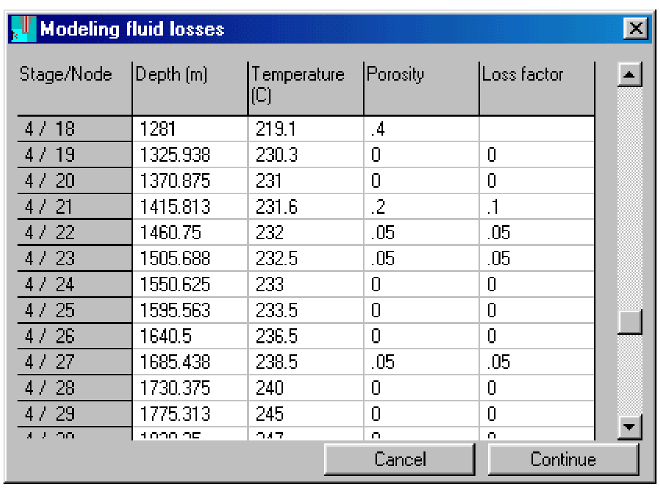
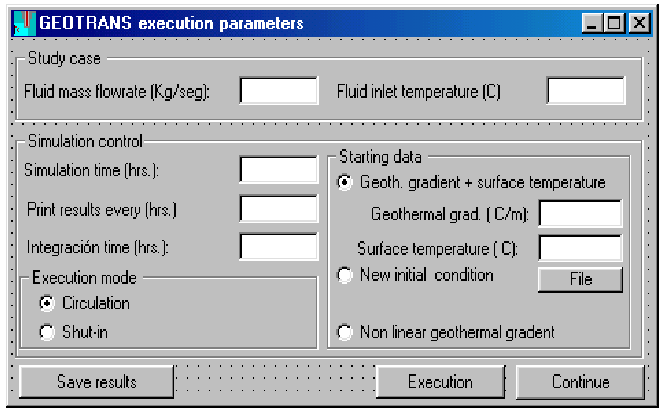


Fig. 6 Window showing required input data for modeling fluid losses and the initial non-linear temperature distribution



.Fig. 7 GEOTRANS execution window.

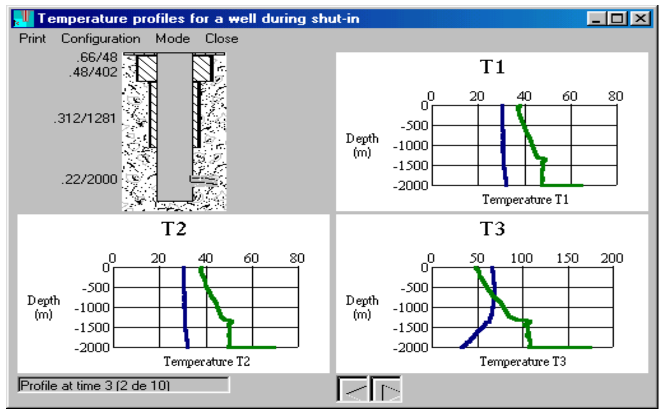


Fig. 8 An example of shut-in simulated drill pipe (T1), wall (T2) and annulus (T3) temperatures.

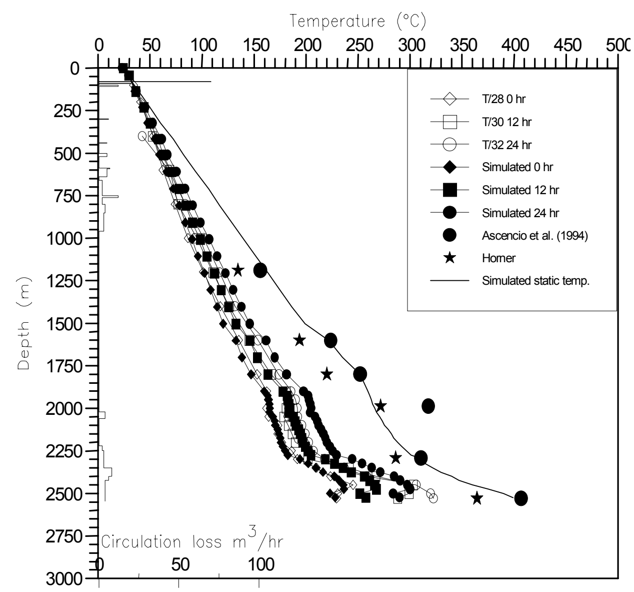


Fig. 9 Measured and simulated temperature profiles of well H-26 during shut-in. Also shown are static temperatures estimated via the Horner and Ascencio et al. (1994) methods. The initial temperature profile is shown as a solid line on the right side o the graph.