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ESTIMATION OF FORMATION TEMPERATURE FROM BOREHOLE MEASUREMENTS IN AGBOR DELTA STATE, NIGERIA

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ABSTRACT

Measurement of temperature in well holes has been the oldest logging technique. A new numerical method that uses inverse methods for thermal stabilization of a borehole after circulation of drilling mud has stopped was discussed. Five geophysical parameters can be estimated from the method: (a) true formation temperature (T_f); (b) mud temperature T_m ; (c) thermal inversion distance (V) into the formation; (d) formation thermal conductivity (K) perpendicular to the borehole and (e) efficiency factor (Z) for heating the mud in the borehole after circulation of mud has stopped. The input data measured include the mud temperature at the surface at the time circulation stops, radius of the borehole, the densities and specific heats of the drilling mud and the formation.

The new inverse procedure shows that the true formation temperature can be estimated from both synthetic data and field data. The mud temperature can be estimated with fairly high degree of accuracy while thermal inversion (V), thermal conductivity (K), and the efficiency factor (Z) can roughly be estimated if high quality data are obtained.

The formation temperature for Agbor, Delta State is within the range of 40 - 49^{0}C.

INTRODUCTION

Measurement of temperature in well holes has been the oldest logging technique. It has been employed mainly to determine heat flow in the ground. True knowledge of formation temperatures are important for geothermal studies, well log interpretation, operation in reservoir engineering and well completion operations. Unfortunately, temperatures recorded in most commercial drilling operations during normal wire line logging are usually lower than the true formation temperature because the shut-in time in these wells is too short to enable the mud in the borehole to reach thermal equilibrium. It usually takes from a few days to a few months for the drilling mud to reestablish thermal equilibrium after mud circulation stops (Bullard, 1947; Luheshi, 1983). It has also been used to locate thermal anomalies caused by fluid and gas flow, abnormal radioactivity, and oxidation regions.

A lot of thermometers have been used, including maximum thermometers, platinum-resistance thermometers, and thermistors. Usually downhole temperature is measured with respect to the surface. The temperature gradients are measured using two detectors at short spacing.

Geothermal gradients vary considerably from one part of the country to the other. In general, the geologically older rocks have lower geothermal gradients than the younger tertiary rocks.

It has been found generally that a rise in temperature of about 18^0F doubles the speed of chemical reactions. The drilling fluids components are relatively stable at surface temperatures but with elevated temperatures found in the well they react readily with one another. An increase in temperature results in excessive reactions of contaminants on the mud system. The high temperatures encountered in deep drilling make the control of drilling fluid properties difficult. In general, mud circulating temperatures are much lower than static formation temperatures.

In the study, two models have been developed to simulate the thermal disturbance associated with drilling followed by subsequent thermal relaxation during the shut-in period. One class attempts to simulate the evolution of the temperature of the complete mud column (Jaeger, 1961; Edwardson et al, 1962; Tragesser et al, 1967, Keller et al, 1973; Holmes and Swift, 1970; and Wooley, 1980). This requires detailed knowledge of the drilling history such as the physical, properties of the rocks, temperature, composition of the mud properties and circulation rate of the fluid. The second class deals with the bottom region of the borehole which measures the borehole temperatures (BHT) (Bullard), 1947; Lachenbruch and Brewer, 1959; Dowdle and Cobb, 1975; Middleton, 1979; Leblanc et al, 1981; Lee, 1982; Middleton, 1982; Jones et al, 1984; and Shen and Beck, 1986).

The models of Middleton (1979) and Leblanc et al (1981) simulate the short-term temperature dissipation in drilling holes, assuming zero disturbance and zero circulation time, and identical mud and rock thermal properties. As a result of this assumption, models which are not dependent upon knowledge of the circulation time were derived. It is often not properly recorded.

In this paper, the formation temperature estimation (FTE) model developed by Song et al (1988) was used to estimate true formation temperature using inverse techniques in some selected boreholes in Agbor Delta State. The model is also based on mathematical and physical principles underlying borehole temperature (BHT) stabilization and is implemented numerically. Five parameters according to Cao et al can be determined by the FTE model,

1. true formation temperature, T_f
2. mud temperature, T_m at the time the mud circulation stops
3. thermal inversion distance, V into the formation
4. the formation thermal conductivity, K perpendicular to the borehole
5. efficiency factor, Z for heating the mud in the borehole after mud circulation stops.

The two parameters considered very well in this paper are (1) and (2) which are input data needed for estimates of T_f and T_m while (3), (4) and (5) are other input data which influences thermal inversion (V), thermal conductivity (K) and the efficiency Z.

Temperature affects hydrocarbon production in several ways. In the reservoir rock, temperature controls the viscosities and mutual solubilities of the three fluids oil, gas and water.

THEORY

FORMATION TEMPERATURE ESTIMATION MODEL

Three basic assumption in the FTE model are

1. Vertical temperature gradients are negligible.
2. The borehole mud and rock formation are homogeneous.
3. Heat transfer is by conduction and heat flow is dominantly radial.

It is also assumed that the mud temperature is constant at the point where the temperatures are measured. The formation is cooled by conduction of the drilling mud.

BOUNDARY CONDITIONS

1. There exist thermal invasion zone close to the borehole with the formation outside this zone being undisturbed by the cooling.
2. The mud in the borehole is uniformly warmed meaning there exist no horizontal thermal gradients in the mud

Applying the heat conduction equation for the model.

$$C_f \frac{\partial T}{\partial t} = K\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) \quad r \geq a \qquad (1)$$

with the initial conditions

$$T_{(r)} = T_m \qquad 0 \leq r \leq a,\ t \leq 0 \qquad (2)$$

$$T_{(r)} = T_m + \left(T_f - T_m\right)\frac{In\left(\frac{r}{a}\right)}{Ln\left(\frac{R}{a}\right)},\ a < r < R,\ t \leq 0 \qquad (3)$$

$$T_{(r)} = T_f,\quad V \leq r < \infty,\ t < 0 \qquad (4)$$

with boundary conditions

$$C_m \pi a^2 \frac{\partial T}{\partial r} = 2Z\pi a K\left(\frac{\partial T}{\partial r}\right)_{r=a},\quad 0 \leq r \leq a \qquad (5)$$

$$T_{(r)} = T_f,\quad V \leq r < \infty,\ t > 0 \qquad (6)$$

where

t = time after mud circulation stops

T_m = mud temperature at $t = 0$

T_f = true formation temperature

K = formation thermal conductivity perpendicular to the borehole

C_m = heat capacity of the mud

C_f = heat capacity of the formation

Z = efficiency factor or fractional factor for heating the mud

a = radius of borehole

To allow for minor sinks of heat from the borehole the factor Z is included. In a purely conductive case, Z = 1. The solution is got by considering equations 1 through 4 and by the boundary conditions of 5 and 6. It takes the form

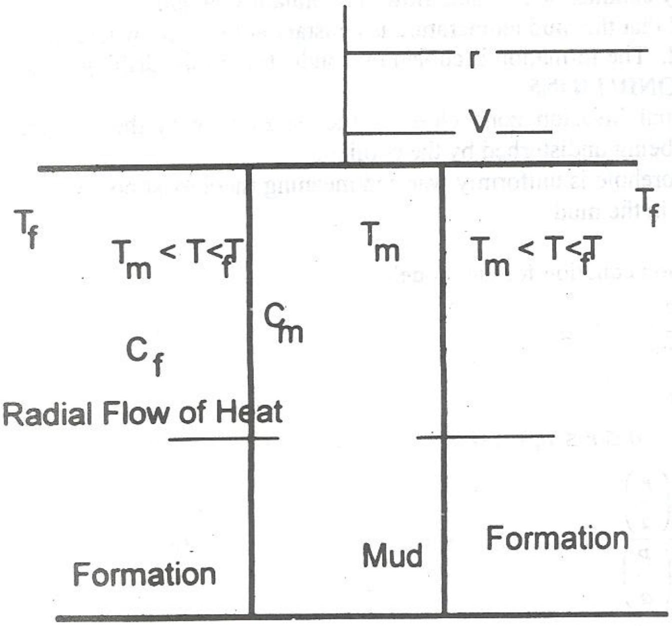

Fig. 1: Assumed physical model for temperature stabilization of a

$$T(t) = T_m + (T_f - T_m)\left[1 - \frac{I(t;\varepsilon, Z_\bullet, \tau)}{I(0;\varepsilon, Z_\bullet, \tau)}\right], r = a \qquad (7)$$

with

$$I(t;\varepsilon, Z, \tau)$$

$$= \int_0^\infty \frac{e^{-s^2\tau}\, ds}{S^3\left\{[SJ_0(S) - Z_\bullet J_1(s)]^2 + [SY_0(s) - Z_\bullet Y_1(s)]^2\right\}} \qquad (8)$$

where J_0, J_1, Y_0, and Y_1 are Bassel functions of the first and second kinds, respectively, ε is a scaling parameter related to the thermal inversion distance V, Z_* is a normalized efficiency factor for heating the mud, and τ = diffusion time scale.

The solution to equation (1) through 5 subject to the constraint that the mud in0 $\leq r \leq a$ is heated uniformly by the invading thermal conduction wave is where T_m is at t = 0 and Z is the efficiency of heating the mud.

$$p\bar{T}(r,p) - T(r,t=0) = \frac{K}{C_f}\left(\frac{\partial^2 \bar{T}}{\partial r^2} + \frac{1}{r}\frac{\partial \bar{T}}{\partial r}\right) \tag{10}$$

where $\bar{T}(r,p)$ is the Laplace transform of $T(r,t)$.

The solution of equation.2 bounded at $r = \infty$ is

$$\bar{T}(r,p) = T(r,t=0)/p + A(p)K_o(qr) \tag{11}$$

with $q^2 = C_f P/K$

If the general prescription of Carslaw and Jaeger (1959) and Luikov (1968), the Laplace transform of equation (9) is

$K_v(x)$ is the modified Bessel function of the second kind of order v and argument x and A(p) is an arbitrary function to be determined from the boundary conditions.

From equation 11 and from inverse transform definition we have

$$T_{(r,t)} = T_{(r)} + \frac{1}{2\pi i}\int_{c-i\infty}^{c+i\infty} A_{(p)}K_o(qr)e^{pt}\,dp,\ t=0 \tag{12}$$

Applying the boundary condition r = a (eqn. 9) to obtain an expression for A(p) in the

$$A(p)\left[K_0(qa) + \frac{2ZKq}{aC_m p}K_1\left(\frac{qa}{p}\right)\right] = \frac{2FK}{aC_m}\,\frac{T_f - T_m}{p^2 a \ln\left(R/a\right)} \tag{13}$$

If $t \geq 0$ we have

$$T_{(r,t)} = T(r,t=0) + \frac{2ZK\left(T_f - T_m\right)}{\left[a^2 C_m \ln\left(R/a\right)\right]}\,\frac{1}{2\pi i}\,x\int_{c-i\infty}^{c+i\infty}\frac{p^{-2}e^{pt}K_o(qr)\,dp}{\left[K_o(qa) + 2ZKqK_1(qa)(aC_m P)^{-1}\right]} \tag{14}$$

The p path of integration is to be chosen so that the integral is zero for $t \leq 0$. The temperature at the borehole wall, r = a, is given by

$$T_{(r,t)} = T_m - \frac{\left(T_f - T_m\right)Z^*}{\ln\left(R/_a\right)} \frac{1}{\pi i} \int \frac{K_o(is)\, e^{-s^2 t/\tau}\, ds}{S^3 \left[K_o(is) + Z^* K_1(is)/is\right]} \tag{15}$$

where τ *is the formation diffusion time given by* $\tau = a^2 C_f/_K$ *and* $S^2 \equiv -p\tau$

$$\text{Where } Z^* = \frac{2ZC_f}{C_m}$$

The p path of integration is to be chosen so that the integral is zero for $t \leq 0$. The temperature at the borehole wall, $r = a$, is given by

If the general prescription given by Carslaw and Jaeger (1959) is followed we can write the modified Bessel function in terms of Bessel functions of the first and second kinds

METHOD ADOPTED

This is an operation to determine temperature at various depths in the hole. The geophysical instrument used was the Abem Terrameter SAS (Signal Averaging System) 300B manufactured in Sweden. The instrument operates in two modes: the resistivity surveying mode and the voltage measuring mode used for logging. It consists of about 200m of logging cable with a logging probe and potential reference electrode (Egbai and Asokhai, 1998).

The cable with down-hole logging probe was lowered into the hole step by step (1m at a time) and readings were taken. This simple logging system makes it possible to delineate formation boundaries with regards to infiltration, porosity and permeability. Water flow boundaries can be detected by measuring temperature changes.

Temperature is measured while the SAS 300 is in the resistivity surveying mode and the MODE selector on the SAS 200 is at the TEMP °C position. The 1 ohm scale and 0.5m A current are used, and 1°C is equivalent to 1 ohm. If the current selector is not at the 0.5m A position, the SAS 300 issues an alarm (beeper signal) and error code 1 appears. Temperature is measured to an accuracy of ±1°C within the 0° --- +50°C range, thus permitting local temperature gradients to be studied in detail.

When using the high precision for temperature gradient studies ample time must be allowed to permit the probe to reach thermal equilibrium vis-a-vis the fluid. The probe was moved slightly up and down a few times while waiting for equilibrium to be established. Resistivity is a function of water temperature, and a standard temperature (usually 25°C) must be specified for reporting resistivities or conductivities. The common standard temperatures are 18, 20 and 25°C. Resistivity is a function of salinity and temperature (Archies, (1952), Edwardson et al. (1962). The net effect of shaliness depends on the amount, types, and distribution of the shale, and on the nature and relative amount of the formation water. The equation used for temperature corrections on resistivity logging for the common standard temperatures (Abem Geophysics, 1988) are

$$R_{18} = R_T\,(0.62 + 0.021T)$$
$$R_{20} = R_T\,(0.58 + 0.021T)$$
$$R_{25} = R_T\,(0.48 + 0.021T)$$

Where T is ^{0}C within the 5 – 50^{0}C range.

RESULTS AND DISCUSSIONS

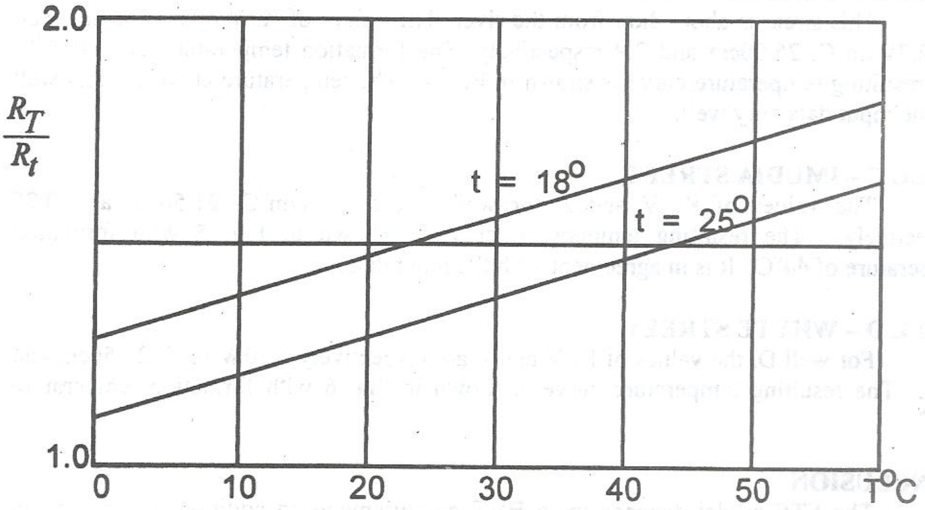

Fig. 2: Graph showing correlation factor curves for standard temperature resistivities. (From Abem Geophysics Handbook1988)

The applicability of the FTE modal was shown using four wells logged at different locations at Agbor, Delta State. For all wells, a = 7.6cm.

The analysis of temperature data from exploration wells are far from perfect, and even data which "look" nice will have errors (Song et al, 1988). The precision of the temperature readings is typically about 1^{0}C. During the course of the research 1^{0}C was added to or subtracted from some of the temperature data. Since the time after circulation was not properly recorded it is also necessary to add or subtract 1hr from the perfect (synthetic) data. The thermal conductivity for sedimentary rocks is typically in the range 0.7 – 7.0 W/m ^{0}C. V is very sensitive to ε. From the work of Edwardson et al (1962), V is expected to be in the range 20 – 80cm for a borehole radius of 10.8cm suggesting that ε most likely should be in the range of 0.18 – 0.6.

For all wells, we used the input parameters density of the mud, ϱ_m = 1.1 g/cm heat capacity of the mud, C_m = 3.2 J/g^{0}C density of the formation, ϱ_f = 2.1J/g^{0}C and heat capacity of formation, C_f = 0.8J/g$_0$C.

WELL A – OKOH STREET

Well A is very close to River Orogodo in Agbor. The aquifer is very shallow which makes temperature fairly low. The values of K, V and Z for this well are 2.10W/m^{0}C, 18.50cm and 0.70 respectively. The formation temperature taken after circulation is 40^{0}C. The resulting temperature curve are shown in Fig. 3.

WELL B – CHARLES STREET

This street is about 3km from the river. The values of K, V and Z for this well are 2.2W/m^{0}C, 25.00cm and 0.9 respectively. The formation temperature T_f = 48.5^{0}C. The resulting temperature curve is shown in Fig. 4. The temperature curve for this well fits the input data very well.

WELL C – IMUDIA STREET

The values of K, V and Z for well C are 1.5W/m^{0}C, 21.50cm and 0.75 respectively. The resulting temperature curve is shown in Fig. 5 with formation temperature of 44^{0}C. It is in agreement with the input data.

WELL D – WHYTE STREET

For well D, the values of K, V and Z are respectively 1.30W/m^{0}C, 24.50cm and 0.85. The resulting temperature curve is shown in Fig. 6 with formation temperature 48^{0}C.

CONCLUSION

The FTE model depends upon BHT measurements in addition to a minimum mud temperature. The input parameters, ϱ_m, ϱ_f, C_m, C_f and a are used to calculate the inversion distance (V), thermal conductivity (K) and the efficiency factor (Z). The three parameters τ (diffusion time scale), ε (scaling parameter related to the thermal inversion distance), and Z* (normalized efficiency factor) are determined using the numerical method. They depend only on the BHT measurements and the minimum mud temperature.

Five physical parameters are involved in the FTE model. These are T_f, T_m, τ, ε and Z*. These are determined using the BHT measurements. The FTE model determines T_f and T_m very accurately but cannot determine τ, ε and Z*.

The prediction of formation temperature is always uncertain when there exist small errors in temperature measurements. If K, V and Z lie outside their acceptable ranges, the predicted formation temperatures will be inaccurate. The study shows the K, V and Z can be roughly estimated if the data are accurate. T_m can be determined if the mud temperature is given a minimum constraint and T_f can be estimated from BHT measurements using a non linear inversion temperature technique when the input temperature data have only negligible error.

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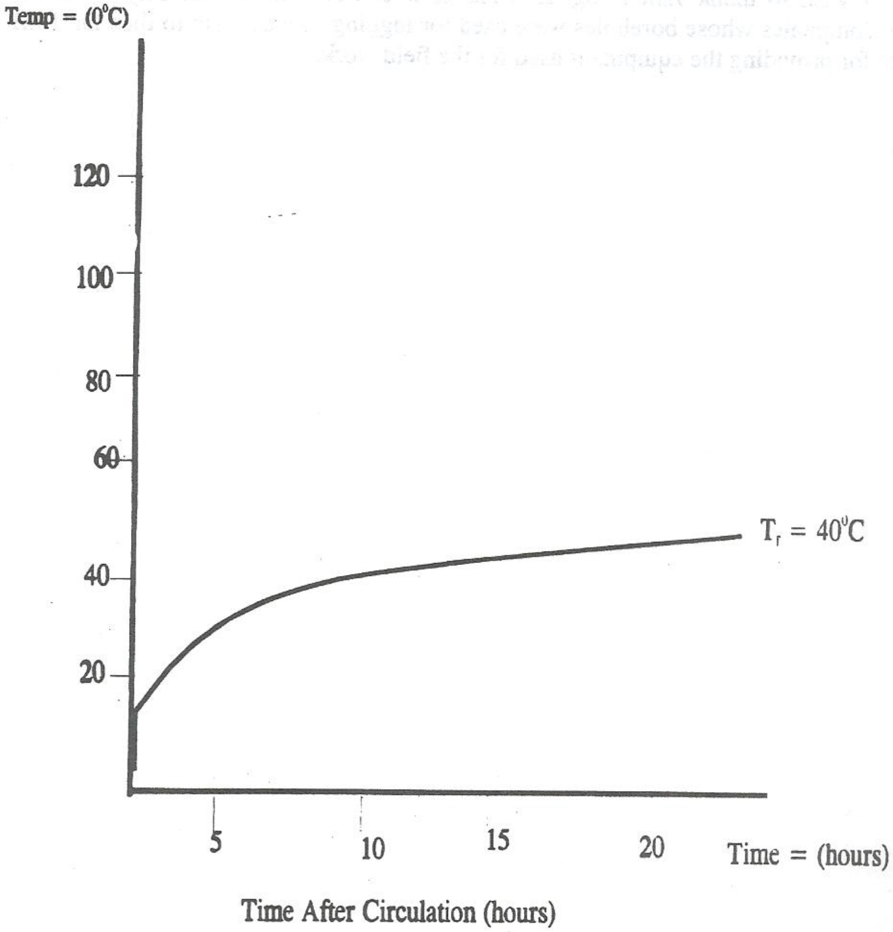
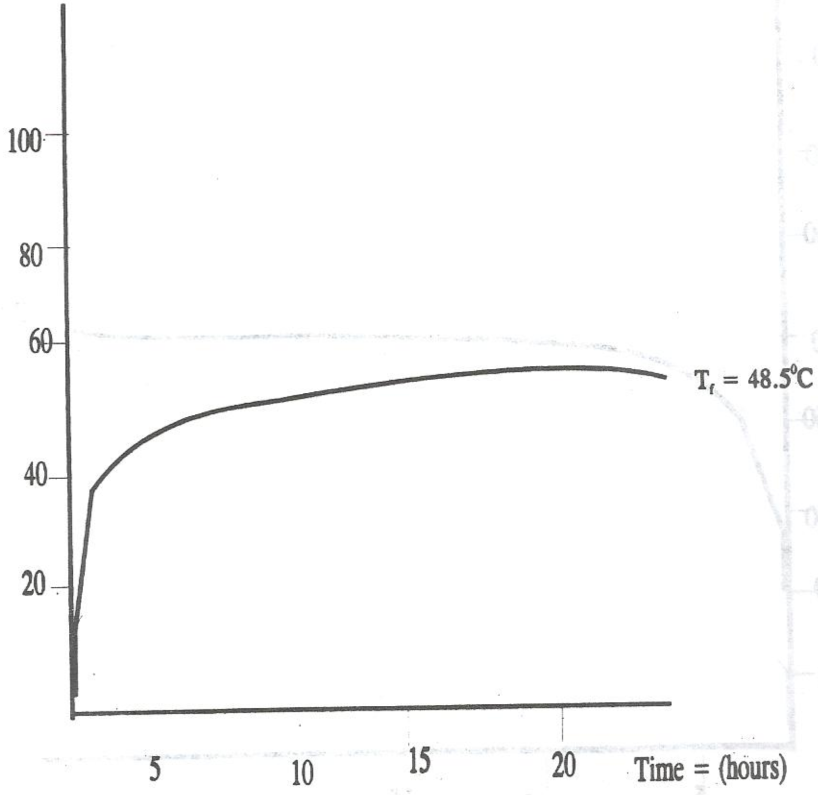


WELL A

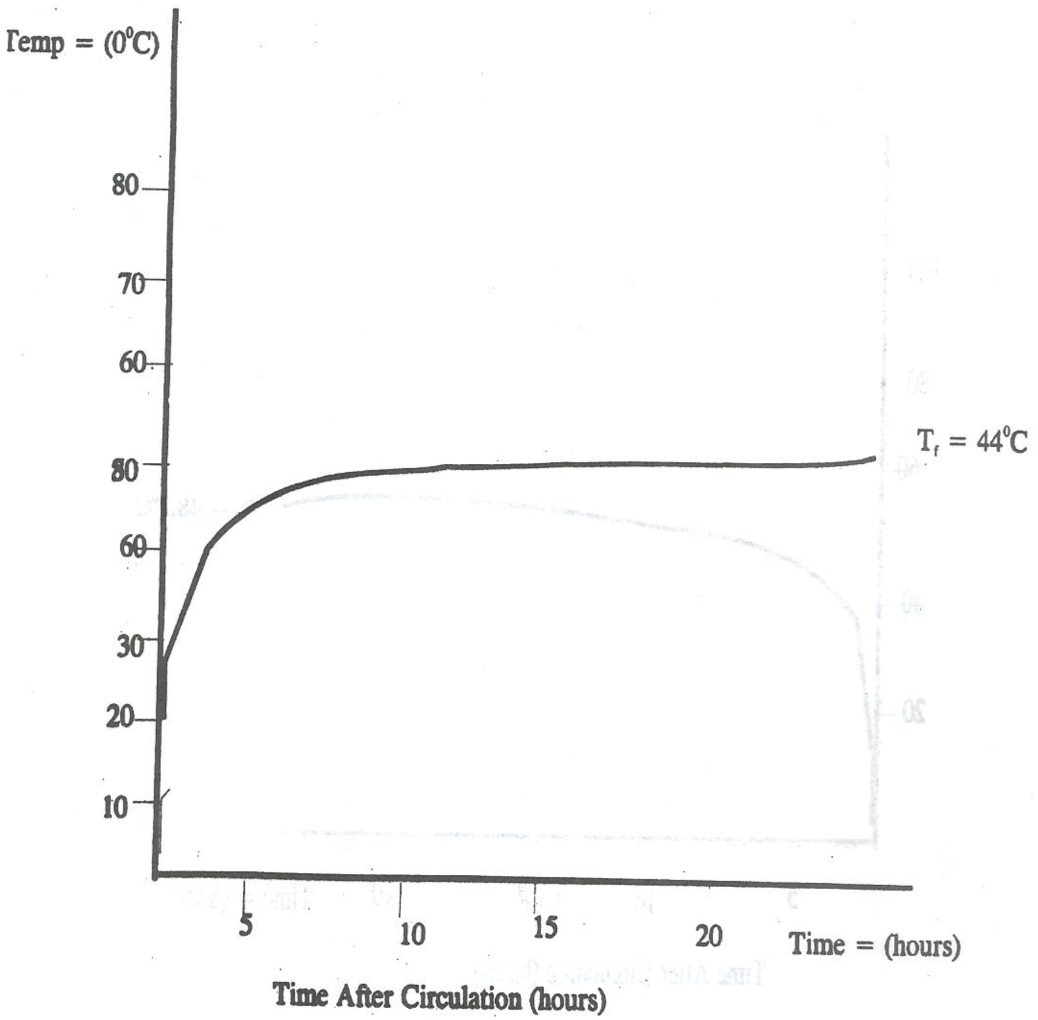
Temp = (0^0C)
120
100
80
60
40
20
T_r = 40^0C
5
10
15
20
Time = (hours)
Time After Circulation (hours)

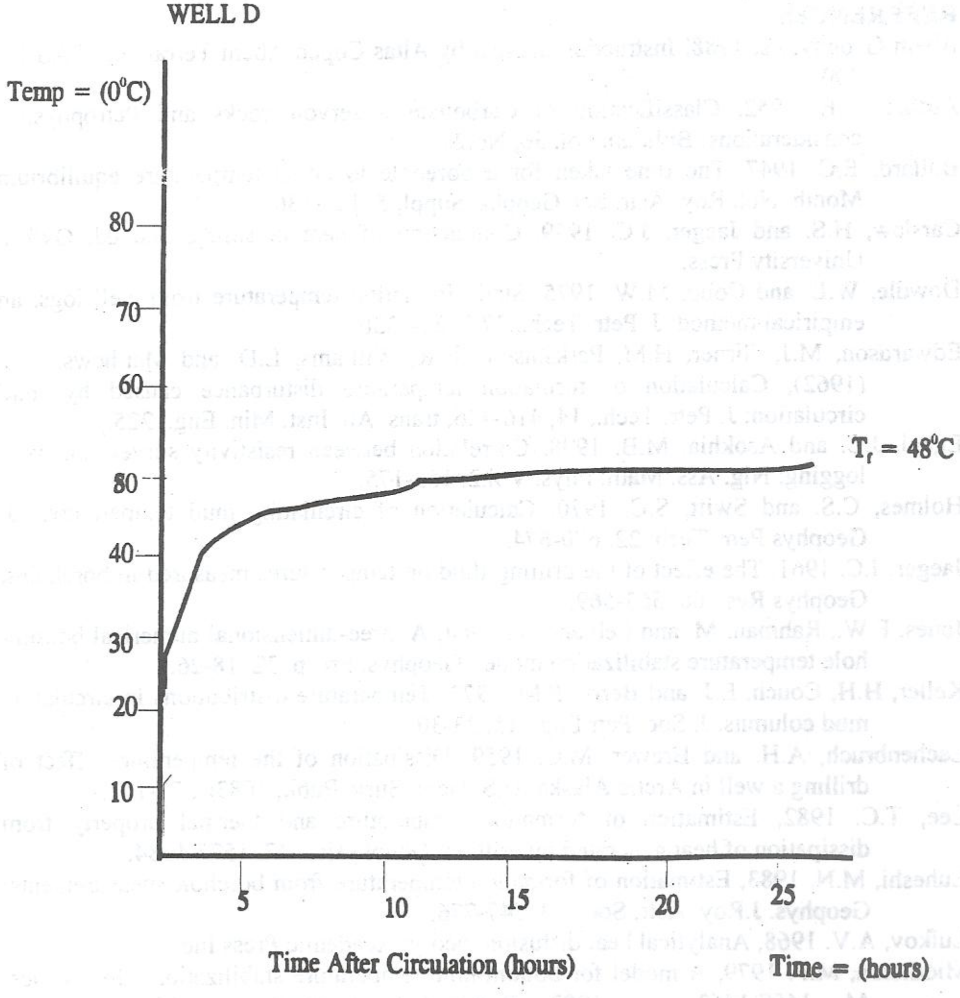
WELL B



Time After Circulation (hours)

WELL C


Γemp = (0°C)
80
70
60
80
60
30
20
10
T$_f$ = 44°C
5
10
15
20
Time = (hours)
Time After Circulation (hours)


WELL D
Temp = (0°C)
80
70
60
50
40
30
20
10
T_f = 48°C
5
10
15
20
25
Time After Circulation (hours)
Time = (hours)

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