AN IMPROVED APPROACH TO ESTIMATING TRUE RESERVOIR TEMPERATURE FROM TRANSIENT TEMPERATURE DATA

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INTRODUCTION

For the purpose of evaluating geothermal reservoirs, the static formation temperature should be established as accurately as possible. A knowledge of the true, static formation temperature is required in estimating the heat content of geothermal reservoirs. The interpretation of electric logs requires accurate formation resistivities, which are dependent on temperature. Reliable static temperature is important in designing completion programs and establishing geothermal gradients.

Unfortunately, the temperatures recorded during logging operations are usually lower than the static temperature. These low temperatures result due to the cooling effect of the mud during circulation. As soon as circulation stops, the temperature around the wellbore begins to build up. Complete temperature recovery in a new well may take anywhere from a few hours to a few months, depending on the formation and well characteristics and the mud circulating time. A long wait for complete temperature recovery would cause sizable increases in drilling costs; hence a quick and easy method is needed for calculating static temperature using early shut-in data.

Following the practice of pressure buildup analysis for wells, the common practice in the goethermal industry is to use Horner plots for estimating static reservoir temperature from temperature buildup data. In this method, the buildup temperature is plotted against the logarithm of dimensionless Horner time, $(t_p + \Delta t)/\Delta t$, where t_p is the circulation time before shut-in and Δt is the buildup time. The data points are then fitted to a straight line, which is extrapolated to infinite Δt, i.e., a dimensionless Horner time of unity. The extrapolated temperature corresponding to this point is taken as the true reservoir temperature. This method is based on the "line source solution" to the diffusivity equation describing the radial conductive heat flow in an infinite system with a vertical line sink withdrawing heat at a constant rate.

Unfortunately, as will be shown later, this conventional Horner plot approach yields values of apparent static temperature that are lower than the true reservoir temperature. The goal of this investigation was to develop an improved approach so that the estimated static temperature will be closer to the true reservoir temperature than is possible from the conventional Horner plot.

THEORY: This paper makes the following simplifying assumptions regarding the system:

1. Cylindrical symmetry exists, with the wellbore as the axis.
2. Heat flow is due to conduction only.
3. Thermal properties of the formation do not vary with temperature.
4. The formation can be treated as though it is radially infinite and homogeneous with regard to heat flow.
5. No vertical heat flow in the formation.
6. The presence of a mud cake is disregarded.
7. The temperature at the formation face is instantaneously dropped to some value and is maintained at this value throughout circulation.
8. After mud circulation ceases, the cumulative radial heat flow at the wellbore is negligible.

A few words should be mentioned to justify the last two assumptions. The assumption 7 implies constant mud temperature which is also taken to be equal to the temperature at the formation face during circulation. To simplify the complex problem, Edwardson, et al.[1] assumed that the difference between the static formation temperature and the mud temperature remained constant during the circulation period. This is not strictly true since the mud which rises in the annulus becomes hotter as the well is drilled deeper. The change in mud temperature in a petroleum well at any depth is of the order of 1 to 2°F/ 100 ft. drilled. However, Edwardson, et al.[1] considered this change slow enough to allow them to take the mud temperature as being constant and numerically solved the equation that describes the temperature buildup in a well for a value of the dimensionless producing time t_{pD} $(= Kt_p/c_p \rho r_w^2)$ equal to $0.4t_p$. *

Figure 1 shows a typical temperature profile for a geothermal well (from Imperial Valley, California) characterized by a finite linear gradient in the conductive zone above the geothermal reservoir, and a practically zero gradient due to convection within the reservoir. Hence, the mud temperature will increase rapidly as the well is drilled deeper in the region above where the sharper break occurs in the geothermal gradient. In the zone below the break point the mud temperature remains relatively constant as the depth of the well is increased. Thus, the mud temperature will not increase but will stay relatively constant as drilling proceeds through the geothermal reservoir.

Now let us look at the assumption 8. After circulation ends, heat will still be flowing into the wellbore. Raymond[2] stated that the amount of fluid in the wellbore is extremely small compared with the volume of formation whose temperature has been affected by circulation. Hence, the conduction of heat into the wellbore can be neglected. An analysis of the system by Raymond[2] also shows that free convection within the wellbore is negligible. It is assumed that the running of logging tools repeatedly in and out of the hole has no effect on the temperature buildup.

With these assumptions the transient temperature in the formation around a well as a function of radial distance and time is given by the

* Nomenclature at the end of the paper

following partial differential equation in terms of dimensionless variables:

$$\frac{\partial^2 T_D}{\partial r_D^2} + \frac{1}{r_D}\frac{\partial T_D}{\partial r_D} = \frac{\partial T_D}{\partial t_D} \tag{1}$$

With Initial Condition: $T_D(r_D,0) = 0$ (2)

Inner Boundary Condition: $T_D(1,t_D) = 1$ (3)

and Outer Boundary Condition: $\lim_{r_D \to \infty} T_D(r_D,t_D) = 0$ (4)

The dimensionless quantities in the above equation are defined as:

$$T_D = \frac{T_i - T(r,t)}{T_i - T_{wf}} \tag{5}$$

$$t_D = Kt/C_p \rho r_w^2 \tag{6}$$

$$r_D = r/r_w \tag{7}$$

Ehlig-Economides[3] solved the problem of pressure buildup for a well produced at constant pressure. This is the same problem as temperature buildup described in this report except that Ehlig-Economides[3] solution deals with pressure instead of temperature. The general solution for temperature buildup is given by the following equation in dimensionless form[3]:

$$\frac{T_i - T_{ws}(\Delta t_D)}{T_i - T_{wf}} = 1 + \int_{t_{pD}}^{t_{pD}+\Delta t_D} q_D(\tau) P_{wD}'(t_{pD} + \Delta t_D - \tau)d\tau \tag{8}$$

A computer program was developed by Ehlig-Economides[3] to integrate numerically Eq. 8. This program was modified and used to develop a family of dimensionless Horner-type temperature buildup curves shown in Figure 2. These curves describe the dimensionless temperature rise (T_{Dws}) at the wellbore as a function of dimensionless producing time, t_{pD}, and the dimensionless Horner time. Dimensionless temperature buildup, T_{Dws}, is defined as:

$$T_{Dws} = 2\pi Kh(T_i - T_{ws})/\overline{q} \tag{9}$$

where $\overline{q}$ is an average heat flow rate at the wellbore during circulation.

Figure 3 shows a typical Horner-type curve considered in this study for a $T_{pD} = 10$. It can be seen from Fig. 3 that if a Horner-type analysis is used with early shut-in data, the temperature extrapolated for a dimensionless Horner time equal to one will always yield values of static temperature lower than they actually are. Dowdle and Cobb[4] were the first ones to point this out in the literature. By looking at Figure 5 it can be seen that using very long shut-in data will yield the proper static temperature. A long shut-in time required to obtain such data ties up expensive rig time.

It is widely believed that straight lines can be drawn through the data when using the conventional Horner technique. The data used in these plots are usually taken over a short period of shut-in time. The problem of calculating static formation temperature from short time shut-in data has been approached in this report in the following manner.

T_{Dws} (Fig. 2) is a function of both dimensionless producing (in this case, producing and circulating are synonymous) time, t_{pD}, and dimensionless Horner time, $(t_p + \Delta t)/\Delta t$. Over short ranges of dimensionless Horner time, we can approximate T_{Dws} as being a straight line on semi-log coordinates (see Fig. 3). The equation of this line is:

$$T_{Dws} = T^*_{Dws}\ (t_{pD}) + b(t_{pD})\ \mathrm{Log}\left[(t_p+\Delta t)/\Delta t\right] \tag{10}$$

where $T^*_{Dws}(t_{pD})$ is the intercept Horner time of unity and $b(t_{pD})$ is the slope of the line. T^*_{Dws} is defined as:

$$T^*_{Dws} = 2\pi Kh\ (T_i - T^*_{ws})/\overline{q} \tag{11}$$

Here T^*_{Dws} corresponds to a dimensionless temperature drop between the true static temperature (T_i) and a false initial temperature (T^*_{ws}) obtained by extrapolation of a conventional Horner line.

Combining Equations (9), (10) and (11) and manipulating the algebra we get

$$T_i = T^*_{ws} + mT_{DB}\ (t_{pD}) \tag{12}$$

where

$$T_{DB}(t_{pD}) = T^*_{Dws}/b(t_{pD}), \tag{13}$$

and m is the slope of the conventional Horner straight line. Equation (12) shows that the term $T_{DB}(t_{pD})$ is the dimensionless correction factor for temperature buildup at a dimensionless time t_{pD}.

APPLICATION

$T_{DB}(t_{pD})$ were determined by least-square fitting T_{Dws} curves in Fig. 2 in ranges of $(t_p+\Delta t)/\Delta t$ where it was felt that the curve could be approximated as a straight line. These ranges of $(t_p+\Delta t)/\Delta t$ were chosen to be 1.25 to 2, 2 to 5, and 5 to 10. The intercept, T^{*p}_{Dws} (t_{pD}), was divided by the slope, $b(t_{pD})$ to give T_{DB}. This procedure was carried out for a number of

t_{pD}'s. Then a smooth curve was fitted through the points. The result is a curve that describes T_{DB} as a function of both t_{pD} and a range of $(t_p+\Delta t)/\Delta t$. See Figures 4 through 6.

The curves in Figure 2 were evaluated using an "average" heat flow rate, $\bar{q}$. Horner[6] suggested that the last established flow rate $q(t_p)$, and a corrected flow time, $t^* = Q(t_p)/q(t_p)$, should be used in the pressure buildup anaysis. Since both $Q(t_p)$ and $q(t_p)$ are very difficult, if not impossible, to determine for the temperature build-up case, an average flow rate $(\bar{q})$ was used so that the true producing time, t_p, could be used in the analysis, and the conventional Horner plot's assumption of constant heat flow rate $(\bar{q})$ can be satisfied.

Jacob and Lohman[7] stated that using the average rate prior to shut-in was justifiable if variation in q_D is small for $0<t_D<t_{pD}$. Ehlig-Economides[3] also confirmed that this method was correct. The buildup equation in terms of the parallel problem of pressure buildup is:

$$2\pi Kh(P_i - P_{ws})/q\mu = 1.1513 \text{ Log}\left[(t_p+\Delta t)/\Delta t\right] \qquad (14)$$

where the constant, 1.1513, is the slope of the semi-log straight line. The straight line in Fig. 2 has this "proper" slope of 1.1513.

Equation (14) is of the same form as the one proposed by earlier authors[8,9,10,11,12]. As is evident from Figure 2, this equation does not match the theoretical buildup curves unless Horner time is less than 1.3. Hence the need for the correction factor presented in this paper.

The nonlinearity of the curves in Fig. 2 are due to two reasons. First, large changes in q occur during circulation. Second, circulating time is usually too short to allow the correct semi-log straight line to develop for early shut in data. Nonlinearity also occurs in buildup curves for systems produced at a constant rate when flow time is short.

As shown before, the correction factor, T_{DB}, used to multiply the slope, m, is a function of t_{pD}. This parameter, t_{pD}, is a function of the thermal conductivity, K, specific heat, C_p, and density, ρ, of the formation as well as the wellbore radius and circulating time. These rock properties are not always known, especially in exploratory regions. These properties can be estimated by examining the drill cuttings and using the data from Somerton[13]. In the author's opinion, it is not critical to know exactly what these thermal properties are. A $\pm$50 percent error in t_{pD} will create an error in the calculated initial temperature in the range of $\pm 10^oF$. If a conventional Horner plot using shut-in data in the range of $(t_p + \Delta t)/\Delta t$ between 5 and 10, is used without correcting T^*_{ws}, the calculated final temperature could be about 30^oF too low.

The solution presented in this report is based on a conductive model and should not be used to estimate the equilibrium temperature for a zone where significant lost circulation has taken place. However, static formation temperature may still be estimated if lost circulation takes place at the bottom of the hole. If this is the case, then a datum can be chosen, far enough away from the point where lost circulation began so that convective heat flow into the reservoir can be ignored.

EXAMPLES

Based on this study we recommend the following procedure for calculating initial reservoir temperature:

1. Choose depth of interest and find the time the bit reached this depth.
2. Determine circulation time, t_p.
3. Read shut-in temperature for depth of interest from temperature log and calculate corresponding shut-in time from data on when logging runs began and ended and the logging speed.
4. Plot T_{ws} vs. $(t_p + \Delta t)/\Delta t$ on semi-log paper and fit the best straight line through the data extrapolating the line to $(t_p + \Delta t)/\Delta t = 1$.
5. Determine T^*_{ws} and m from plot of T_{ws} vs. $(t_p + \Delta t)/\Delta t$.
6. Calculate t_{pD} using Equation 6.
7. Determine range of $(t_p + \Delta t)/\Delta t$ that the shut-in data falls into. Then go to Figures 4 through 6, choosing the one that corresponds to this range, and find T_{DB} as a function of t_{pD}.
8. Calculate T_i using T*, m, and T_{DB} with Equation 12.

Reference 5 provides a TI59 pocket calculator program for quickly determining the initial reservoir temperature at the drilling site. Two field examples of the proposed method are given below.

Example 1: Data are plotted in Figure 7.

Shut-In Wellbore Temperature
Depth - 4980 ft.
Circulation Time, t_p = 15 hours

Shut-in Time Δt (hours)	Dimensionless Horner Time $(t_p + \Delta t)/\Delta t$	Shut-in Temperature T_{ws} ($^\circ$F)
7	3.14	286.0
11	2.33	308.0
13.50	2.11	312.0

From Fig. 7, $T^*_{ws} = 364.5^\circ$F and m = 155.1

Since the parameters K, C_p, ρ, and r_w were not given with the above data, it has been assumed that for the purpose of this example, that $K/C_p \rho r_w^2$ is equal to 0.4/hours, which is a good average number for most common lithologies. Then t_{pD} = 15 hours (0.4/hours) = 6.0.

From Figure 5, T_{DB} = 0.137. The initial reservoir temperature may now be computed by means of Equation 12.

$$T_i = 364.5 + (155.1)\ (0.137) = 385.8^\circ F.$$

The static temperature for this depth was later determined to be 379°F. Thus, the predicted final temperature was within 2 percent of the equilibrium temperature, while conventional Horner analysis yields a value of 364.5°F.

Example 2: This example is from Kelley Hot Springs geothermal reservoir, Modoc County, California and the data are from 3,395 Ft.

Circulation Time, tp = 12 hours

Shut-In Time Δt (hours)	Dimensionless Horner Time $(t_p + \Delta t)/\Delta t$	Shut-In Temperature T_w (^oF)
14.3	1.84	183
22.3	1.54	194
29.3	1.41	202

The data are plotted in Fig. 8, from which we get $T^* = 225.2^oF$ and $m = 166.1$.

The parameter $K/c_p\rho r_w^2$ is 0.27/hour. Thus $t_{pD} = 0.27 \times 12 = 3.24$

From Figure 4, $T_{DB} = 0.0345$.

Using Eq. 12, $T_i = 225.2 + (166.1)).0345 = 230.9^oF$

The initial reservoir temperature for this depth was later found to be 239^oF, as compared to a value of 225.2^oF estimated from conventional Horner analysis.

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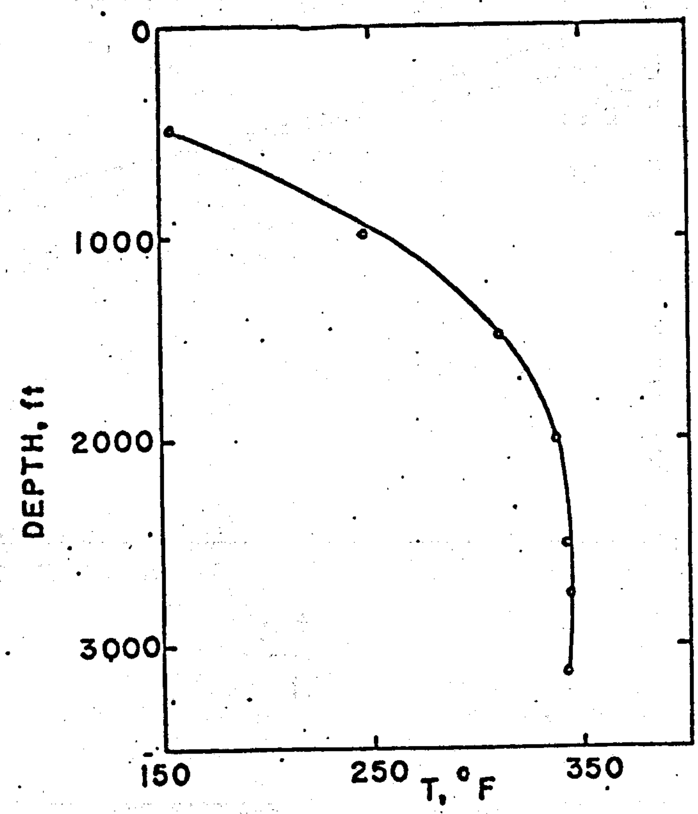

FIG. 1: TEMPERATURE PROFILE IN TYPICAL GEOTHERMAL WELL

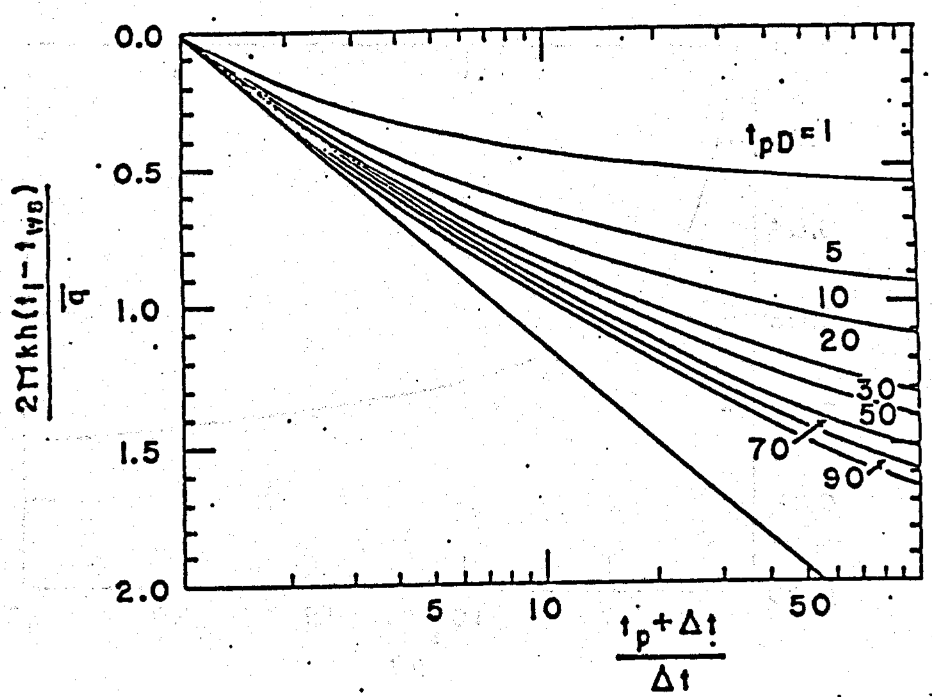

FIG. 2: DIMENSIONLESS HORNER-TYPE TEMPERATURE BUILDUP CURVES USED IN THIS STUDY

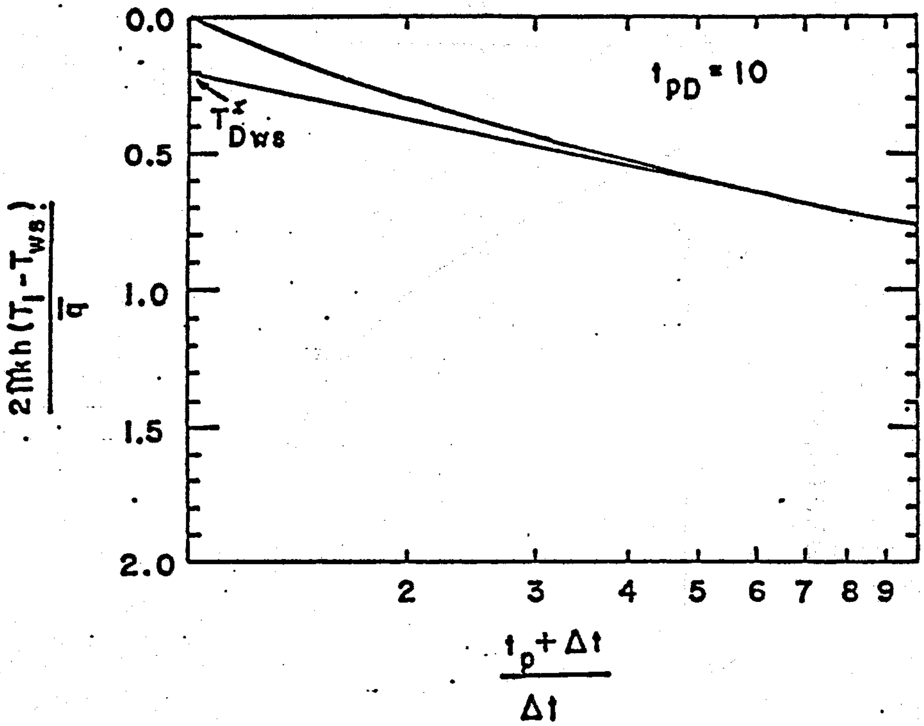

FIG. 3: A TYPICAL HORNER-TYPE TEMPERATURE BUILDUP CURVE FOR $t_D = 10$

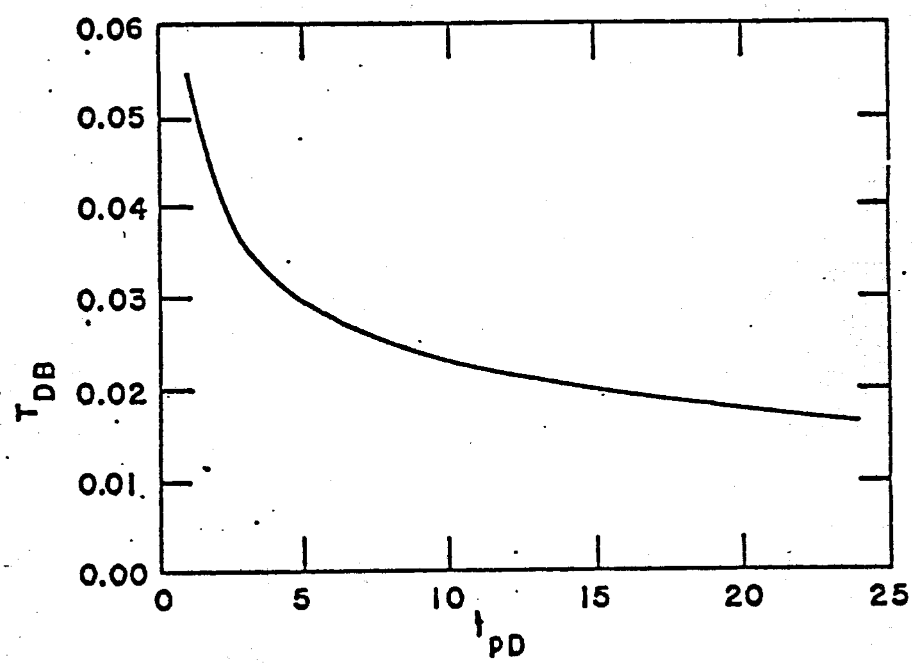

FIG. 4: T_{DB} VALUES AS A FUNCTION OF t_{pD} FOR A HORNER TIME OF 1.25 TO 2

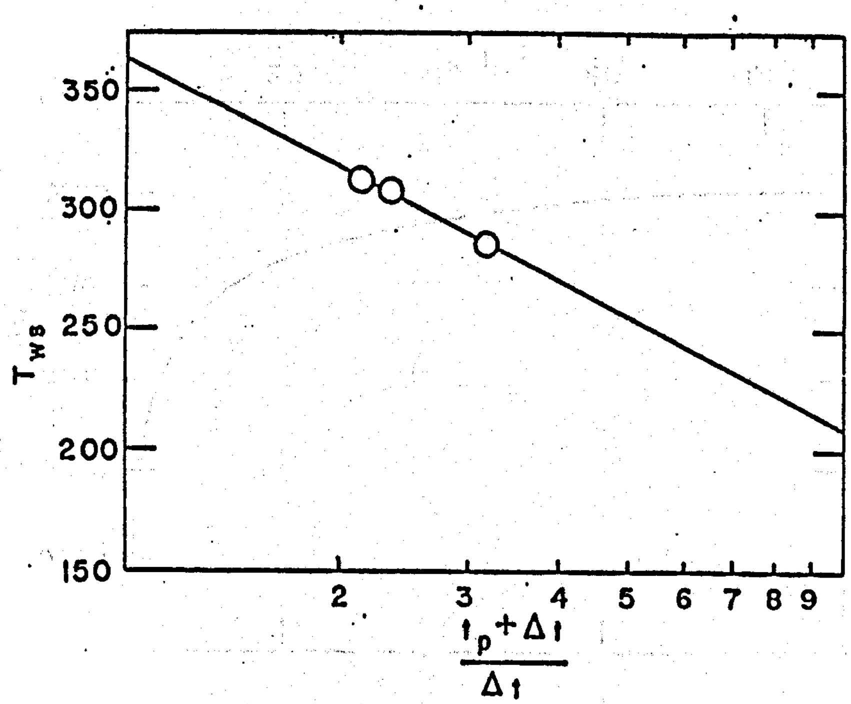

FIG. 7: HORNER PLOT FOR EXAMPLE 1

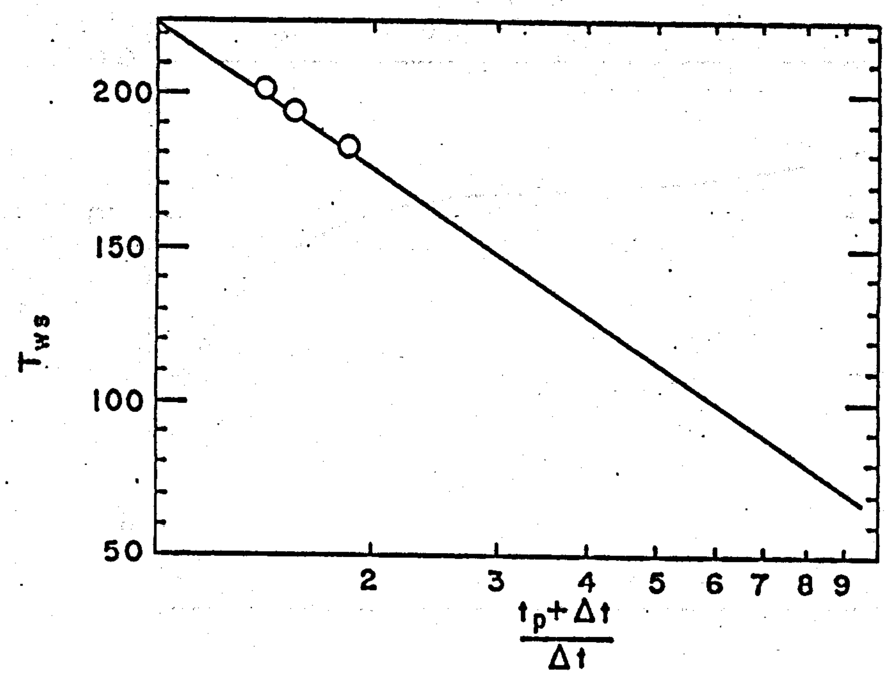

FIG. 8: HORNER PLOT FOR EXAMPLE 2

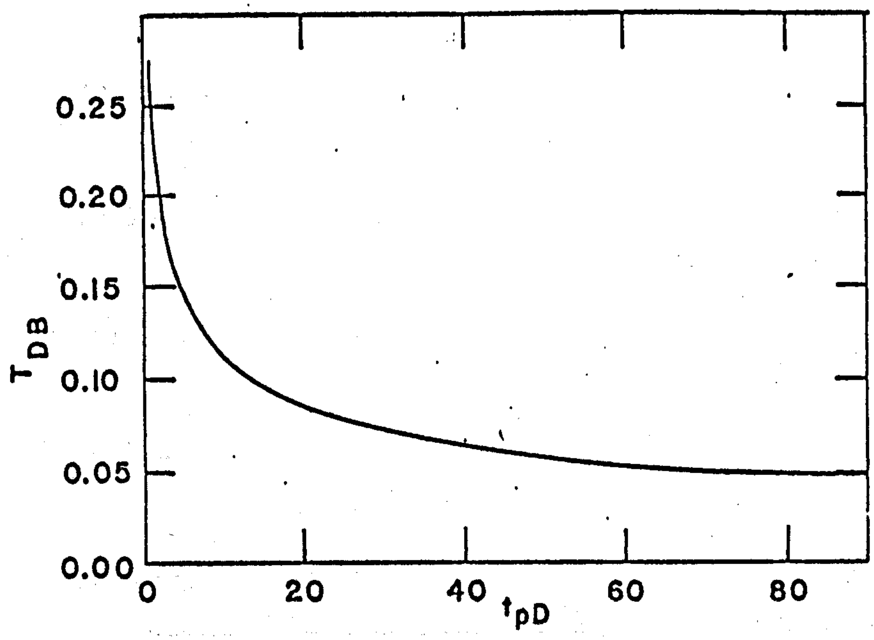

FIG. 5: T_{DB} VALUES AS A FUNCTION OF t_{pD} FOR HORNER TIME OF 2 TO 5

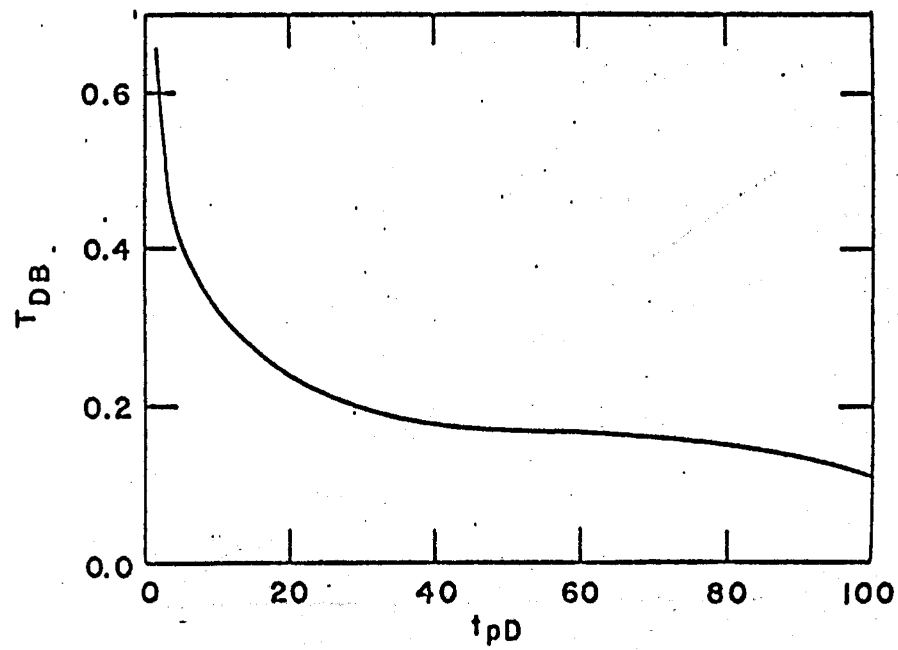

FIG. 6: T_{DB} VALUES AS A FUNCTION OF t_{pD} FOR HORNER TIME OF 5 TO 10