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An Improved Horner Method for Determination of Formation Temperature

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ABSTRACT

A new technique has been developed for determination of the formation temperature from bottom-hole temperature logs. The adjusted circulation time concept and a semi-analytical equation for the dimensionless temperature at the wall of an infinite long cylindrical source with a constant heat flow rate is used to obtain the working formula. It is shown that the transient shut-in temperature is a function of the mud circulation and shut-in time, formation temperature, thermal diffusivity of formations, and well radius. The sensitivity of the predicted values of formation temperature to the thermal diffusivity is shown. Two examples of calculations are presented.

1. INTRODUCTION

The establishing of geothermal gradients, determination of heat flow density, well log interpretation, well drilling and completion operations, and evaluation of geothermal energy resources require knowledge of the undisturbed reservoir temperature. In most of the cases bottom-hole temperature surveys are mainly used to determine the temperature of the earth's interior. The drilling process, however, greatly alters the temperature of the reservoir immediately surrounding the well. The temperature change is affected by the duration of drilling fluid circulation, the temperature difference between the reservoir and the drilling fluid, the well radius, the thermal diffusivity of the reservoir, and the drilling technology used. Given these factors, the exact determination of formation temperature at any depth requires a certain length of time in which the well is not in operation. In theory, this shut-in time is infinitely long. There is, however, a practical limit to the time required for the difference in temperature between the well wall and surrounding reservoir to become vanishingly small.

The objective of this paper is to suggest a new approach in utilizing bottom-hole temperature logs in deep wells and to present a working formula for determining the undisturbed formation temperature. For this reason we do not here conduct a review and analysis of relevant publications. We will discuss only the Horner method, which is often used in processing field data. Earlier we used the condition of material balance to describe the pressure build-up for wells produced at constant bottom-hole pressure (Kutasov 1989). The build-up pressure equation was derived on the basis of an initial condition approximating the pressure profile in the wellbore and in the reservoir at the time of shut-in. It was shown that a modified Horner method could be used to estimate the initial reservoir pressure and formation permeability.

In this paper we will consider only bottom-hole temperature logs. This means that the thermal disturbance of formations (near the well's bottom) is caused by short drilling time and, mainly, by one (prior to logging) continuous drilling fluid circulation period. The duration of this period is usually 3-12 hours.

It is known that the same differential diffusivity equation describes the transient flow of incompressible fluid in porous medium and heat conduction in solids. As a result, a correspondence exists between the following parameters: volumetric flow rate, pressure gradient, mobility (formation permeability and viscosity ratio), hydraulic diffusivity coefficient; and heat flow rate, temperature gradient, thermal conductivity and thermal diffusivity. Thus, the same analytical solutions of the diffusivity equation (at corresponding initial and boundary conditions) can be utilized for determination of the above-mentioned parameters. In this study we will use a similar technique (Kutasov 1989) for determination undisturbed (initial) formation temperature from bottom-hole temperature logs. As will be shown below, by introducing the adjusted circulation time concept, a new method of determining static formation temperature can be developed.

2. MATHEMATICAL MODELS

The determination of static formation temperatures from well logs requires knowledge of the temperature disturbance produced by circulating drilling mud.

To determine the temperature distribution $T(r,t)$ in formations we will consider three mathematical models to describe the thermal effect of the circulating drilling fluid.

2.1 Constant bore-face temperature

The results of field and analytical investigations have shown that in many cases the temperature of the circulating fluid (mud) at a given depth can be assumed constant during drilling or production (Lachenbruch and Brewer 1959; Ramey 1962; Edwardson *et al*. 1962; Jaeger 1961; Kutasov, Lubimova and Firsov 1966; Raymond 1969). In this case it is necessary to obtain a solution of the diffusivity equation for the following boundary and initial conditions:

$$\left.\begin{cases} T(r,0) = T_i & r_w \le r < \infty \qquad t > 0 \\ T(r_w,t) = T_w & T(\infty,t) = T_i \end{cases}\right\}. \qquad (1)$$

It is known that in this case the diffusivity equation has a solution in complex integral form (Jaeger (1956); Carslaw and Jaeger (1959)). Jaeger (1956) presented results of a numerical solution for the dimensionless temperature $T_D(r_D,\ t_D)$ with values of r_D ranging from 1.1 to 100 and t_D ranging from 0.001 to 1000.

The dimensionless temperature T_D, dimensionless distance r_D, and dimensionless time t_D are:

$$T_D(r_D,t_D) = \frac{T(r,t)-T_i}{T_w - T_i},$$
$$r_D = \frac{r}{r_w}, \qquad t_D = \frac{\chi t}{r_w^2}. \tag{2}$$

Lachenbruch and Brewer (1959) have shown that the wellbore shut-in temperature mainly depends on the amount of thermal energy transferred to (or from) formations during drilling. For this reason we present below formulas that allow us to calculate the heat flow rate and cumulative heat flow from the wellbore per unit of length:

$$q = 2\pi\lambda(T_w - T_i)q_D(t_D). \tag{3}$$

Analytical expressions for the function $q_D = f(t_D)$ are available only for asymptotic cases or for large values of t_D. The dimensionless flow rate was first calculated and presented in a tabulated form by Jacob and Lohman (1952). Sengul (1983) computed values of q_D for a wider range of t_D and with more table entries. We have found (Kutasov, 1987) that for any values of dimensionless production time a semi-theoretical (4) can be used to forecast the dimensionless heat flow rate:

$$q_D = \frac{1}{\ln\left(1 + D\sqrt{t_D}\right)}, \tag{4}$$

$$D = d + \frac{1}{\sqrt{t_D} + b}, \qquad d = \frac{\pi}{2},$$

$$b = \frac{2}{2\sqrt{\pi} - \pi}. \tag{5}$$

The cumulative heat flow from (or into) the wellbore per unit of length is given by:

$$Q = 2\pi\rho c_p r_w^2 (T_w - T_i) Q_D(t_D), \tag{6}$$

where $Q_D(t_D)$ is the dimensionless cumulative heat flow (Kutasov, 1987).

2.2 Cylindrical source with a constant heat flow rate

In this case the transient temperature T_w is a function of time, thermal conductivity, and volumetric heat capacity of formations. Analytical expression for the function T_w is available only for large values of the dimensionless time (t_D). To determine the temperature T_w it is necessary to obtain the solution of the diffusivity equation under the following boundary and initial conditions:

$$T(t=0,r) = T_i, \qquad r_w \le r < \infty, \tag{7}$$

$$\left(r\frac{\partial T}{\partial r}\right)_{r_w} = -\frac{q}{2\pi\lambda},$$
$$T(t, r\to\infty) \to T_i, \qquad t > 0. \tag{8}$$

It is well-known that in this case the diffusivity equation has a solution in complex integral form (Van Everdingen and Hurst (1949); Carslaw and Jaeger (1959)). Chatas (Lee, 1982) tabulated this integral for $r = r_w$ over a wide range of values of t_D.

For the wall transient temperature we obtained the following semi-analytical equation (Kutasov, 2003)

$$T_w = T(t, r_w) = T_i + \frac{q}{2\pi\lambda}\ln\left[1 + \left(c - \frac{1}{a+\sqrt{t_D}}\right)\sqrt{t_D}\right], \tag{9}$$

$$a = 2.7010505, \qquad c = 1.4986055.$$

Let us introduce the dimensionless wall temperature

$$T_{wD}(t_D) = \frac{2\pi\lambda(T_w - T_i)}{q}. \tag{10}$$

Then

$$T_{wD}(t_D) = \ln\left[1 + \left(c - \frac{1}{a+\sqrt{t_D}}\right)\sqrt{t_D}\right]. \tag{11}$$

Values of T_{wD} calculated from (11) and results of a numerical solution ("exact" solution) by Chatas (Lee, 1982) were compared (Kutasov, 2003). The agreement between values of T_D calculated by these two methods was very good. For this reason the principle of superposition can be used without any limitations.

2.3 Well as a linear source

It is clear from physical considerations that, for large values of dimensionless time, the solutions for cylindrical and linear sources should converge. To develop the solution for a linear source, the boundary condition expressed by (8) should be replaced by the condition

$$\lim_{r\to 0}\left(r\frac{\partial T}{\partial r}\right) = -\frac{q}{2\pi\lambda}, \qquad t > 0 \tag{12}$$

and the well known solution for an infinitely long linear source with a constant heat flux rate in an infinite-acting medium is (Carslaw and Jaeger, 1959)

$$T_r(r,t) = T_i - \frac{q}{4\pi\lambda}Ei\left(-\frac{r^2}{4\chi t}\right), \tag{13}$$

where $Ei(-x)$ is the exponential integral.

Introducing the dimensionless radial temperature

$$T_{rD}(r_D,t_D) = \frac{T(r,t)-T_i}{T_w - T_i}, \tag{14}$$

we obtain

$$T_{wD}(t_D) = -\frac{1}{2}Ei\left(-\frac{1}{4t_D}\right), \tag{15}$$

$$T_{rD}(r_D,t_D) = \frac{Ei\left(-\frac{r_D^2}{4t_D}\right)}{Ei\left(-\frac{1}{4t_D}\right)}. \tag{16}$$

3 ADJUSTED CIRCULATION TIME

In this Section we will show that by using the adjusted circulation time concept (Kutasov, 1987; 1989) a well with a constant bore-face temperature can be substituted by a cylindrical source with a constant heat flow rate. Let us assume that at a given depth the fluid circulation started at the moment of time t = 0 and stopped at t = t_c. The corresponding values of the dimensionless heat flow rates (4) are

$$q_D(t=0)=\infty, \qquad q_D(t=t_c)=q_D \tag{17}$$

and the values of the dimensionless cumulative heat flow are

$$Q_D(0)=0, \qquad Q_D(t_c)=Q_D. \tag{18}$$

If the assumption is made that during the adjusted (equivalent) circulation period the heat flow rate is constant and equal to,

$$q(t=t_c)=2\pi\lambda(T_w-T_i)q_D(t_{cD}), \quad t_{cD}=\frac{\chi t_c}{r_w^2} \tag{19}$$

then from (3) and (6) (using the condition of thermal energy balance) we obtain an equation for the adjusted circulation time

$$Q=2\pi\rho c_p r_w^2(T_w-T_i)Q_D(t_D)= \\ 2\pi\lambda(T_w-T_i)q_D(t_{cD})\cdot t_c^* \tag{20}$$

or

$$t_D^*=\frac{\chi t_c^*}{r_w^2}=\frac{\lambda t_c^*}{\rho c_p r_w^2}=\frac{Q_D}{q_D} \tag{21}$$

The values of q_D and Q_D are presented in the literature (Van Everdingen and Hurst, 1949; Jacob and Lohman, 1952; Edwardson *et al*. 1962; Sengul, 1983). Using these data we obtained (Kutasov, 1987):

$$t_{cD}^*=Gt_{cD}, \tag{22}$$

$$\left\{\begin{array}{ll} G=1+\dfrac{1}{1+AF} & t_{cD}\le 10 \\ F=[\ln(1+t_{cD})]^n & n=2/3 \quad A=7/8 \end{array}\right\}, \tag{23}$$

$$G=\frac{\ln t_{cD}-\exp\left(-0.236\sqrt{t_{cD}}\right)}{\ln t_{cD}-1}, \quad t_{cD}>10. \tag{24}$$

The correlation coefficient $G(t_{cD})$ varies in the narrow limits: $G(0)$ = 2 and $G(\infty)$ = 1 (Figure 1).

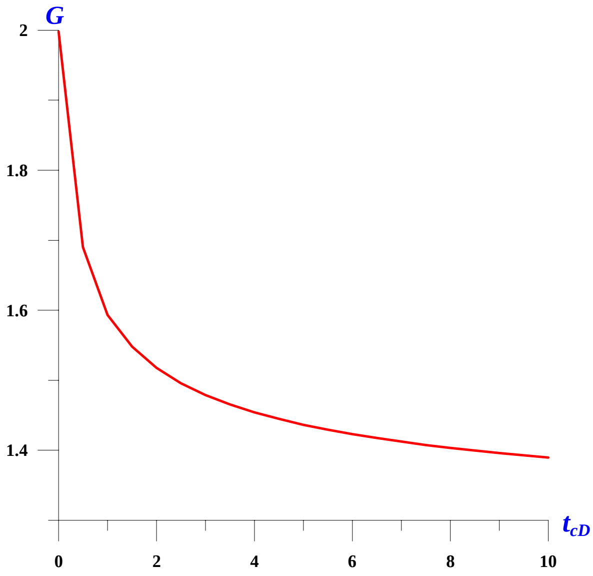

Figure 1. Correlation coefficient versus dimensionless time

4 CIRCULATION PERIOD

Field investigations have shown that the bottom-hole circulating (without penetration) fluid temperature after some stabilization time can be considered constant (Figures 2 and 3). The solid curves in Figure 2 present the calculated circulating mud temperatures (at a constant heat transfer coefficient) by using the Raymond (1969) model.

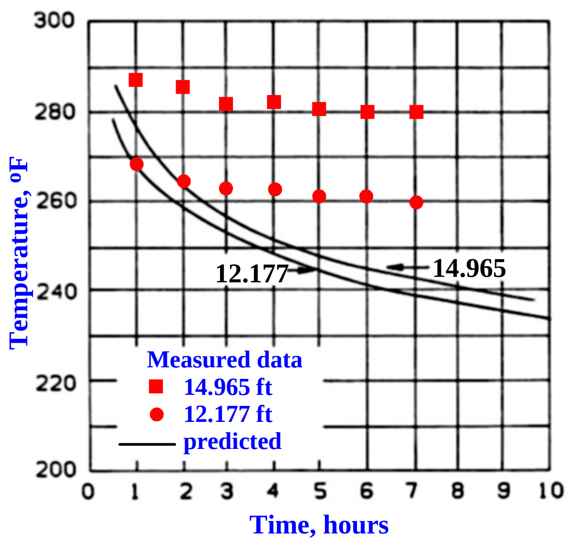

Figure 2. Comparison of measured and predicted circulating mud temperatures, Well 1 (after Sump and Williams, 1973).

We also found that the exponential integral can be used to describe the temperature field of formations around a well with a constant bore-face temperature (Kutasov, 1987)

$$T_{rD}(r_D,t_D)=\frac{T(r,t)-T_i}{T_w-T_i}=\frac{Ei\left(-\dfrac{r_D{}^2}{4t_{cD}^*}\right)}{Ei\left(-\dfrac{1}{4t_{cD}^*}\right)}. \tag{25}$$

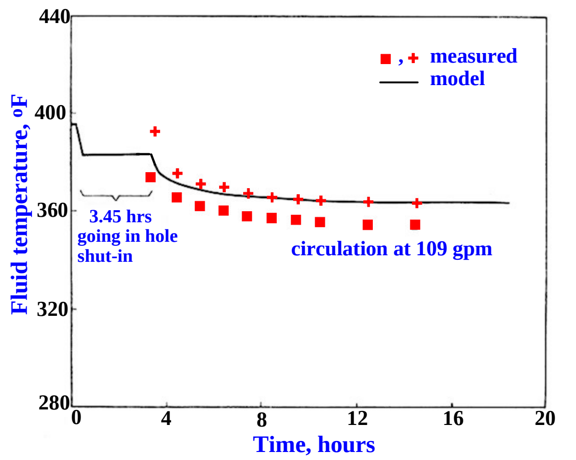

Figure 3. Circulating mud temperature at 23,669 ft (7214 m) – Mississippi well (Wooley et al., 1984). Courtesy of Society of Petroleum Engineers.

In Table 1 values of $T_{rD}(r_D, t_D)$ calculated after (25) and results of a numerical solution are compared. The agreement between values of r_D and $T_D(r_D, t_D)$ calculated by these two methods is seen to be good. It is easy to see that (16) and (25) are similar and identical at $G\to 1$. Introducing the adjusted circulation time into (9) we obtain

$$T_w = T(t, r_w) = T_i + \frac{q}{2\pi\lambda}\ln\left[1 + \left(c - \frac{1}{a + \sqrt{Gt_D}}\right)\sqrt{Gt_D}\right], \quad (26)$$

where $q = q(t = t_c)$.

Table 1. Dimensionless radial temperature $T_{rD}(r_D, t_D)$ for a well with constant bore-face temperature, first line – (25), second line – numerical solution (Jaeger, 1956).

$T_{rD}\cdot 1000$

t_D/r_D	1.1	1.2	1.5	2.0	3.0	5.0	7.0	10.0
2.0	912	834	642	418	172	22	1	0
	924	854	677	458	194	22	1	0
5.0	934	875	726	543	310	97	26	2
	940	886	746	568	332	101	24	2
10.0	945	896	771	614	404	180	77	18
	949	903	784	631	422	188	77	16
20.0	953	912	804	668	481	266	148	59
	956	916	813	681	497	277	153	57
30.0	957	919	820	694	520	314	194	93
	959	922	827	705	534	325	201	94
50.0	961	926	837	723	564	370	253	144
	963	929	843	731	574	381	260	146

5 HORNER METHOD

The Horner (1951) method is widely used in petroleum reservoir engineering and in hydrogeological explorations to process the pressure-build-up test data for wells produced at a constant flow rate. From a simple semilog linear plot the initial reservoir pressure and formation permeability can be estimated. Using the similarity between the transient response of pressure and temperature build-up, it was suggested to use the Horner method for prediction of formation temperature from bottom-hole temperature surveys (Timko and Fertl, 1972; Dowdle and Cobb, 1975; Fertl and Wichmann, 1977; Cermak et al., 1968; Judge et al., 1979; Leblanc et al., 1982; Beck and Balling, 1988; Prensky, 1992; Ikeuchi et al., 1998, Jorden and Campbell, 1984, etc.). It is assumed that the wellbore can be considered as a linear source of heat.

It should be noted that many authors (for instance, Lachenbruch and Brewer (1959), Kostanev (1985), Wilhelm (1990), Majorowicz et al. (1990), Stulc (1994)) proposed some modifications of the Horner method. However, these modifications gained little acceptance among hydrogeological and geothermal investigators. In the geothermal industry is often used Brennand (1984) method for temperature buildup analysis.

Santoyo et al. (2000) performed an interesting thermal evolution study of the LV-3 well in the Tres Virgenes geothermal field, Mexico. Several series of temperature logs were run during LV-3 drilling and shut-in operations. The temperature build-up tests were limited to short shut-in times (up to 24 hours). Static formation temperatures (SFT) were computed by five analytical methods (including the Horner plot), which are the most commonly used in the geothermal industry. The authors observed that the SFT predictions made by use of the Horner method were always less that the temperatures provided by other methods. In the Horner method the thermal effect of drilling is approximated by a constant linear heat source. This energy source is in operation for some time t_c and represents the time elapsed since the drill bit first reached the given depth.

For a continuous drilling period the value of t_c is identical with the duration of mud circulation at a given depth. The well-known expression for the borehole temperature is ((13) $r = r_w$)

$$T_w(r_w, t_c) - T_i = -\frac{q}{4\pi\lambda} Ei\left(-\frac{1}{4t_{cD}}\right), \quad (27)$$

Using the principle of superposition the following equation for shut-in temperature can be obtained:

$$T_s(r_w, t_s) - T_i = \frac{q}{4\pi\lambda}\left[-Ei\left(-\frac{1}{4(t_{cD} + t_{sD})}\right) + Ei\left(-\frac{1}{4t_{sD}}\right)\right], \quad t_{sD} = \frac{\chi \Delta t}{r_w^2}, \quad (28)$$

where Δt is the shut-in time. The logarithmic approximation of the exponential integral function (with a good accuracy) is valid for small arguments

$$Ei(-x) = \ln x + 0.57722, \qquad x < 0.01. \quad (29)$$

From (28) and (29) we obtain the Horner equation

$$T_s(r_w,t_s) = T_i + M\ln\left(1+\frac{t_c}{\Delta t}\right), \quad M = \frac{q}{4\pi\lambda}. \qquad (30)$$

Thus from a semilog plot we can obtain the undisturbed formation temperature and the parameter M. In many cases the dimensionless parameters t_{cD} and t_{sD} are small and (29) cannot be applied. In addition, as was shown by Lachenbruch and Brewer (1959), the heat source strength (at a given depth) while drilling might more realistically be considered as a decreasing function of time. It should be also taken into account that drilling records show that the mud is circulating only a certain part of the time required to drilling the well. The evaluation and limitations of the Horner technique are discussed in the literature (Dowdle and Cobb, 1975; Drury, 1984; Beck and Balling, 1988). In Table 2 the function $T_D*(t_D) = T_D(t_D)$ (15) and the "Exact" solution of Chatas (Lee, 1982) are compared. Thus we can make a conclusion that at small values of t_D (due to short drilling fluid circulation time and low values of thermal diffusivity of formations) the borehole cannot be considered as a linear heat source.

Below we present a simple example. Let us assume that: the well radius = 0.1 m, the thermal diffusivity = 0.0040 m^2/h, the fluid circulation time = 5 hours, the shut-in time is 2 and 5 hours. Then the value $t_D(t = 1\text{ hr}) = (1\cdot 0.0040)/(0.1\cdot 0.1) = 0.4$, and in (28) the corresponding values of dimensionless time are: $t_D(t = 7\text{ hr}) = 2.8$; $t_D(t = 2\text{ hr}) = 0.8$; $t_D(t = 10\text{ hr}) = 4.0$; $t_D(t = 5\text{ hr}) = 2.0$. From Table 2 follows that (28) and (29) cannot be used to process field data. We consider (30) only as an extrapolation formula.

Table 2. Comparison of the values of dimensionless wall temperature[a]

t_D	T_{DCh}	$T_{wD}*$	$T_{DCh} - T_D*$	R, %
0.4	0.5645	0.2161	0.3484	61.71
0.8	0.7387	0.4378	0.3009	40.73
1.0	0.8019	0.5221	0.2798	34.89
1.4	0.9160	0.6582	0.2578	28.14
2	1.0195	0.8117	0.2078	20.38
4	1.2750	1.1285	0.1465	11.49
6	1.4362	1.3210	0.1152	8.02
8	1.5557	1.4598	0.0959	6.17
10	1.6509	1.5683	0.0826	5.01
15	1.8294	1.7669	0.0625	3.42
20	1.9601	1.9086	0.0515	2.63
30	2.1470	2.1093	0.0377	1.76
40	2.2824	2.2521	0.0303	1.33
50	2.3884	2.3630	0.0254	1.06

[a] T_{DCh} - "Exact" solution, $T_{wD}*$ - (15), $R = (T_{DCh} - T_D*)/T_{DCh} \cdot 100$, %

6 THE NEW EQUATION

It is well-known that Horner-type extrapolation usually underestimates the predicted value of formation temperature (Hermanrud et al. (1990), Nielsen et al. (1990)). We propose that the developed approach will be free of this shortcoming.

Using (26) and the principle of superposition for a well as a cylindrical source with a constant heat flow rate $q = q(t_c)$ which operates during the time $t = G\cdot t_c$ and shut-in thereafter, we obtain a working formula for processing field data

$$T(r_w,t_s) = T_i + m\ln X, \qquad (31)$$

$$X = \frac{1+\left(c-\dfrac{1}{a+\sqrt{Gt_{cD}+t_{sD}}}\right)\sqrt{Gt_{cD}+t_{sD}}}{1+\left(c-\dfrac{1}{a+\sqrt{t_{sD}}}\right)\sqrt{t_{sD}}}, \qquad (32)$$

$$m = \frac{q}{2\pi\lambda}. \qquad (33)$$

The constants a and c were defined earlier (9). As can be seen (31) the processing of field data (semilog linear log) is similar of that of the Horner method. For this reason we have given the name *"**Improved** Horner Method"* to the procedure just described for determining the static temperature of formations. It is easy to see that for large values of t_{cD} ($G \to 1$) and t_{sD} we obtain the well-known Horner equation (30). To calculate the ratio X the thermal diffusivity of formations (χ) should be determined with a reasonable accuracy. The effect of variation of this parameter on the accuracy of determining undisturbed formation temperature will be shown below. The value of $\chi = 0.04$ ft^2/hr = 0.0037 m^2/hr was found to be a good estimate for sedimentary rocks (Ramey, 1962).

7 EXAMPLES

As will be shown by the following example, it is difficult to determine the accuracy of the Horner method in predicting undisturbed formation temperatures.

7.1 Example 1

Basic data used in the example (Schoeppel and Gilarranz, 1966) are shown in Table 3. The example applies to a borehole to 10,000 ft (3,050 m). The geothermal gradient is 1.4°F/100 ft (2.55°C/100 m) and the bottom-hole circulating temperature is determined to be 145 °F (62.8°C). The undisturbed formation temperature is 214 °F (101.1 °C), the well radius is 0.329 ft (0.10 m), and the formation diffusivity is 0.0431 ft^2/hr (0.0040 m^2/hr).

Figure 4 shows the computed temperature-time relation. We used (30) and (31) and a computer linear regression program for input data processing. The predicted values of T_i are presented in Table 4.

The accuracy of the T_i prediction in this example depends on the duration of the shut-in period.

Table 3. Shut-in temperatures and data used in Example 1 (Schoeppel and Gilarranz, 1966).

№	t_s, hr	T_s, °F	T_s, °C	t_s/t_c
1	1.0	179.50	81.94	0.333
2	2.0	187.80	86.56	0.667
3	3.0	191.92	88.84	1.000
4	4.0	195.37	90.76	1.333
5	5.0	198.13	92.29	1.667
6	6.0	200.20	93.44	2.000
7	7.0	201.58	94.21	2.333
8	8.0	202.27	94.59	2.667
9	9.0	202.96	94.98	3.000
10	10.0	203.65	95.36	3.333
11	11.0	204.34	95.74	3.667
12	12.0	205.03	96.13	4.000

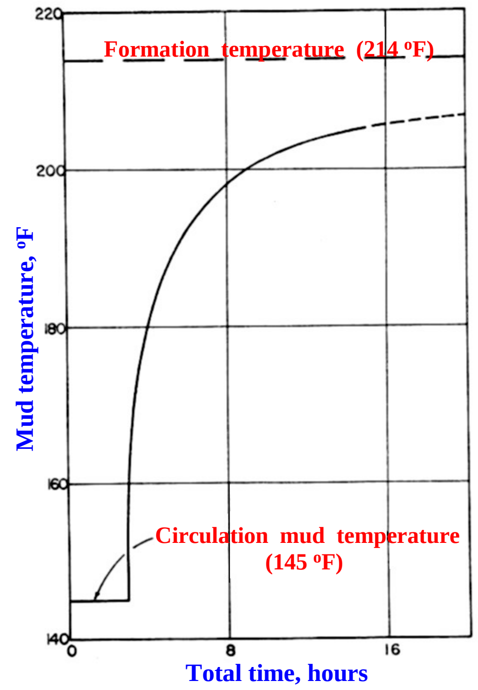

Figure 4. Shut-in temperatures for Example 1 (after Schoeppel and Gilarranz, 1966).

Table 4. Predicted formation temperature for Example 1.

Combination	(31)			(30)		
	T_i, °C	$-m$, °C	R, %	T_i, °C	$-M$, °C	R, %
1-3	101.04	37.89	0.1	95.70	9.94	0.0
1-4	101.19	38.24	0.1	96.31	10.45	0.2
1-5	101.51	38.99	0.2	96.94	11.01	0.4
1-6	101.77	39.61	0.2	97.45	11.49	0.5
1-7	101.88	39.89	0.2	97.82	11.84	0.6
1-8	101.80	39.68	0.2	98.01	12.03	0.6
1-9	101.68	39.37	0.2	98.13	12.16	0.6
1-10	101.58	39.08	0.2	98.24	12.28	0.5
1-11	101.50	38.86	0.2	98.34	12.38	0.5
1-12	101.46	38.74	0.2	98.45	12.51	0.5

For example, if the shut-in period is 3 hours, the ΔT_i =101.11-95.70 = 5.41 (°C). At the same time the temperature deviations (R) from the Horner plot are small (Table 4). Now let us assume that the thermal diffusivity of the formation is determined with the accuracy of ±20%, then for the last combination (12 points) we obtain (after (31)): $\Delta T_i = T_i(\chi = 0.0048\ m^2/hr) - T_i(\chi = 0.0040\ m^2/hr)$ = 101.26 – 101.46 = -0.20(°C); $\Delta T_i = T_i(\chi = 0.0032\ m^2/hr) - T_i(\chi = 0.0040\ m^2/hr)$ = 101.71 –101.46=0.25(°C). Thus the effect of variation of thermal diffusivity of formations on the value of T_i can be estimated.

7.2 Example 2

This example is from Kelley Hot Springs geothermal reservoir, Moduc County of California. Depth 1035 m (3395 ft) (Roux et al., 1980). The parameter $\chi/r_w^2 = 0.27/hr$ and t_c = 12 hours. The results of temperature measurements and predicted formation temperatures are presented in Table 5.

Table 5. Predicted formation temperature for Example 2.

t_s, hr	T_s, °C	(31)			(30)		
		T_f, °C	$-m$, °C	R, %	T_f, °C	$-M$, °C	R, %
14.3	83.9	111.32	84.64	0.4	107.26	38.68	0.5
22.3	90.0						
29.3	94.4						

CONCLUSIONS

A new method of determination of formation temperature from bottom-hole temperature logs is developed. It is assumed that the circulating mud temperature is constant. A semi-analytical equation for the transient bore-face temperature during shut-in is presented. At large values of shut-in and mud circulation dimensionless time the suggested equation transforms to the Horner formula (plot). To verify applicability of the suggested method new field data are needed.

NOMENCLATURE

c_p	heat capacity of formations
r	radial coordinate
r_w	radius of the borehole
R	relative accuracy, percent
T	temperature
T_i	initial (undisturbed) formation temperature
T_c	circulating mud temperature
T_s	wellbore temperature after shut-in
T_w	wall temperature
T_r	radial temperature distribution
X	parameter (32)
t	time
t_c	circulating time at a given depth
t_c^*	adjusted circulating time
q	heat flow rate
Q	cumulative heat flow

Greek symbols

χ	thermal diffusivity of formations
λ	thermal conductivity of formations
Δt	shut-in time
ρ	density of formations

Subscripts

D	dimensionless

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