PREDICTION OF FINAL TEMPERATURE

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The engineering necessity of achieving maximum cooling of the borehole during drilling and logging operations on geothermal wells prohibits the determination of equilibrium temperature in the subsurface before virtual rebound from the drilling disturbance some months after operations cease. Clearly, substantial economic benefits would accrue, in many cases, if a reasonable prediction of equilibrium temperature can be made while the rig is still over the borehole. Certain flow tests are desirable when commercial temperatures are known to be present in the reservoir. The manner in which the well is to be completed depends on its anticipated uses in the future. Before the rig is released a decision must be made as to the drilling of a confirmation well.

Several methods have been worked out to predict equilibrium temperatures; all are based on (1) rebound following the physical law of logarithmic decay, and (2) rebound being by conductive processes. Perhaps the most sophisticated method is one worked out by Albright (1975); unfortunately, the amount of data required to apply the method is not generated in the course of normal drilling operations. Since temperature rebound follows the same logarithmic decay law as does pressure buildup following a reservoir flow test, a Horner plot is suggested as a graphical method of predicting equilibrium temperature, and the Horner plot is a commonly used device. Its mathematical expression in several forms is given as the Lachenbruch-Brewer equations (1959, p. 79) which are applied herein.

The purpose of this brief report is to provide an abbreviated explanation of the physical principles of temperature rebound and provide a convenient plotting method similar to the Horner plot in order to standardize temperature prediction in Geothermal Operations. It has the further purpose of outlining methods to determine an approximate thermal conductivity value for reservoir rocks and rebound times after drilling from the nature of the rebound curve.

During the drilling of geothermal wells the drilling fluids serve the additional purpose of cooling the rocks adjacent to the bore in order to prolong the life of bits and drill string, and to control potential blowouts. The temperature of the fluid changes with cooling variations of the mud on the surface and with depth as the wallrock temperature changes.

Fluids moving in or out of the borehole via fractures transfer heat by nonconductive processes; and, if such fluid movements involve large volumes at or near the depth where equilibrium temperature is to be predicted, the conductive methods treated here are not applicable. If the well tries to produce, however, a relatively short flow test makes possible an approximate determination of reservoir temperature.

Line Source Solution

The well bore closely approximates a line source heat sink during drilling operations. All subsequent temperature measurements are made on this line, usually during multiple log runs.

Assuming the rock intersected by the bore is homogeneous, heat (cooling) of strength Q, applied instantaneously along the axial line at time $t = t_o$, produces rebound according to:

$$T_f - T_n = \frac{Q}{4\pi K} \frac{1}{t_n - t_o} \qquad t_n > t_o \tag{1}$$

where T_f is final equilibrium temperature, T_n is temperature measured at some time after t_o, and K is thermal conductivity. The quantity t is time since the drill bit first reached the depth in question.

But cooling at a given depth is applied not instantaneously but over a period of time, usually irregularly. Rebound is obtained by

$$T_f - T_n = \frac{Q}{4\pi K} \int_o^s \frac{q(\Delta t)}{t_n - \Delta t} dt \quad t > s \tag{2}$$

where q(t) is a continuous source in units of heat per unit time per unit depth and s is the time elapsed since the bit reached the depth in question to the time drilling (circulation) ceased. Ordinarily s, like t, is different for each depth.

If q(t) is a constant, or is averaged and applied during time s, that is, $q(t) = \bar{q}s$, then the solution of the integral is

$$T_f - T_n = \frac{\bar{q}s}{4\pi K} \ln \frac{t_n}{t_n - s} \qquad t > s \tag{3}$$

Graphical solution

The last equation forms the basis for the graphical solution of final temperature (Fig. 1); it was solved repeatedly to produce the graph. In practice the T_n's, T_1, T_2, T_3...., are plotted against the log term, to graphically solve for the final temperature, T_f.

After the first maximum borehole temperature, T_1 is obtained, from the first logging run, a convenient temperature value is chosen and labeled on the bottom line. This value, in general, is a multiple of ten next below T_1. After this datum value is chosen, the ordinate is labeled at the same scale as the upper part of the graph. Each temperature is plotted against $\ln t_n/t_n - s$ as it becomes available with each logging run.

The last tool to go into the hole is ordinarily a continuous temperature log. This run provides an opportunity to determine the depth of the maximum temperature, which is not always at T.D. The same maximum reading thermometers, clamped in turn onto the Schlumberger logging line, should be placed onto the wire line of the temperature sonde in order to check the correlation between the two tools. The maximum reading thermometers, usually two or three run simultaneously, should be clamped onto the Agnew and Sweet wire line 30 ft. above the bottom of the tool. This is the approximate average height of the thermometers above the base of the Schlumberger sondes.

After all the temperatures are plotted, the best fit straight line is passed through the points. When the fit is difficult, the last few data obtained should be given more weight. This is because the short term fluctuations of temperature during drilling damp out early and the later measurements better follow the average heat sink temperatures assumed in construction of the graph. The line projected through the plots, and perhaps even some of the control points may plot into the upper part of the graph. This is of no consequence.

The intersection of the line with the $\ln t_n/t_n - s = 0$ ordinate gives the predicted final temperature, T_f.

In the event tables or a calculator are not available for calculating the natural logarithms, the ratio t/s, can be worked out by longhand and plotted using the logarithmic scale across the top of the graph. Plotting with a logarithmic scale is a little less accurate, however.

The graph is designed for two further operations. With a parallel ruler the best fit line is moved into the upper part of graph to the position at which it passes through the "origin" of the family of guidelines, at the left side of the graph. The interpolated value of the guideline that coincides with the plotted line is then determined. This guideline value is the ratio, $\bar{q}s/K$, in equation (3). If either value of the quotient is known, the other can be determined. This also can be solved graphically with the small graph in the upper right corner.

Knowledge of the term $\bar{q}s$ is of no particular intrinsic value, but thermal conductivity, K, is. No convenient method for determining $\bar{q}s$ can be outlined at this time; however, the duration of the disturbance, s, is known and it is possible that $\bar{q}$ can be estimated empirically from flow line temperatures or some other indicator, but further work to demonstrate this is required. When K can be determined, the information will aid in interpreting other temperature data on the prospect and will make possible a calculation of rebound time.

Two dashed lines pass through the larger graph, one labeled 5° and the other 1°. These lines indicate the times when the well has rebounded to within $5^{\circ}C$ and $1^{\circ}C$ respectively of the final equilibrium temperature. These specific rebound times can be determined by picking the $\ln t_n/t_n - s$ value where the plotted line intersects the 5° or 1° line, whichever is of interest, say the 5° line. With this $\ln t_n/t_n - s$ value, enter the graph in the lower right corner through the bottom scale and move vertically up to intersection with the appropriate s line, the duration of the temperature disturbance. Moving to the left scale gives the rebound time, t - s, in hours, and moving to the right scale gives t - s in days.

Knowledge of rebound time to temperatures within 5° and 1° of complete rebound is helpful in planning followup temperature surveys. Without this knowledge more surveys may be run than are necessary, and each cost between $1000 and $2000.

Example

Roosevelt Hot Springs #9 - 1 data from Utah are tabulated and plotted in figure 2 to illustrate the method. The drilling history indicates that the duration of circulation, s, at a depth of 1518 m., prior to taking temperature measurements, was 15 hours, distributed in drilling, coring and well conditioning. The scatter about the best fit straight line is not large, and probably reflects, in the main, small inaccuracies in time and temperature measurements.

The line projects to $186.3^{\circ}C$ at $\ln t_n/t_n - s = 0$. After the logging runs that produced these temperature readings, Well #9 - 1 was deepened to 2096 m., reaching this T.D. on April 8, 1975. Approximately three months later, on July 14, 1975, a continuous temperature log was run to T.D. This log shows a temperature of $192.8^{\circ}C$ at depth 1518 m. Thus, this prediction scheme predicted a final temperature below steady state equilibrium temperature by a minimum of $6.5^{\circ}C$.

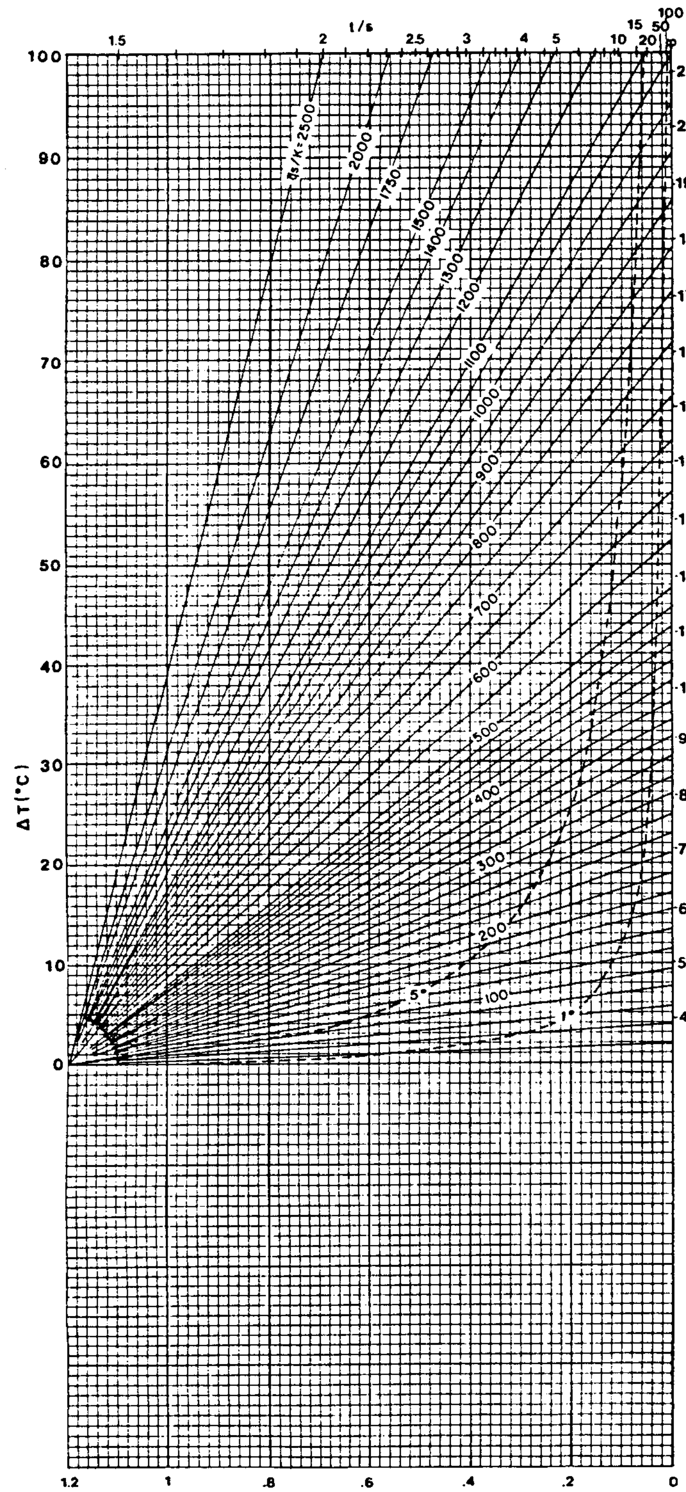
Moving the best fit line into the upper part of the diagram, using parallel rulers, to the position at which it passes through the "origin" of the family of curves, the interpolated value for $\bar{q}s/K$ is 508. Making use of the diagram in the upper right corner, the quantity $\bar{q}s$ is 508 when K = 1, 254 when K = 2, 169 when K = 3, and so on. The units of $\bar{q}$ are calories per unit depth per second times 3.6 X 10^3. Flow line temperature during drilling and coring at this depth averaged 50°C, but they are unknown during circulation to condition the hole. A core was obtained a few feet below the point of temperature measurements; namely, in the interval 1524-1525.5m. Thermal conductivity measurements on recovered granodiorite produced a K value of 4.77. In this case, where K and s are known, $\bar{q}$ is restrained at 107. When enough data of these types are available, it may be possible to determine a reasonable value for thermal conductivity by estimating $\bar{q}$ through flow line temperatures.

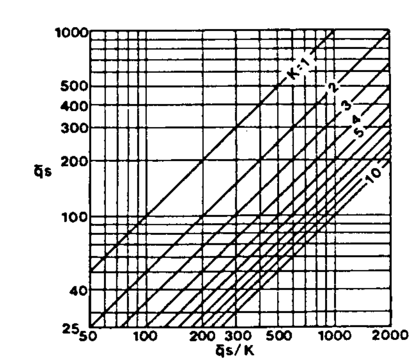
It is important to know how far from complete rebound the well was on July 14, 97 days after circulation ceased, when the last temperatures were measured. The best answer can only be an approximation in this case because the well was deepened after the temperature measurements were made, and thus s changed. Using the data available to complete the example, however, the best fit line, with $\bar{q}s/K = 508$, intersects the 5° and 1° dashed lines at $\ln t_n/t_n - s = .13$, and $= .03$, respectively. Entering the graph in the lower right corner with these values the well was within 5°C of final temperature in about 5 days, and within 1° in about 22 days. Thus, the temperature on the run of July 14 was probably less than 1°C from equilibrium.

References Cited

Albright, J. N., 1975, A new and more accurate method for the direct measurement of earth temperature gradients in deep boreholes: Proc., Second U. N. Symposium on Development and Use of Geothermal Resources, San Francisco, p. 847 - 851

Lachenbruch, A. H. and Brewer, M. C., 1959, Dissipation of the temperature effect of drilling a well in Arctic Alaska: U. S. Geothermal Survey Bull. 1083 - C, p. 73 - 109.





t	T	Ln t_n/t_n-s
s		
t_1		
t_2		
t_3		
t_4		
t_5		
t_6		
t_7		

Well ________ Field ________

Co. ________ St. ________

Date ________ Int. ________

Comments ________

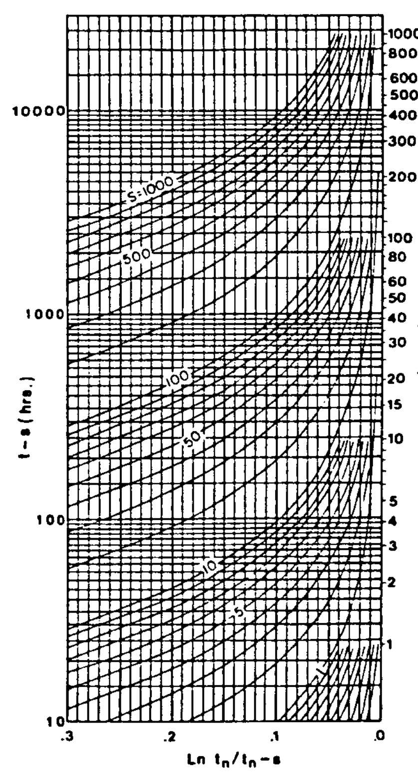
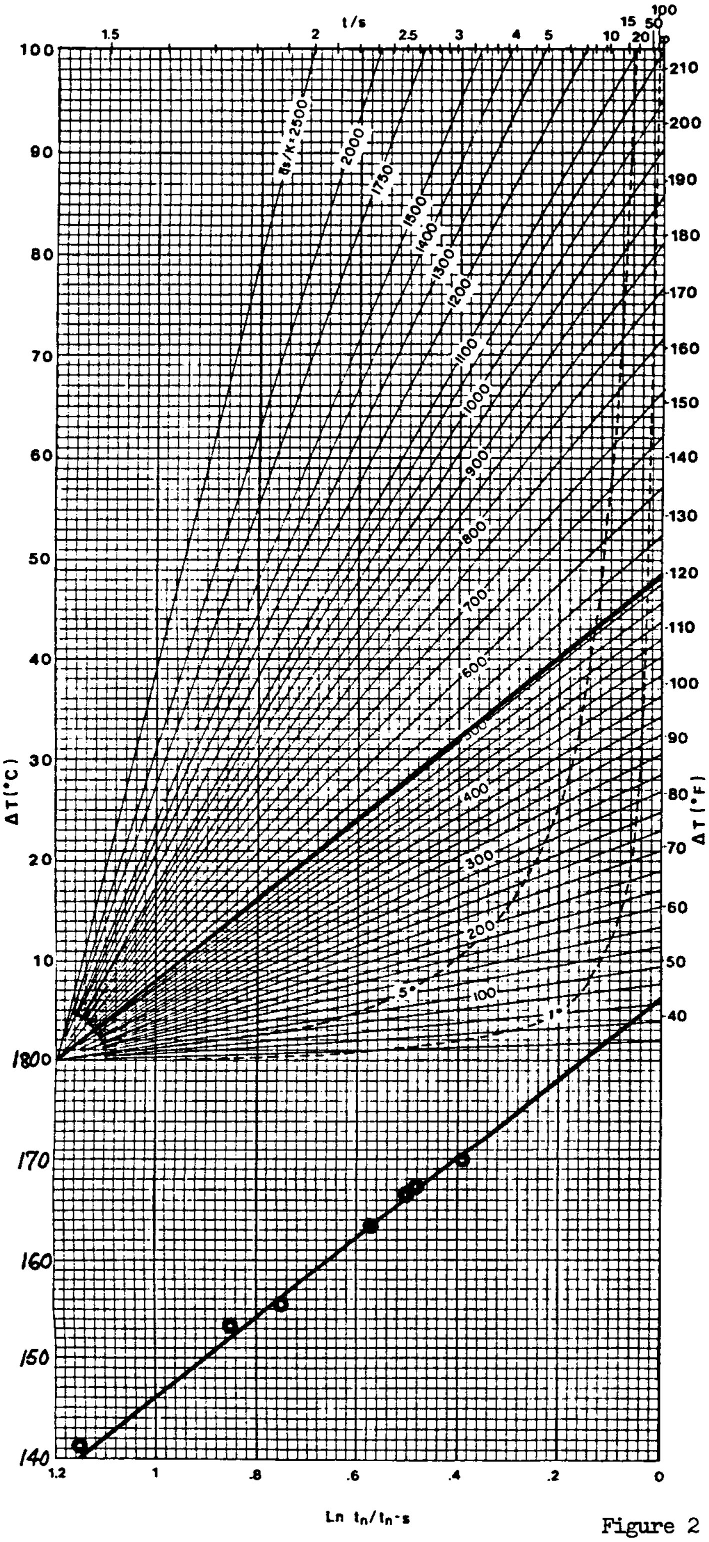
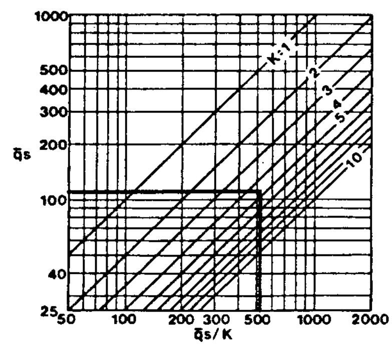


Figure 1





	t	T	Ln t_n/t_n-s
s	15.00		
t_1	22.00	141.11	1.15
t_2	26.25	153.33	.85
t_3	28.50	155.56	.75
t_4	34.50	163.33	.57
t_5	38.33	166.67	.50
t_6	39.60	167.22	.48
t_7	46.00	170.00	.39

Well #9-1 Field Roosevelt

Co. Beaver St. Utah

Date 8/25/77 Int. GWC

Comments Depth of measurements - 1518 m. Well drilled to 2096 m TD on 4/8/75. Temp. at 1518 m on 7/14/75 was 192.8 °C.

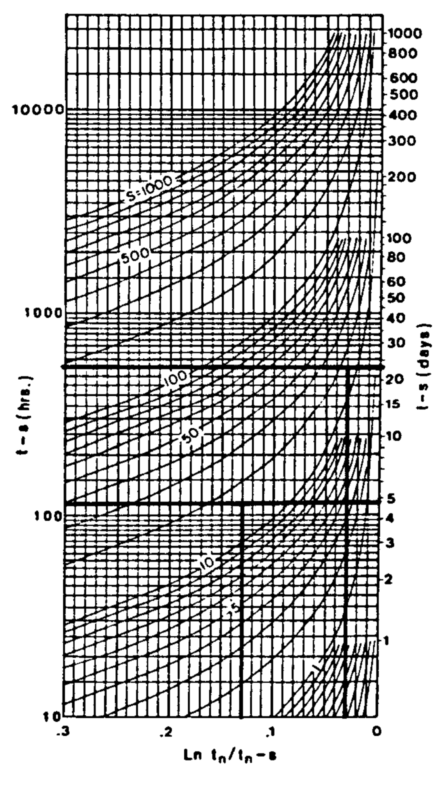


Figure 2