8 Temperature Logging

Among the reasons for using temperature logs are:

1. To find the cement top after a recent cementing operation
2. To find a lost-circulation zone in a currently drilling well
3. To find fluid entry and exit points in production and injection wells

Temperature logging tools employ a variety of sensors including temperature-sensitive resistors, thermistors and diodes. In order to react quickly to temperature changes, temperature logging tools are designed with the sensing element exposed directly to the wellbore fluids. For this reason, they are delicate instruments easily damaged by physical abuse or by the junk normally found at the bottom of a well.

Resistance Temperature Detector (RTD)

Most premium tools contain a platinum resistance temperature detector (RTD) which exploits the tendency of a metallic conductor to exhibit a change in resistance with temperature. An RTD is essentially a temperature-sensitive resistor with a positive temperature coefficient, which means that the resistance of the metal increases with temperature. RTDs are made from a number of different metals, but the platinum RTD has captured most of the industrial market, and is now used in most modern temperature logging tools. The major drawback is a rather small change in resistance per degree of temperature change, mandating special signal processing for signal amplification.

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Thermistors

Some tools contain thermistor sensors which are metal oxide semiconductor devices. Thermistors provide a large change in resistance per degree change in temperature, but they are highly nonlinear devices. There are a number of linearizing schemes used, but in logging tools, where a dynamic range of 300 °F or more may be needed, thermistors are problematic.

Diodes

Diodes have been used as temperature sensors in a few tools. Diodes produce a relatively high change in voltage per degree, but they are limited with respect to high wellbore temperatures.

Figure 8.1 illustrates a temperature logging tool and Fig. 8.2 a typical temperature log.

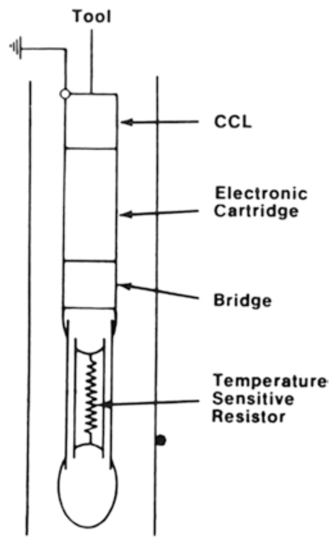

Fig. 8.1 High-resolution thermometer. Courtesy Schlumberger

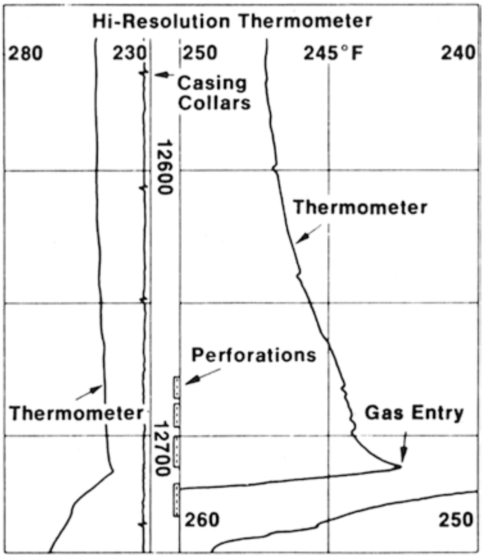

Fig. 8.2 Typical temperature log. Courtesy Schlumberger

Fundamentals

Undisturbed formation temperature increases predictably with depth. This increase in temperature with depth is known as the *geothermal gradient* (G) and is usually in the range of 1–2 °F per 100 ft. Figure 8.3 is a useful guide to geothermal gradients—the temperature at any depth may be extrapolated using the relationship.

$$T_{\text{form}} = T_{\text{surf}} + \text{depth} \bullet G.$$

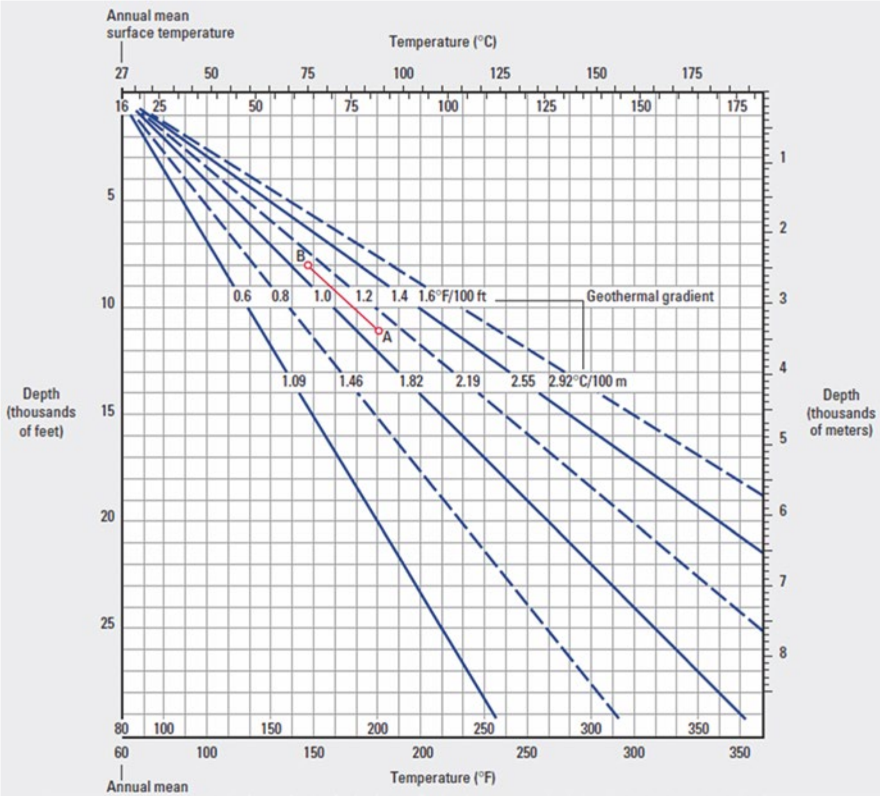

Fig. 8.3 Geothermal gradients. Courtesy Schlumberger

Obviously, the actual temperature on the surface fluctuates seasonally so the value used for the *surface temperature* is actually the mean annual surface temperature and will be in the range of 60–70 °F in temperate climates. Seasonal near-surface temperature changes do not penetrate very deeply into the ground and well logging purposes can be ignored. One exception is the permafrost zone that can exist near polar regions.

Estimation of formation temperature from open-hole logs can be made provided it is borne in mind that at the time a logging run is made the wellbore is cooler than the surrounding formation, due to mud circulation. If several logging runs are made in the same hole, undisturbed formation temperature can be estimated from a plot of temperature against time. The method of Dowdle and Cobb is recommended.

Bottomhole Temperature Extrapolation

If t_k is the circulation time and Δt is the time since circulation stopped, then a plot of the observed temperature at time Δt against $(t_k + \Delta t)/\Delta t$ on a log scale should give a straight line with an intercept at $(t_k + \Delta t)/\Delta t = 1$ which will indicate the undisturbed formation temperature, T_i. Figure 8.4 illustrates the method. A worked example is shown below. Table 8.1 lists time and temperature data recoded on sequential logging runs in the same hole. The well was drilled to a depth of 7,646 ft and drilling stopped at 22:00 on the 2nd. Circulation stopped at 02:30 on the 3rd giving a circulation time of 4½ h. Analysis of this data is shown on the plot in Fig. 8.4 that indicates an undisturbed formation temperature close to 116 °F.

Table 8.1 Time and temperature data

Logging run	Thermometer depth (ft)	Time off bottom	Time since circulation stopped (h)	Temperature °F
1	7,608	07:36/3rd	5:06	99
2	7,608	12:48/3rd	10:18	106
3	7,620	14:29/3rd	14:29	107
4	7,620	20:37/3rd	18:07	110

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Depth: 16,200 ft.
Drilling stopped: 00:30 h.
Circulation stopped: 04:00 h.
Circulation time: 3.5 h.

Three log runs were made, the corresponding times and temperatures were:

Tool	Time off bottom	Time since circulation stopped	Temp. (°F)
Induction	12:15	8:15	241
Density	15:00	11:00	257
Dipmeter	17:30	13:30	262

Plot temperature vs. $(t_k + \Delta t)/\Delta t$ and deduced static formation temperature.

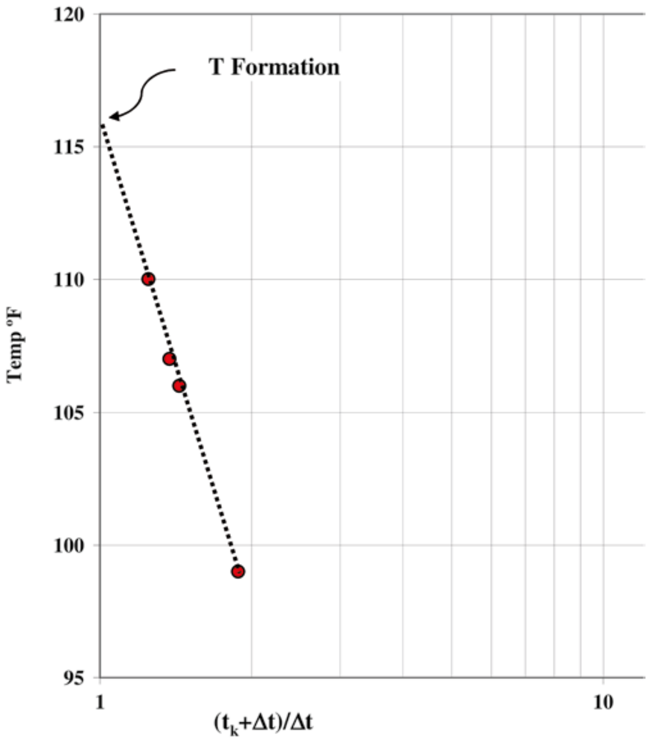

Fig. 8.4 Determination of static formation temperature. Reprinted with permission of the SPE-AIME from Dowdle and Cobb (1975)

Cement-Top Evaluation

Although no longer widely used for finding cement tops in recently cemented wells, the temperature log may be used for this purpose—its advantage being that it is cheap and demands less rig time. Its disadvantage is that it gives no indication of the cement quality or the ability of the cement job to make a hydraulic seal. The principle involved is the exothermic chemical reaction that takes place while cement is curing. The heat given off raises the temperature in and around the borehole at those places where cement is placed. Thus, a marked drop in temperature may be expected at the cement top. Figure 8.5 shows a temperature log run in a recently cemented well and the corresponding pick for the cement top.

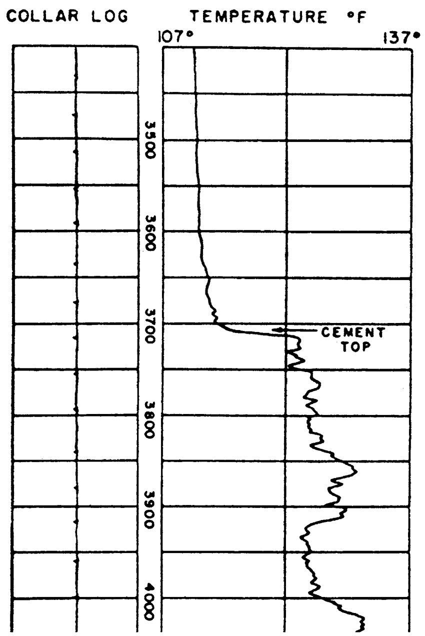

Fig. 8.5 Cement-top pick from temperature log

Lost-Circulation Zones

In the event that circulation is lost in a currently drilling well, a temperature log can be a useful indicator of the thief zone in question. Just below the point of lost circulation, the mud in the hole is likely to have been stagnant for some time and therefore to have assumed a higher temperature than the mud in the column, which is still free to circulate. Thus, a temperature discontinuity will exist across the lost-circulation zone. Figure 8.6 illustrates the effect.

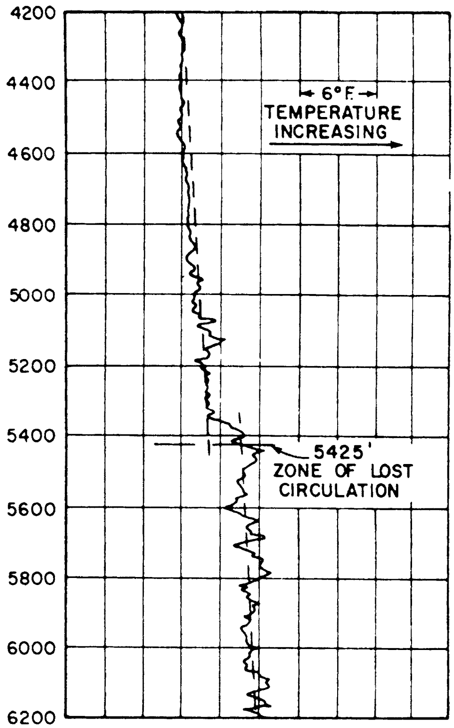

Fig. 8.6 Lost-circulation zone detection with a temperature log

Temperature Profiles in Production and Injection Wells

General

If left undisturbed, the temperature in a well bore will assume the ambient temperature of the surrounding formations; and a log of temperature against depth will indicate the geothermal gradient. However, if the well is flowing, either due to production or injection of fluids, then the observed temperature profile will depart from the geothermal gradient. This surprisingly simple rule should always be borne in mind when analyzing temperature logs. Look for departures from the geothermal gradient as the prime indicator of fluid movement. Once a particular flow regime has reached thermal equilibrium, the difference between the observed temperature in the borehole and the geothermal gradient is related to the mass flow by the equation:

$$\Delta T = bM / G$$

where: ΔT = the temperature difference, b = a constant that depends on the physical characteristics of the fluid produced and on the thermal conductivity of the formation, M = the mass flow rate, and G = the geothermal gradient.

Thus, other things being equal, the ΔT is proportional to the weight of fluid produced or injected per unit time.

Liquid Production

Figure 8.7 shows a temperature profile for a single-point entry of liquid production. Things to note include:

(a) Below the production point, the temperature profile follows the geothermal profile.
(b) At the production point, the temperature profile is vertical.
(c) Above the production point, the temperature profile asymptotically approaches a new gradient offset from the geothermal by an amount ΔT.

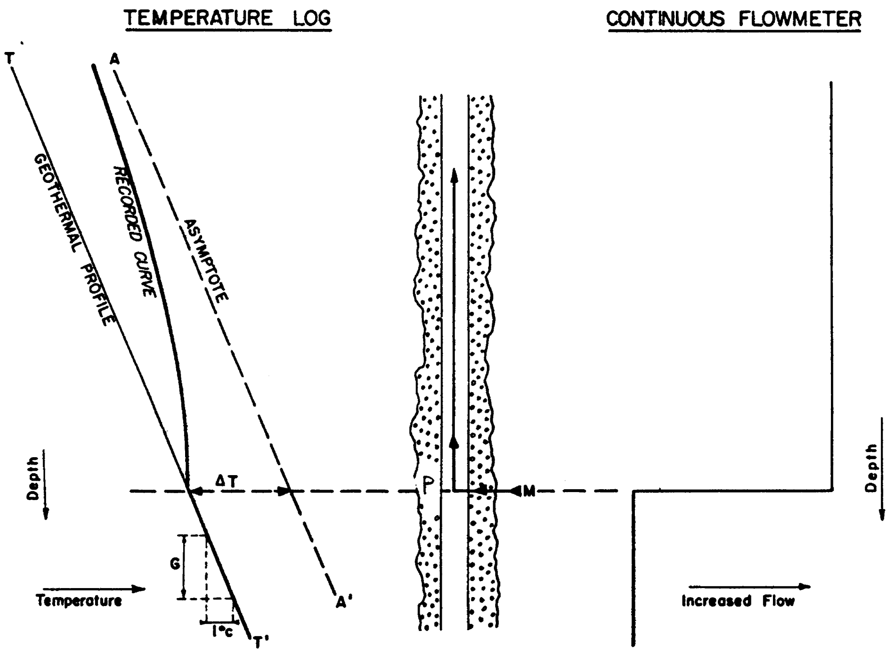

Fig. 8.7 Liquid-production temperature profile. Courtesy Schlumberger

Gas Production

Figure 8.8 shows temperature profiles for a single-point entry of gas. Things to note include:

(a) Below the production point, the temperature profile follows the geothermal profile.
(b) At the production point, the temperature profile is *horizontal* and shows a marked cooling effect due to gas expansion from reservoir pressure to well flowing pressure.

(c) Above the production point, the temperature rises, crosses the geothermal, and approaches an asymptote offset ΔT above the geothermal.

Two traces are shown on Fig. 8.8—one for a high-permeability formation and one for a low-permeability formation. Note that the initial cooling effect at the point of production is less for the high-permeability formation than for the low.

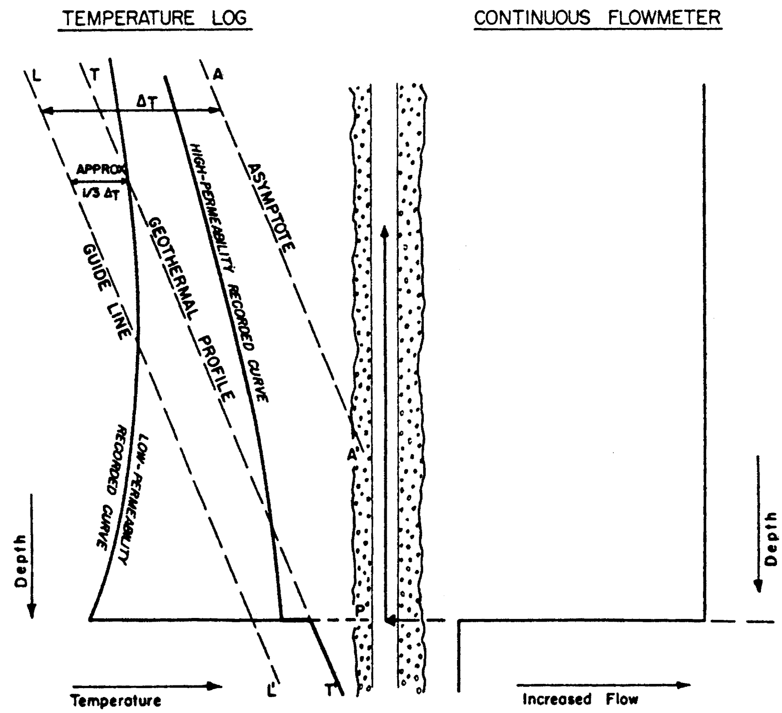

Fig. 8.8 Gas-production temperature profiles. Courtesy Schlumberger

Water Injection

Figure 8.9 illustrates the temperature profiles to be expected in a water-injection well. Things to note are:

(a) Depending on the temperature of the injected water relative to the undisturbed formation temperature, the temperature profile above the injection point may show an increase or a decrease with depth.
(b) At the injection point, the temperature profile is horizontal.
(c) Below the injection point, the temperature profile returns to geothermal.

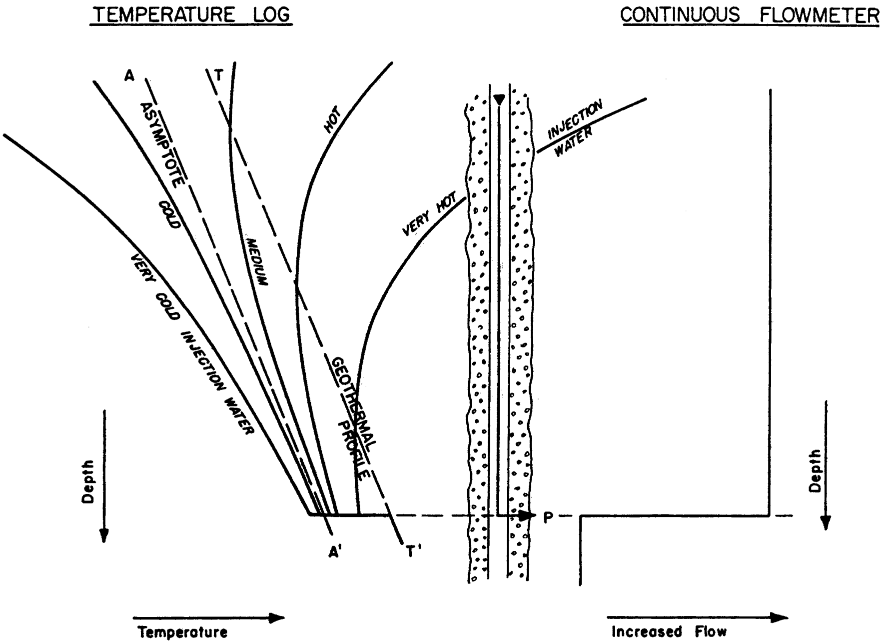

Fig. 8.9 Water-injection temperature profiles. Courtesy Schlumberger

Gas Injection

The temperature profiles for a gas-injection well (Fig. 8.10) are entirely similar to those of a water-injection well, and the same observations apply.

Further examples of liquid and gas production and injection profiles—together with the effects of casing leaks, casing-formation annulus flow, etc. are given in a paper entitled "Temperature Logs in Production and Injection Wells," by A. Poupon and J. Loeb. The reader is encouraged to read this paper in its entirety.

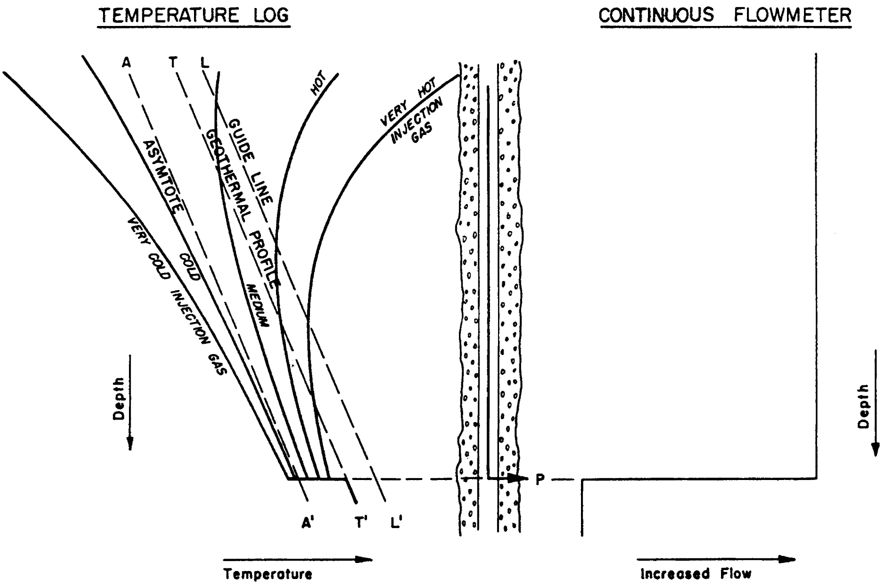

Fig. 8.10 Gas-injection temperature profiles. Courtesy Schlumberger

Logging Techniques

Several special logging techniques can improve interpretation of temperature profiles. These include:

1. Shut-in temperature surveys
2. Differential-temperature logs
3. Radial differential-temperature logs

Shut-In Temperature Surveys

If more than one zone is taking water in an injection well, it is sometimes difficult to judge from the flowing temperature profile which zone is taking what percentage of the injected total. Two techniques are offered here. The first simply relates the ΔT value to the volumetric flow. Figure 8.11 illustrates the concept. In the figure, T_G is the undisturbed formation temperature and T_h is the temperature observed in the borehole.

A second useful technique is to stop injection altogether and repeat the temperature profile several times at various time intervals, such as at 3, 6, 12, and 24 h. Or, depending on the local conditions, at 12, 24, and 48 h. Zones that were taking relatively cool injection water will remain cooler than surrounding formations for a relatively long time and will be visible on the repeat profiles. Figure 8.12 shows such an example.

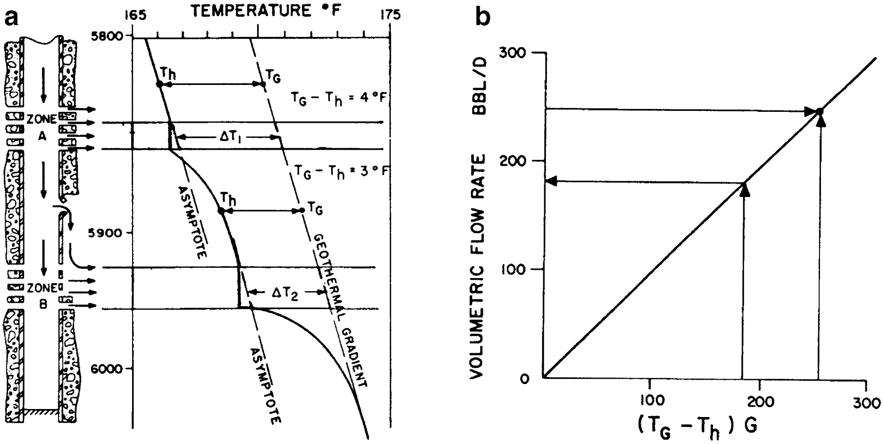

Fig. 8.11 Water injection: (**a**) Temperature Profile, (**b**) Flow rate vs. ΔT. Reprinted with permission of the SPE-AIME from Witterholt and Tixier (1972)

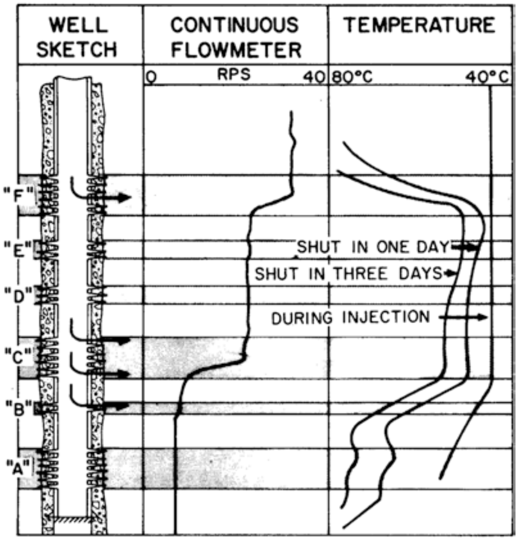

Fig. 8.12 Shut-in temperature survey. Reprinted with permission of the SPE-AIME from Witterholt and Tixier (1972)

Differential-Temperature Surveys

A differential-temperature log is a recording made, versus depth, of the difference in temperature between two points in the well. Effectively, the trace is a differentiation of the temperature curve itself. In practice this is accomplished either by having matched sensors on the logging probe some short distance apart or by memorizing the temperature taken at one point and comparing it to the temperature taken at some other point, such as 1 ft deeper, or shallower, depending on the direction of logging. Differentiation can be on a depth or on a time basis. Provided that the logging speed remains constant, both methods produce the same answer. Figure 8.13 shows a conventional temperature survey together with a differential-temperature curve. Note that where even slight changes in temperature occur the differential curve accentuates the occurrence. Where the temperature does not change with depth, the differential curve is likewise unchanged.

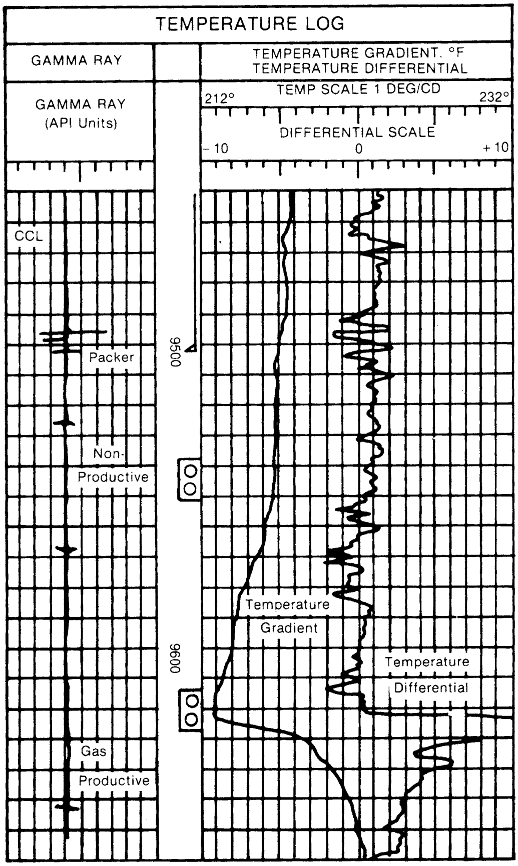

Fig. 8.13 Differential-temperature log. Courtesy Baker Hughes

Radial Differential-Temperature Tool

The radial differential-temperature tool (RDT) was designed to detect channels behind pipe. The operating principle relies on the probability that the temperature in the channel is different from the temperature in the surrounding formation. If fluid is channeling from above or below it is probable that such a temperature difference will be present. Figure 8.14 shows a plan view of a channel. The temperature on the side of the casing near the channel, T_{w1}, is likely to be different from the temperature of the casing opposite the channel, T_{w2}. Thus, a temperature sensor held stationary at a given depth, but free to rotate through 360°, should observe a temperature fluctuation if a channel with fluid flowing in it is present.

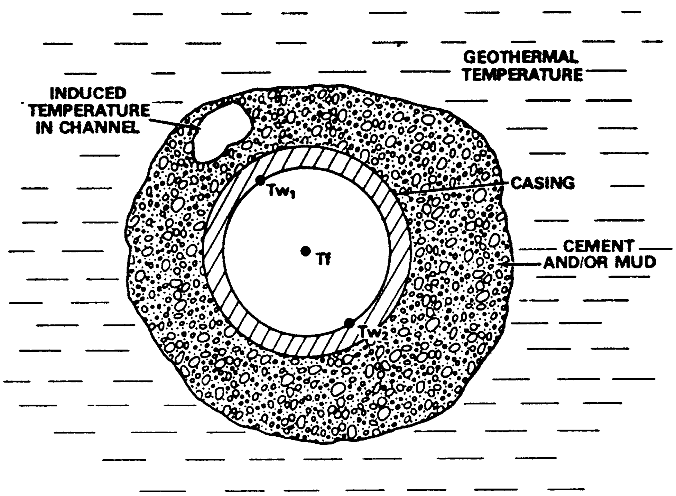

Fig. 8.14 Temperatures in and around a cased well. Reprinted with permission of the SPE-AIME from Cooke (1979)

The method used to make the horizontal scan is shown in Fig. 8.15. Anchor springs hold the tool in the casing and a rotation motor is actuated to cause the RDT sensor to scan round the casing. The resulting log is shown in Fig. 8.16. Note that the log is a record of temperature versus degrees of rotation round the casing. This particular survey with measurements made at 6,400, 6,440, 6,500, and 6,560 ft shows that gas is channeling from the lower sand (marked "L" on the figure) to the upper sand (marked "U"). For remedial action, the tool carries a perforating gun that can shoot squeeze perforations directly into the channel once it is detected.

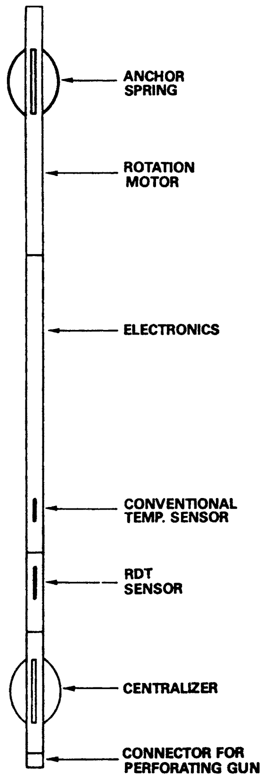

Fig. 8.15 RDT tool. Reprinted with permission of the SPE-AIME from Cooke (1979)

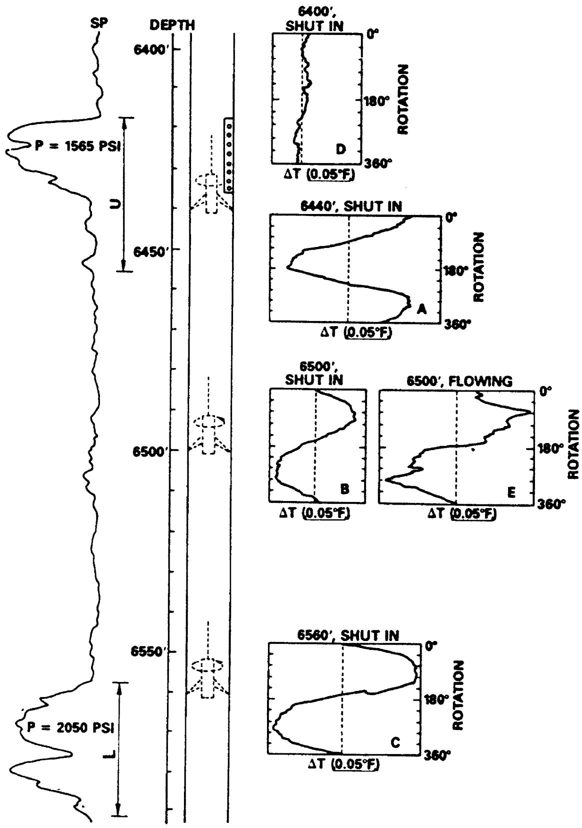

Fig. 8.16 RDT scan showing gas channel. Reprinted with permission of the SPE-AIME from Cooke (1979)

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Answer to Text Question

Question # 8.1

297 °F