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The Challenge of Correcting Bottom-Hole Temperatures – An Example from FORGE 58-32, near Milford, Utah

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ABSTRACT

A very detailed and complete thermal dataset collected from well 58-32 at the Milford-Utah FORGE site allows testing of methods to extrapolate equilibrium temperatures when the drilling is stopped for 24 hours. During short drilling breaks to measure deviation of the hole, maximum reading thermometer measurements were taken at approximately 300 ft (90 m) intervals. However, these measurements proved to be poor indicators of bottom-hole temperature because the thermometer was about 30 m above the bit and therefore a relatively long thermal recovery time due to the effects of mud circulation. When the drilling was stopped at 2073 m (6800 ft) and the drilling rods were pulled out of the hole, the circulation time at the bottom of the hole was estimated to be 2 ± 0.5 hours. Four logging runs to obtain bottom-hole temperatures were then run over a period of 24 hours. The mud circulation temperature at the bottom of the hole was close to 60°C when drilling stopped, and the temperature rose from 130 to 160°C over the subsequent 24 hours. A temperature log of the hole after 37 days showed the near-equilibrium temperature was 181°C at this depth. The temperature logs at 2073 m showed the vertical temperature difference over the lowermost 30 m varies between 11°C at 8.1 hours and 6°C after 24.2 hours, explaining why the effects of drilling disturbance are too large to estimate for all depths except for a few meters at the bottom of the hole. An unexpected result from each of the four logging runs at 2073 m was that temperatures at the bottom of the hole rose by 5–8°C over 4–8 minutes while the probe was stationary. This is attributed to radial temperature gradients in fluid in the hole that disappeared due to mixing effects caused by probe movement. These effects were not seen in the 37-day logging run because the fluid had presumably come to equilibrium with the drill hole walls. The most reliable estimate of equilibrium temperature was obtained by using measurements after 12 hours and extrapolating using traditional Horner methods. The best-fit trendline for the 12-24 hours values predicted the 37-day temperature to within a few degrees Celsius. The slope of the thermal recovery line of 280°C/thermal recovery unit on a natural log plot is similar to that derived from several other exploration wells around the Roosevelt Hot Spring system, suggesting this may be a characteristic of bottom-hole temperatures in wells drilled into granite with a 8.75 inch diameter bit.

1. INTRODUCTION

Numerous studies have investigated the thermal recovery at the bottom of wells caused by the cooling of circulating drilling fluids. Some recent examples include Henrickson and Chapman (2004), Ascencio et al. (2006), Gourtoube et al. (2007), Edwards and Chapman (2013), and Gwynn et al. (2014), with older references contained in these publications. The most common correction is the Horner method, where temperature T is plotted against $\ln (t_s/(t_s+t_c))$, with t_c being the circulation time, and t_s being the time since circulation stopped (shut-in time). A semi-log plot should yield a straight line at long time which extrapolates to the equilibrium temperature at infinite time (intercept on the temperature axis). Radial heat flow is assumed. The linear approximation applies when $r^2/4st_s \ll 1$, where r is the borehole radius, and s is the thermal diffusivity. At shorter times, Bullard (1947) derived a solution:

$$T(t_s) = T_\infty - (Q/4\pi s)[Ei(-r^2/4st_s) - Ei(-r^2/4s(t_s+t_c))] \tag{1}$$

where Q is the line heat source (sink) strength and Ei are exponential integrals.

The Ascencio method (Ascencio et al., 2006, and earlier papers) assumes spherical-radial heat flow at the bottom of the well, and at long time yields a linear plot of T against $1/\sqrt{t_s}$, with the intercept being the equilibrium temperature. Ascencio et al. (1997, 2006) note that the Horner method results in consistently lower temperatures than the Ascencio method.

Many processes can influence the thermal recovery, including invasion of drilling fluid near the hole bottom, changes in well diameter (washouts), poorly recorded circulation time (includes the drilling rate near the hole bottom), and the temperature sensor not reaching the bottom of the hole during the thermal recovery measurements. In this paper we use very detailed and complete thermal data from the recently drilled 58-32 well at the FORGE site near Milford, Utah (Figure 1) to test several methods of estimating the equilibrium temperature. The drilling was stopped at 2073 m (6800 ft) depth for 24 hours to determine if the well had encountered the minumum temperature of 175°C specified by the U.S. Department of Energy (DOE) for a FORGE site (https://energy.gov/eere/forge/forge-home). The drilling history leading up to the stoppage had been monitored; the drilling rate averaged 3 m/hour, the drilling fluid temperature was 50°C flowing into the well and 57°C flowing out to the mud cooler, and the mud was circulated for 20 minutes to clean out the cuttings before the drill string was pulled out of the hole (Figure 2). Based on these parameters, the circulation (thermal disturbance) time at 2073 m was estimated to be 2 ± 0.5 hours. No drilling fluid losses had been recorded, suggesting a thermally conductive regime. Four temperature profiles to the hole bottom were run at approximately 6 hour intervals by Di Drill Survey Services, with the absolute measurement accuracy less than ± 0.1°C, and a relative accuracy of 0.01°C. The temperature profile was measured again 37 days after the hole reached 2305 m (7536 ft) and injection tests were completed, giving a near-equilibrium temperature at 2073 m of 181°C.

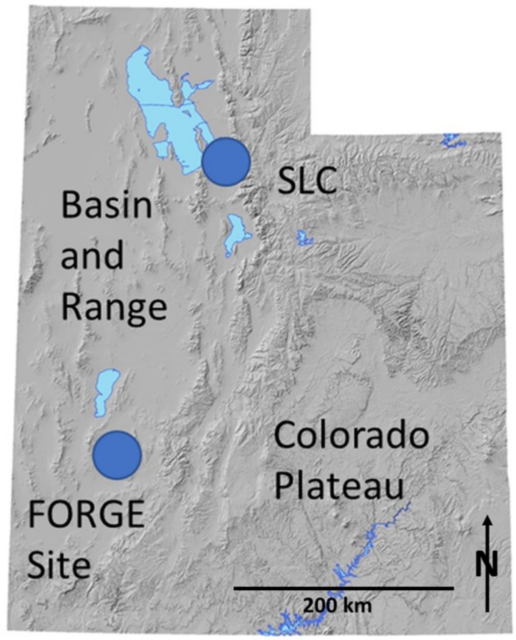

Figure 1: Location map of the FORGE site near Milford, Utah. The FORGE site has well 58-32, and is 3 km west of Roosevelt Hot Springs. SLC is Salt Lake City.

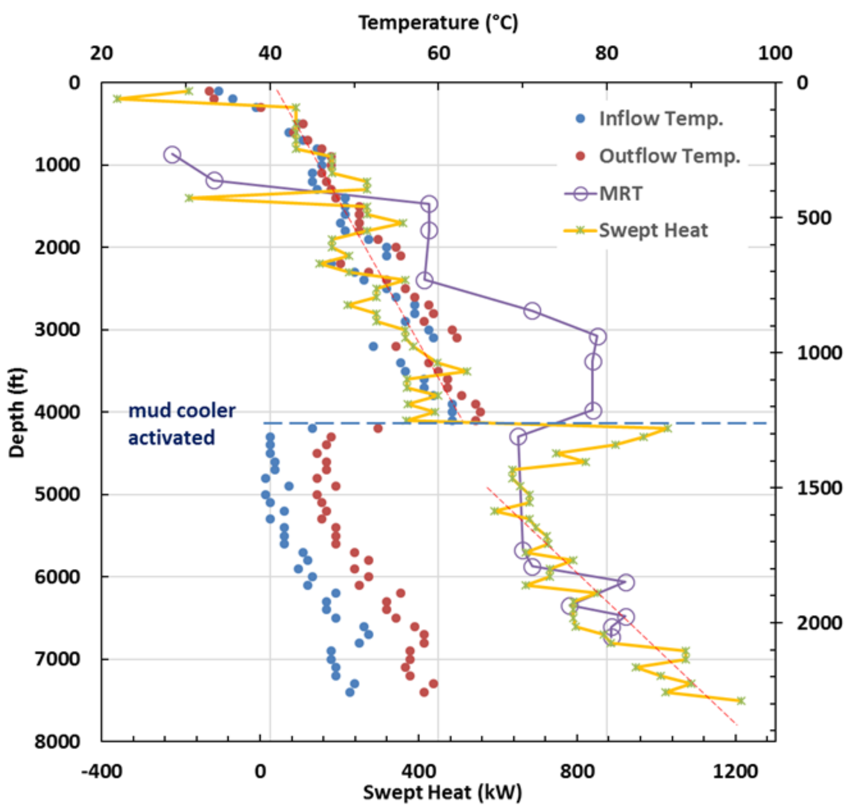

Figure 2: Thermal information acquired while drilling 58-32. MRT is the temperature from a maximum reading thermometer located at the top of a probe run inside the drill string used to measure the hole deviation.

2. THERMAL DATA

The drilling mud temperature was monitored continuously, and increased steadily with depth (Figure 2). At 1250 m, the outflowing mud was at a temperature of 65°C, and the mud cooler was activated, causing an immediate 20°C decrease in mud temperature. The amount of heat swept from the hole by the circulating mud was calculated using the mud flow rate and the temperature difference between the inflowing and outflowing mud. As would be expected, the swept heat steadily increased with depth, apart from a surge in heat output when the hole was suddenly cooled by activating the mud cooler. Near the final depth of 2305 m, the mud outflow temperature was close to 60°C again, and the rate of heat extraction was about 1 MW_{th}. No drilling losses had occurred, so this heat was solely due to conductive heating from the hole walls.

A maximum reading thermometer (MRT) was included at the top of the tool every time the hole deviation was measured within the drill-string. This measurement occurred typically about an hour after mud circulation ceased. When the bottom of the tool was just above the drill bit, the thermometer was at least 27 m from the hole bottom. Both the long time for thermal recovery and the distance of the MRT above the hole bottom meant that these temperatures were a poor indication of the downhole temperature. For example, at 1000 m depth, the MRT yielded a temperature of almost 80°C compared to the 37-day temperature at that depth of 100°C. However, once the mud cooler was used, the additional cooling meant that by 2000 m depth the MRT values were 85°C compared to the 37-day temperature of 175°C.

The four temperature profiles measured when the well depth reached 2073 m, and the 37-day profile after the drill rig departed, are shown in Figure 3. The cross-over between rebound cooling of the hole at shallow depth and rebound heating of the hole at greater depth occurs between 500 and 600 m depth and at a temperature of 60°C. This cross-over is consistent with the mud outflow temperature of 57°C when drilling at about 2000 m depth. The profiles highlight the importance of the temperature survey reaching the bottom of the hole. The vertical temperature difference over the lowermost 30 m varies from 11°C at 8.1 hours and 6°C after 24.2 hours. The circulation time 30 m above the hole bottom at 2073 m was about 11 hours compared to the 2 hours estimated for bottom of the hole, which explains why the MRT values having 1 hour of recovery are far from thermal equilibrium. The large uncertainty in temperature just 30 m above the bottom of the hole also indicates why deriving a reasonable estimate of the equilibrium thermal gradient is not possible with just 24 hours of recovery. Deriving an estimate of the equilibrium temperature at the bottom of the hole is the main goal of these measurements.

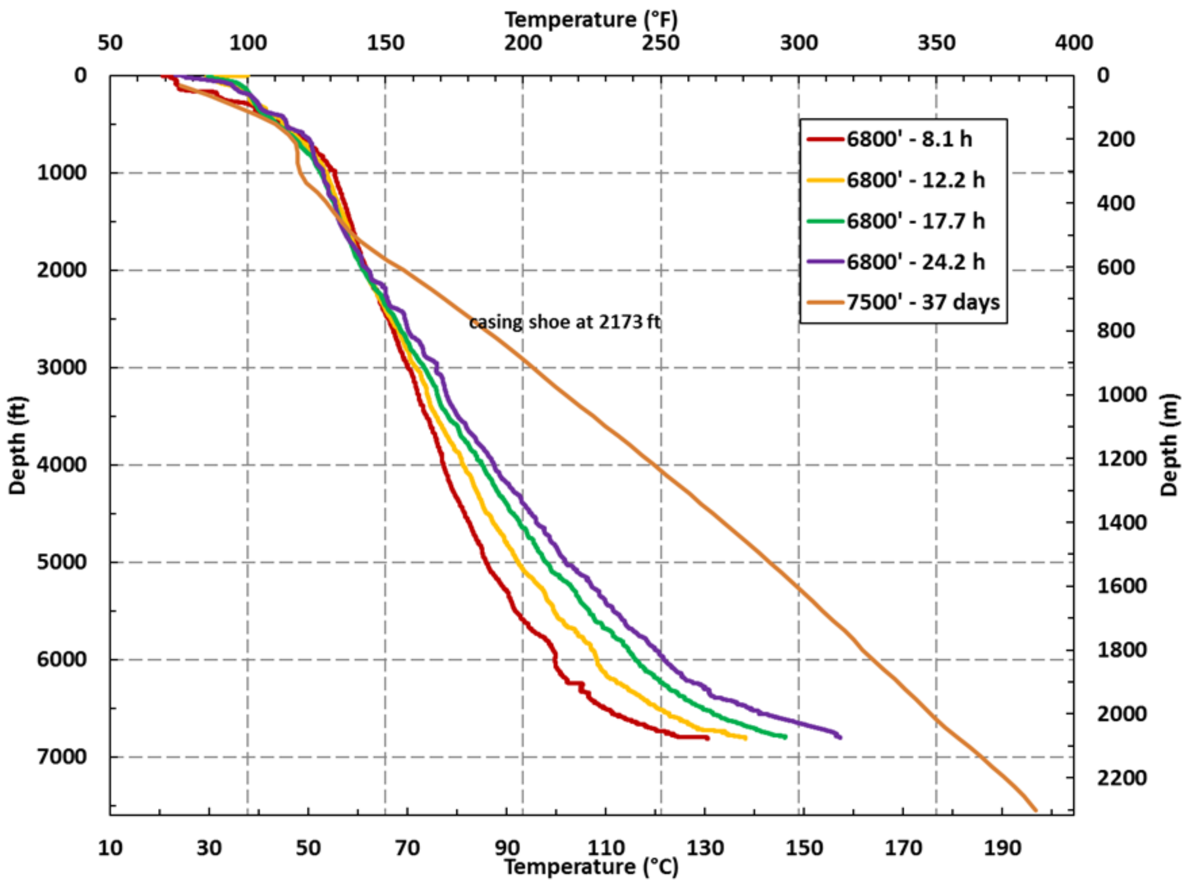

Figure 3: Temperature profiles from the four logging runs while the bottom of the hole was at 2073 m. The 7500-ft run was 37 days after drilling and testing stopped (total depth at 2305 m).

Each logging run was carried out at a rate of 10–15 m/minute (40–50 ft/minute), recording while running into the hole. The sensor was a resistance thermometer in a 3-mm steel probe protected by a slotted steel cage. A photo of the logging during night-time is shown in Figure 4.

Figure 4: View of the drill rig, with boom of the temperature logging truck on left.

The logger did not want the probe to stay sitting on the hole bottom because of the almost 1500 m of open hole above it. To ensure thermal equilibrium of the probe at the bottom of the hole, the probe touched bottom and was pulled up 3–6 m to confirm the temperature. An unexpected feature of the bottom-hole temperature, which was viewed in real time in the logging truck, was that the temperature slowly rose 5–8°C during the ensuing 5–8 minutes (Figure 5). The logger stated that the thermal time constant of the probe was a few seconds and he had never seen this response before. During the 2305 m logging run 37 days later, the logging was stopped every 300 m for 5 minutes to see if this sort of behavior was a feature of the probe. These measurements confirmed that the probe response time was less than a few seconds, and that the drill-hole temperature was almost immediately stable.

The simplest explanation for this response at 2073 m is that there was a temperature gradient radially across the borehole near the bottom of the hole as the hole was rapidly heating up during the first 24 hours. The fluid against the surrounding rock wall was presumably hotter than that in the center of the hole, and the logging process had apparently triggered mixing, resulting in a local rise in temperature. Once the drill hole fluid and the surrounding rock had come close to thermal equilibrium (37-day log), this radial temperature gradient disappeared. The extrapolation to an equilibrium temperature discussed below uses both the set of "instant" measurement of the temperature when the probe touched the bottom of the hole, and the "delayed" measurements after 4–7 minutes of local convection. Although the delayed measurements had not stabilized, we used the last recorded temperature rather than guessing the temperature of the fully mixed fluid at the bottom of the hole.

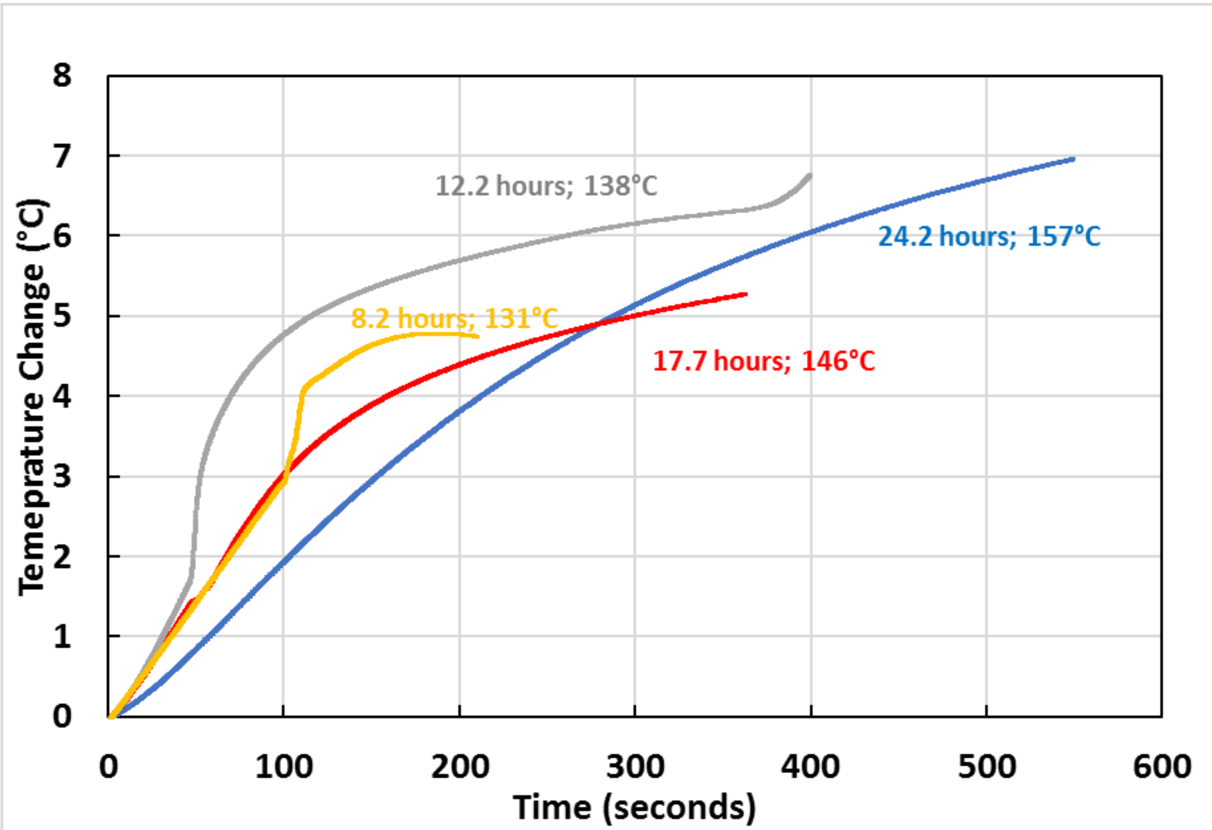

Figure 5: Thermal response when the probe was stationary between 3–6 m above the bottom of the hole (2073 m) after recording the temperature while running down the hole. The time axis is the time after reaching the bottom of the hole. The labels show time in hours since circulation stopped, and the temperature recorded when the probe touched the bottom of the hole for that logging run. In all four cases, the temperatures continued to rise 5–7°C over the ensuing 4–10 minutes.

3. ESTIMATING EQUILIBRIUM TEMPERATURE AT 2073 M

The estimated equilibrium temperature from the four logging runs over 24 hours were compared to the 37-day temperature of 181°C at 2073 m to test the accuracy of the estimations. A common peculiarity of the plots from all three methods (Horner, Bullard, and Ascencio) is that the bottom hole temperatures from the four logging runs did not form a straight line (Figures 6–8). The temperature trends had a convex-upwards pattern with decreasing thermal recovery factor (that is, increasing recovery slope with shut-in time). The slope of the recovery line between the 17.7- and 24.2-hour points is three times that between the 8.2- and 12.2-hour points in the Horner plot. This presents a challenge in deciding how best to extrapolate an equilibrium temperature.

To assist with interpreting the slope of the recovery line on the semi-log Horner plot, the temperature information from logs in four other wells drilled into granite around the Roosevelt Hot Springs system (RHS) were reviewed and compared to the later equilibrium profiles for those wells. In all cases the drill-hole diameter was the same as that for 58-32. For the six RHS data points having thermal recovery factors between -0.15 and zero (that is, more than 12 hours recovery with 2 hours of circulation time), the best-fit line that also goes through the zero intercept has a slope of 280°C (500°F) per thermal recovery factor unit (on natural log scale).

When the best-fit trendline for the three points in 58-32 having recovery times of more than 12 hours are plotted, the slope of the instant and delayed lines are very similar to that of the other RHS wells. The trendline of the delayed temperatures intersects the temperature axis at 181°C. This good agreement with the 37-day temperature is likely fortuitous given the scatter in the three points about the line.

The instant temperature trend based on the three points having more than 12 hours recovery under-predicts the 37-day temperature by 6°C. If trendlines had been fitted through all four points, both the delayed and instant lines significantly under-predict the temperature.

The full exponential integral solution was tested to see whether all four temperature measurements could be used to improve control of the slope of the recovery line (Figure 7). Lines for the three points (12–24 hours) are similar to those in Figure 6 because the logarithmic Horner simplification approximates the exponential solution at long recovery times. The trendlines for the four points on Figure 7 significantly under-predict the 37-day temperature, showing the exponential integral solution is unhelpful here for representing the early-time behavior of the thermal recovery.

Ascencio et al.'s (2006) spherical-radial model was also tested (Figure 8.) The model over-predicts the 37-day temperature, an aspect noted by Ascencio et al. (1997, 2006). Most of the measurements were made at "early" solution times, but allowing for that would have caused even higher equilibrium temperatures. Restricting the slope of the extrapolation line to just the three points having more than 12 hours of recovery would also have increased the predicted equilibrium temperature.

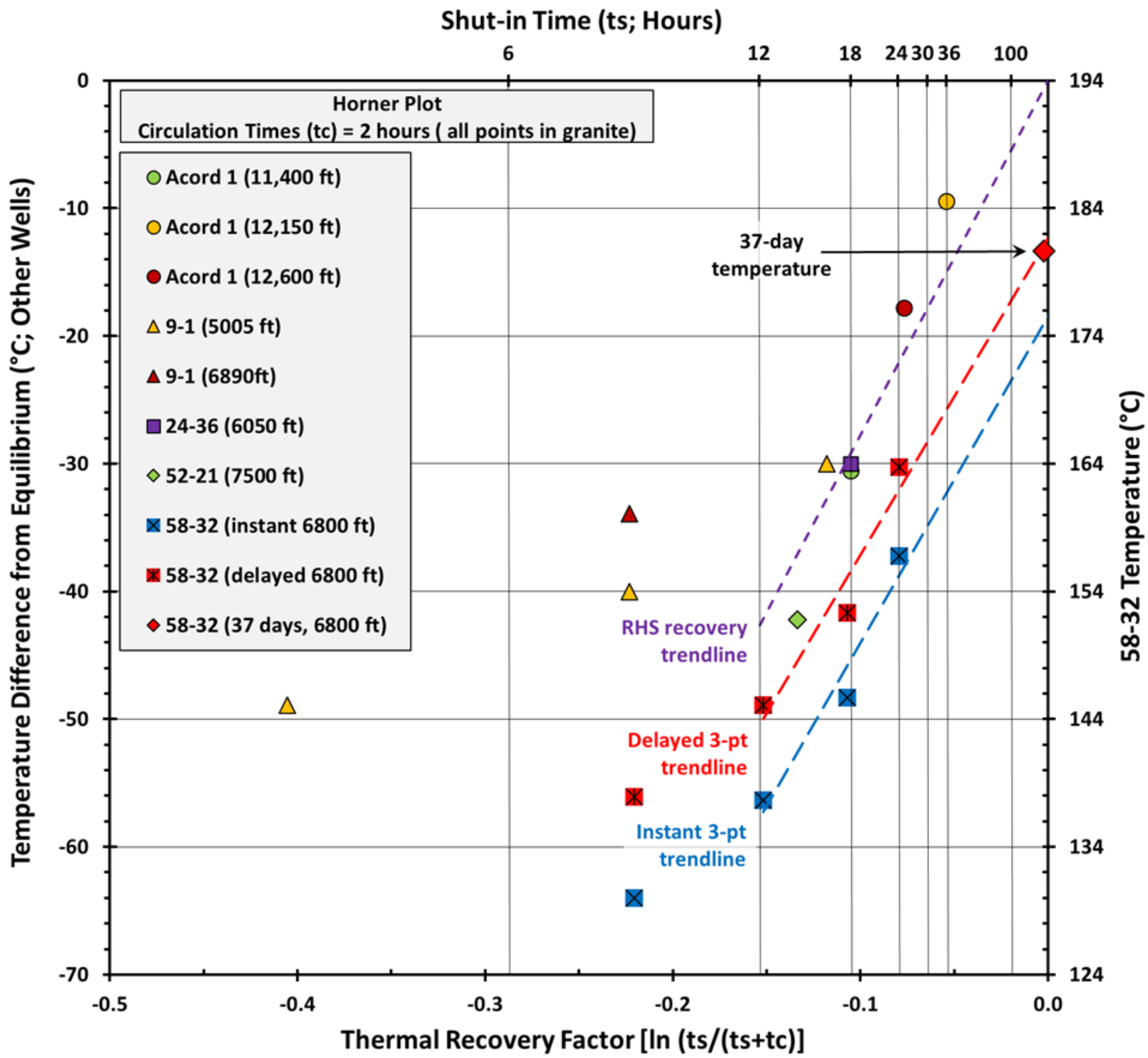

Figure 6: Horner plot of recovering temperatures at the bottom of well 58-32 (right axis; 2073 m [6800 ft]), compared to known recovery trends from several other exploration wells in the Roosevelt Hot Springs geothermal system (left axis). "Instant" temperatures in 58-32 are the maximum temperatures measured as the probe touched the bottom of the hole. The "delayed" temperatures in 58-32 are after 4–7 minutes of inferred mixing of water near the bottom of the hole caused by the movement of the probe (see Figure 5).

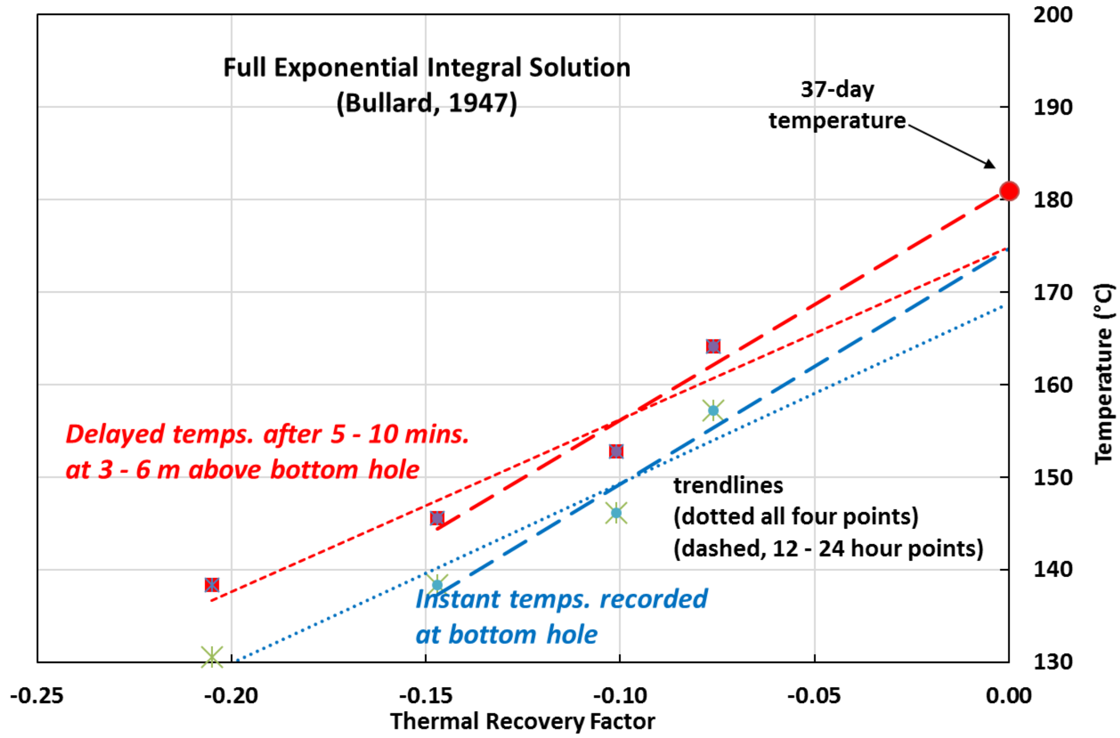

Figure 7: Thermal recovery of temperatures at 2073 m in 58-32 using the full exponential integral solution of Bullard (1947).

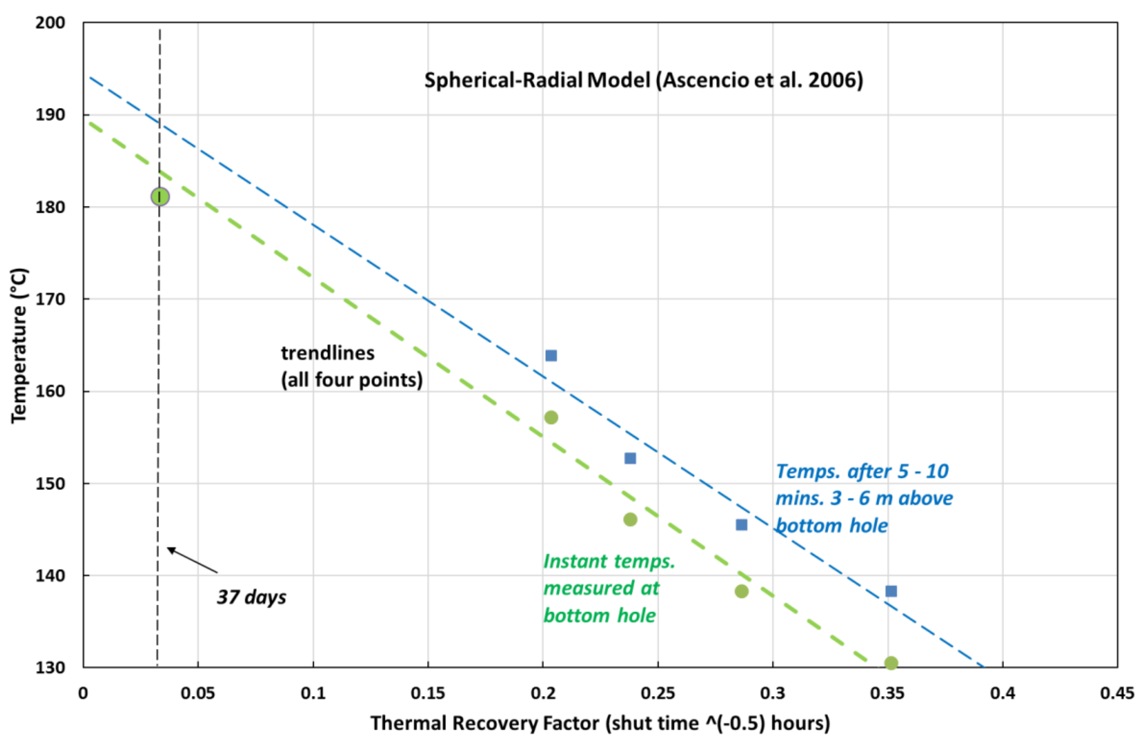

Figure 8: Thermal recovery of temperatures at 2073 m in 58-32 using the spherical-radial solution of Ascencio et al. (1997, 2006).

3. CONCLUSIONS

A very detailed thermal dataset collected during and after the drilling of well 58-32 as part of the FORGE project at Milford, Utah, has allowed us to test the utility of several different methods for approximating thermal recovery from the effects of drilling. The recovery trend, recorded by four thermal logging runs over 24 hours when the well had reached 2073 m, did not have strong linear characteristics when modeled using the standard Horner model (semi-log plot), the exponential integral model of Bullard (1947), or the spherical-radial model of Ascencio (2006).

All three models showed a convex-upwards trend with 17.7 and 24.2-hour temperatures increasing at a much greater rate than the 8.2 and 12.2 hour temperatures. An unexpected feature of the thermal regime at the bottom of the hole during this recovery time was that temperatures continued to rise for at least 5 minutes and at least 5°C after the probe reached the bottom of the hole. This phenomenon did not occur when the same logging tool was used 37 days later in this hole. There was a radial temperature gradient within the hole with warmer water adjacent to the drill-hole walls than in the center of the hole where the temperature probe was hanging. The movement of the probe had apparently caused mixing of the water. The increased temperatures caused by this mixing gave a better prediction of the equilibrium temperature than the temperatures first measured as the probe reached the hole bottom.

Of the three models tested, the Horner plot proved to be the simplest and most reliable indicator of equilibrium temperature. The best-fit slope using the measurements after 12 hours of recovery gave a good prediction of the 37-day temperature (in this case, 181°C). The slope of the recovery trend (280°C/thermal recovery unit on natural log plot) was similar to the slope of a trendline derived from four earlier exploration wells around RHS. These wells are in granite and the hole diameter at the bottom of the hole was 8.75 inches. No fluid losses occurred while 58-32 was being drilled, implying low permeability and a thermally conductive regime. Where these characteristics occur in other geothermal exploration wells, the similar recovery slope value seen here may be helpful in confirming the equilibrium temperature where conflicting data exist. However, the measurements should be at times longer than 12 hours (that is, thermal recovery factor less than 0.15), and the measurements must be made within a few meters of the total drilled depth.

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