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Newberry Exploratory Slimhole

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ABSTRACT

During July-November, 1995, Sandia National Laboratories, in cooperation with CE Exploration, drilled a 5360’ exploratory slimhole (3.895” diameter) in the Newberry Known Geothermal Resource Area (KGRA) near Bend, Oregon. This well was part of Sandia’s program to evaluate slimholes as a geothermal exploration tool. During and after drilling we performed numerous temperature logs, and at the completion of drilling attempted to perform injection tests. In addition to these measurements, the well’s data set includes: over 4000’ of continuous core (with detailed log); daily drilling reports from Sandia and from drilling contractor personnel; daily drilling fluid record; and comparative data from other wells drilled in the Newberry KGRA.

Introduction

The Geothermal Research Department at Sandia National Laboratories is working with industry to evaluate slimhole drilling as a geothermal exploration technique. Traditionally, diamond-cored “slimholes”—usually 3” to 4” in diameter—have been used to measure temperature gradients while selecting sites for production-size exploration wells. If we can demonstrate that improved testing in slimholes reliably identifies a productive geothermal resource, the cost savings and reduced environmental impact, compared to production-size holes, are compelling incentives to use slimholes for exploration.1 The cost-share Sandia/CalEnergy agreement was based on the assumption that two slimholes were to be drilled in this area, with at least four production wells to be drilled within the next year. The first slimhole, TCH 88-21, was drilled to a depth of 4840’ and has a stable bottomhole temperature of 410°F. While drilling the lower part of this hole at HQ diameter (3.895”), the core rods stuck while drilling at 3709’ and could not be freed. The rest of the hole was then drilled with NQ (2.98” hole diameter) coring tools, and 2” tubing was run to approximately 4835’. This tubing serves to keep the hole open for temperature logs and should be removable if the hole is eventually deepened. It is unlikely that, at the present depth, this hole has potential for either production or injection tests because of the low permeability indicated by drilling (almost no lost circulation in the lower hole) and by temperature logs (see Figure 1.)

Summary of Operations

The cost-shared exploratory slimhole, TCH 76-15, was drilled on the outer north-west flank of Newberry Crater. Its primary objective was to improve evaluation, by measurements of temperature and permeability, of this area’s potential for commercial geothermal power production. The plan for data acquisition on this hole was that preliminary temperature measurements would be taken with the Sandia logging tools and truck. If bottomhole temperature and permeability (implied by lost circulation or measured by injection) indicated the possi-
bility of a production flow test, then we would attempt to air-lift, or otherwise stimulate the hole for production. Flow-test data would be taken by a combination of Sandia and service-company instrumentation.

The drilling plan was to set 7" surface casing to approximately 500', then set 4-1/2" casing to a depth dependent on the expected bottomhole temperature at TD, and finally directionally drill/core toward the postulated geothermal resource. Directional drilling was done below the 4-1/2" casing and was aimed toward the south-east, or toward the center of the caldera. Final well configuration is shown in Figure 2.

Drilling operations were lengthy, taking 116 days to TD. This was caused by a number of factors, including, to some degree: extensive lost circulation, stuck pipe, reaming the upper core-hole to accept casing, directional-drilling problems, and forest fires. In spite of the time required for this hole, and the corresponding lessons learned, it still proved to be a cost-effective method of geothermal exploration. Temperature gradients in the lower parts of the two slimholes were similar to each other and were reasonably predictive of gradients in nearby production-size holes.

Although the temperature gradient in the lower part of TCH 76-15 was very similar to that in TCH 88-21 (compare Figures 1 and 3), the near-isothermal portion of 76-15 extended much deeper, resulting in a lower bottomhole temperature (350°F @ 5360') than in 88-21. This temperature, coupled with the reduction to NQ hole size (3") and almost complete lack of permeability (measured by an attempted injection test), indicated that a production flow test was extremely unlikely at this depth. Wellbore simulations based on extending this gradient, in NQ-size hole, to the potential TD of 7500' indicated that a production test from that depth would be problematic. These factors, coupled with the very slow and difficult drilling at this depth and with the fact that two nearby production wells were already at TD, led to the decision for termination of drilling at this depth.

Equipment and Methods

The drill rig used for this hole was a Longyear truck-mounted Model HD602, with a 60' mast, capable of pulling 40' stands of pipe, and a hoist rated at 60,000 pounds. The rig was supported on a hydraulic jack-up substructure which provided approximately 8' clearance between the bottom of the substructure and ground level. Two mud pumps were available; a Gardner-Denver duplex (150 gpm @ 260 psi) for surface drilling and reaming, and an FMC Model M12 triplex (60 gpm @ 1000 psi) for coring. A 40' parts trailer contained tools, bits, spare parts, and a welder. Core recovery in this hole was very good, more than 96% for the cored portion of the well (the interval to the first casing point at 544', and the portion which was directionally-drilled, were not cored).

Several instruments were placed at and near the wellhead, with data collected and recorded continuously in the Sandia mobile office. These measurements comprised the following:

- **Drilling fluid inflow**—Flow rate was measured directly by a Doppler flow-meter mounted on the standpipe and indirectly by volume calculated from mud pump speed, obtained by a shaft encoder on the pump's crankshaft. When these readings were compared, the pump-stroke value was usually higher, because inefficiencies in the pump led to less-than-theoretical fluid delivery. The Doppler meter was especially valuable because it included a totalizer, giving an integrated total flow volume after a specified starting time. This enabled very accurate placement of mud, cement, LCM pills, mineral oil, etc.

- **Annulus inflow**—When drilling without returns, drilling fluid was sometimes pumped down the annulus between drill rods and casing. This measurement was made with an encoder on the pump.
• Drilling fluid outflow—Return flow was measured by a magnetic flow meter (magmeter) on the line from the pitcher nipple back to the mud pits. When outflow becomes significantly less than inflow, this is usually an indication of lost circulation.

• Drilling fluid temperatures—Temperature transducers were placed in the flow lines into and out of the wellbore.

• Standpipe pressure—Pressure delivered to the drillpipe is measured. This pressure is not only important as an insight on drilling performance, but sudden drops in this pressure can indicate a hole or washout in the drillpipe.

• Ambient air temperature—Weather conditions were indicated by the air temperature measured under the rig.

• Rotary speed—Drill-string rotary speed signal was taken off the rig’s tachometer.

• Chuck height—During the latter part of the drilling operations, a linear-displacement transducer was connected to the chuck which rotates the drillpipe and travels down as the drill advances. Hole depth at the start of a core run was entered by the driller. Chuck-height versus time gives rate of penetration, which is sometimes useful to identify different lithologies.

All transducers were connected to a signal-processing station at the drill rig and then, via a simple twisted-pair wire to the data-logging computer in the Sandia trailer. Each morning, data from the computer was down-loaded onto diskettes.

Downhole data collection during this operation was primarily limited to temperature measurements. These temperature logs were taken with Sandia’s platinum-resistance-thermometer (PRT) tool which, along with a Sandia logging truck, remained on-site for the entire project. This instrument uses a simple resistance bridge, with changes in resistance measured from the surface through a four-conductor cable. Since there are no downhole electronics, temperature drift with time is negligible and the PRT temperature measurements are considered a reference standard for this kind of drilling.

Data Analysis

Downhole temperatures were taken during drilling with maximum-reading-thermometers (MRTs) which can be attached to the overshot which is sent downhole to retrieve the core tube or can be loaded into the running gear of the single-shot camera which is used to survey the hole trajectory. During reasonably good drilling, these will provide temperature readings approximately once a day. An MRT is simple and cheap, but does have several drawbacks: It requires some residence time to reach the wellbore temperature; it is subject to pressure effects below 4,000-5,000 feet; it records the highest temperature it has seen, which may not be at the bottom of the hole; and it measures temperature during a short pause in drilling fluid circulation, which tends to cool the wellbore. This latter effect is less important in core drilling, where drilling-fluid flow rates are less than 10% of those in rotary-drilled wells, and the MRT readings for the Newberry slimholes tended to give good agreement with post-drilling logs (see Figure 4).

Logs taken days or weeks after drilling show that temperature gradients in the lower sections of the two slimholes are quite similar, but that the point at which the gradient reaches a relatively constant -8°F/100' is approximately 1000' deeper in TCH 76-15 than in TCH 88-21. It is likely that this effect is related to the relative elevations of the two drill sites; the TCH 76-15 pad is 800' higher than the TCH 88-21 location. Gradients in the slimholes are also reasonably similar to two production-size wells, one very near 88-21 and the other roughly halfway between the slimholes.

Even though there was little lost circulation in the last 1000' of TCH 76-15, implying little permeability, it was important to quantify the transmissivity of the potential reservoir. After circulating the mud out of the hole and replacing it with clear water, we attempted two injection tests; one into the open hole section (5116' - 5360') below the HQ liner, and one into the annulus outside the uncemented part (2748' - ~4800') of the liner. The much greater wellbore area exposed outside the liner was offset by the presence of mud which had been sitting there for several weeks, undoubtedly reducing the effective permeability. In both cases, however, surface injection pressures over 300 psi (which was the pressure limit for the instrumentation) could only drive a flow rate of less than 3 gpm. It was not even clear that this small flow rate was into the formation, because a defective joint in the HQ liner may have allowed this amount of leakage into or out of the liner. In either case, the formation was, for all practical purposes, impermeable.

![Figure 4. Comparison of MRT measurements with temperature logs in TCH 88-21.](image-url)
Discussion

Lost Circulation

The upper 800' of 76-15 suffered extensive lost circulation. Even though it is possible to drill blind (without fluid returns), especially while coring, the drilling plan was to repair loss zones as they were penetrated, thus improving the probability of a competent cement job on the casing. This was an important objective, because the test plan included a production flow test, which requires good cement around the casing. The cost of this repair, however, was high.

In the interval from surface to 839', seventeen cement plugs were set to combat lost circulation. This led to direct costs for: 376 cubic feet of cement, 114 hours waiting on cement, time to drill out 1033' of cured cement, and trip time for running in and out of the hole with open-ended drill pipe. There were other costs, less well-defined, for: three days and five casing-advance bits consumed by stuck pipe directly attributable to cementing, discarded drilling fluid made unusable by drilling cement, and extra bit wear from drilling cement. Assuming an average daily cost of $8,000, lost circulation resulted in at least $80,000 in additional expense. These costs would have been much higher if a commercial cementing contractor had been used for the lost circulation plugs, but cement quantities were small enough that the rig crews could mix cement in tanks and pump it with the rig pumps. Although the costs just mentioned apply solely to TCH 76-15, the experience was similar in TCH 88-21, which required 21 days to set 7" casing at 510'.

Directional Drilling

Changing the hole trajectory was also a long process, requiring 12 days to directionally-drill and ream the interval from 2848' to 3388'. A large part of this time was spent in trying to get the proper equipment into the hole. An oil-field directional drilling company was used first, but their motor was inadequate for the job. When a minerals-drilling directional company was later contracted, the mud-motor work went much better, although the deviated section still required considerable reaming. The lesson to be learned from this is to hire companies who are accustomed to doing the job you want done.

Choice of the interval to be directionally-drilled is frequently affected by the casing design. In this hole, the decision was made to turn the hole below the 4.5" casing shoe. The alternative, directional drilling higher in the well so that the turn would be in the cased section of the hole, would have allowed the use of larger directionally-drilling tools and would have put any potential dog-legs behind pipe. Later experience with downhole vibration and difficulty working some of the coring tools through the directional interval indicates that this might have been a better choice.

The value of the trajectory change was also unclear. The directional work turned the hole to an inclination of about 7°, which later built without further deliberate action to about 10°, giving a lateral hole-bottom displacement of about 300 feet. Even considering the hole's previous inclination and azimuth (i.e., where the hole would have gone without correction), the total effect of directional drilling was to change position of the hole-bottom by about 500 lateral feet. It is not clear from geologic data that this could have had much effect on bottom-hole temperatures or permeability.

Reduction in Hole Size

A major objective of this drilling was to reach a potential reservoir, down to the maximum target of 7500', which could be tested with a production flow test. As depth increases, the penalty of small wellbore-diameter becomes more significant in a slimhole, compared to a production-size well. For that reason, we tried to keep the hole at HQ (3.9") diameter as long as possible, even after drilling problems indicated that we should reduce to NQ (2.98") diameter.

That decision was costly; the last section of the hole from 4756' to TD required 31 drilling days, an average less than 20 feet per day. Most of the problems in this interval were related to caving, sloughing, squeezing clay, and differentially stuck pipe. If we had set an HQ liner from approximately 2700' (just above the 4.5" casing shoe) to 4800' and reduced to NQ drilling at that point, it is likely that (a) the drilling time in the 4800'-5360' interval would have been reduced by 50-75%, and (b) we would have had the option of continuing the hole to greater depth. Computer modeling, using a wellbore simulator, of production flow tests indicates that this diameter reduction would not have seriously diminished the ability to run a flow test, had the formation been suitable. In short, the decision to maintain HQ diameter after hole problems became severe led to excessive drilling cost which probably could have been avoided with an earlier reduction in hole size.

Cost Comparison

During drilling operations at TCH 76-15 detailed daily cost records were kept by on-site Sandia personnel. A summary of those records is in Reference 3. CalEnergy has also released daily reports and total cost figures on the two production wells which were drilled during the same period as the slimhole. That information, and comparable data on the slimhole, is summarized in Table 1. The significant cost difference between the big wells is primarily due to two workovers in 88-21, but even averaging the costs between them ($331.29 per foot) shows that the slimhole cost per foot was 200/331, or 60.4% of the large holes.

Conclusions

The principal purpose of drilling a slimhole is prediction of productivity in a large well; in effect, prediction of temperature and permeability. To examine temperature first, the temperature gradients in the two slimholes (TCH 88-21 and TCH 76-15) and in the two production wells (86-21 and 23-22) are given in Table 2. These gradients are in the same 1000' interval relative to sea-level elevation; that is, they are not at the same measured depths in the wells. Note that the temperature gradients (derived from temperature logs) are corrected for the inclination of the wells and are defined as °F/100 vertical feet. Note
also that 88-21 and 86-21 are within 1000' of each other, 23-22 is approximately 2400' north-east of them, and 76-15 is approximately 4700' north-east of 23-22.

Table 1. Comparison of Slimhole 76-15 to Production wells 86-21 and 23-22

<table>
<thead>
<tr>
<th>Well Number</th>
<th>86-21</th>
<th>23-22</th>
<th>76-15</th>
</tr>
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<tr>
<td>Depth</td>
<td>8869' TVD</td>
<td>9040' TVD</td>
<td>~5335' TVD</td>
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<td></td>
<td>9200' TMD</td>
<td>9602' TMD</td>
<td>5360' TMD</td>
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<td>Drilling days to TD</td>
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<td>81</td>
<td>116</td>
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<td>Casing program</td>
<td>20' @ 905'</td>
<td>20' @ 795'</td>
<td>7' @ 538'</td>
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<tr>
<td></td>
<td>13-3/8' @ 4199'</td>
<td>13-3/8' @ 4418'</td>
<td>4-1/2' @ 2748'</td>
</tr>
<tr>
<td></td>
<td>9-5/8' @ 3987-9185'</td>
<td>9-5/8' @ 4200-9577'</td>
<td>8-1/4' @ 3400-5577'</td>
</tr>
<tr>
<td>Total Cost</td>
<td>$3,333,427</td>
<td>$2,895,493</td>
<td>$1,070,876</td>
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<tr>
<td>Cost per foot</td>
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<td>$301.55</td>
<td>$199.79</td>
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</table>

Temperature gradients in the slimholes were consistently higher than in the production wells, which would lead to over-prediction of reservoir temperatures, but there are several possible explanations for this discrepancy. First, it is possible that the production wells actually did have lower gradients, although 88-21 and 86-21 were only about 1000' apart and 23-22 is spaced between the two slimholes. It does not seem reasonable that the slimholes' formations would have uniformly higher gradients than the production wells. A more likely scenario is related to the way the holes were made. The slimholes were drilled with minerals-type diamond coring tools, which have very low flow rates (15-25 gpm) compared with the production wells drilled with conventional rotary rigs having mud flows of 500-600 gallons per minute.

The cooling effect on the wellbore is also much greater in the larger holes and, therefore, so is the temperature recovery once drilling is done. Figure 4 shows the MRT readings in 88-21 compared with a temperature log taken two weeks after the end of drilling. Temperature recovery is only a few degrees, but regulatory agencies normally assume 50°F recovery in conventional wells. The cooling effect is also aggravated by the short times after drilling at which the logs were done in the production wells; approximately two weeks after end of drilling operations in 86-21, and only four days after circulation and testing in 23-22. Later temperature logs in the production wells show that, although the temperature has recovered somewhat, the gradients have not changed significantly.

Circulation within the wellbore has a greater effect on the cold-water aquifer ("rain curtain") in the big wells, raising its temperature relative to that in the slimholes. [This zone, at about 6000' ASL, is 90°F in the big wells, but only 50°F in the slimholes, implying that the aquifer is heated by the greater circulation in the production wells.] Wellbore circulation past the warmer aquifer in the big wells, then, causes the top of the well to be warmer and the bottom of the well to be cooler, relative to the slimholes, lowering the temperature gradient.

Because the production wells were approximately 9000' deep and the slimholes were about 5000', predicting permeability is even more chancy. In fact, permeability was low in all the wells. It is certainly not the case that corresponding permeabilities would necessarily be similar over this depth range, but the slimholes did reflect the production wells' permeabilities.

In general, the slimholes were informative, particularly in terms of the temperature-gradient data and in the lithologic data inherent in the core samples. They were not, however, especially predictive of reservoir potential because they did not reach the postulated reservoir depth. Even if the temperatures had been accurately extrapolated from the slimhole profiles, little would have been known about the permeability and productivity in a horizon several thousand feet deeper than the slimholes reached. Finally, if the development schedule had permitted the slimholes to be drilled to the target horizon before the big wells were spudded, it is possible that at least one of the production wells would not have been drilled, with a cost savings of several million dollars.

**Recommendations**

It would be worthwhile to further evaluate data collected from the slimholes so that we can better understand their benefits and shortcomings. Two major issues to be resolved are the discrepancy between temperature gradients in the slimholes and in the production wells, and the effect of surface elevation on comparison of data among wells. Several activities might clarify these questions:

- Late-time (months after drilling) temperature logs in the production wells would show whether there is any significant change since the immediate post-drilling logs.
- Monitoring water level in all the wells could help resolve the effect of wellhead elevation.
- Comparison of lithologic data (especially from core) might enable correlation of strata among the different locations.

**Brief Geologic Description**

Summarized from Jensen, R.A.—The Newberry Volcano, covering more than 500 square miles, is one of the largest Qua-
ternary volcanoes in the conterminous United States. It lies at the west end of the High Lava Plains province in central Oregon, an extensive volcanic zone measuring approximately 150 miles east-west and 50 miles north-south. There have been many volcanic events in the Newberry area since the first lava flows about 1,200,000 years ago (ya), with major eruptions as recently as 1,250 ya.

At the summit of the gently rising volcano, there is a four- to-five-mile-wide caldera called Newberry Crater. This depression contains East Lake and Paulina Lake, each approximately 1.5 miles in diameter, and is a collapse structure made up of several nested sets of walls. It is probably the result of several large tephra eruptions, possibly from more than one magma chamber, each accompanied by chamber collapse. These eruptions are believed to have taken place over a period from about 500,000 ya to 200,000 ya. The caldera floor contains more than 1500 feet of assorted, mostly rhyolite, fill, including domes, flows, ash fall, and explosion breccias.

Since the caldera was formed, there have been three other major eruptive sequences, grouped around the periods 10,000-12,000 ya, 7,000 ya, and 1250 ya. Ages of most flows at Newberry are described in relation to the eruption of Mt. Mazama, about 7,600 ya, which formed the crater now occupied by Crater Lake. This event, approximately 65 miles south of Newberry, covered this area with two to three feet of ash, so local flows which over- or underlie the Mazama ash can be easily dated with reference to it.

During the period 12,000 to 10,000 ya, most eruptive activity was to the south and east of the crater, but about 7,000 ya (shortly after the Mt. Mazama eruption) the Northwest Eruptive Period occurred along the Northwest Rift Zone, which extends nearly 20 miles from the caldera (to the vicinity of the present Lava Lands Visitor Center.) Later (about 3,500 ya) the East Lake Eruptive Period produced two small obsidian flows but they were later covered by ashfall from the most recent and well-known event at Newberry, the Big Obsidian Eruptive Period. At present, the east and west flanks of the volcano are mostly covered by ash flows, pumice falls, mudflows, and other pyroclastic deposits; the north and south flanks probably also have these deposits at depth, but they are overlain by basalt and andesite flows.

The Newberry National Volcanic Monument, roughly including Newberry Crater and the Northwest Rift Zone, was created in 1990. The Monument is bounded in places by a Special Management Area, in which surface occupancy is prohibited but directional drilling beneath the SMA is allowed. The wells described in this report are just outside the SMA, generally north-west of Paulina Lake.

Acknowledgments

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References


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