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SLIM HOLE DRILLING AND TESTING STRATEGIES

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ABSTRACT

The financial and geologic advantages of drilling slim holes instead of large production wells in the early stages of geothermal reservoir assessment has been understood for many years. However, the practice has not been fully embraced by geothermal developers. We believe that the reason for this is that there is a poor understanding of testing and reservoir analysis that can be conducted in slim holes. In addition to reservoir engineering information, coring through the cap rock and into the reservoir provides important data for designing subsequent production well drilling and completion. Core drilling requires significantly less mud volume than conventional rotary drilling, and it is typically not necessary to cure lost circulation zones (LCZ). LCZs should be tested by either production or injection methods as they are encountered. The testing methodologies are similar to those conducted on large-diameter wells; although produced and/or injected fluid volumes are much less. Pressure, temperature and spinner (PTS) surveys in slim holes under static conditions can used to characterize temperature and pressure distribution in the geothermal reservoir. In many cases it is possible to discharge slim holes and obtain fluid samples to delineate the geochemical properties of the reservoir fluid. Also in the latter case, drawdown and buildup data obtained using a downhole pressure tool can be employed to determine formation transmissivity and well properties. Even if it proves difficult to discharge a slim hole, an injection test can be performed to obtain formation transmissivity. Given the discharge (or injection) data from a slimhole, discharge properties of a large-diameter well can be inferred using wellbore modeling. Finally, slim hole data (pressure, temperature, transmissivity, fluid properties) together with reservoir simulation can help predict the ability of the geothermal reservoir to sustain power production.

Key words: Coring, Reservoir Testing, Lost Circulation Zones, Pressure-Temperature-Spinner Surveys, Injection

INTRODUCTION

Slim-hole drilling, and specifically coring, has long been used in the geothermal industry. The Geothermal Resources Council and Sandia National Laboratories presented a comprehensive "Slimhole Technology Workshop" in 1996 that summarized experience up to that time. Much of the slim-hole activity in the geothermal industry has focused on temperature gradient drilling, but we are promoting a comprehensive reservoir assessment approach. Coring has been used for reservoir assessment at several sites in Japan (Garg and Combs, 1997), Steamboat Springs in Nevada (Combs and Goranson, 1994), The Geysers in California (Hulen *et al*., 1994) and Tiwi in the Philippines (Nielson *et al*. 1996). In Indonesia, coring has been used at Awibengkok (Hulen and Anderson, 1998; Stimac and Sugiaman, 2000), Karaha (Moore *et al*., 2000), Wayang Windu and Darajat (White *et al*., 2010).

Unocal used a hybrid drilling technique to core numerous exploration holes in the evaluation of the Sarulla Block in North Sumatra (Gunderson *et al*., 2000). Hybrid technology has also been used to drill several scientific holes, including the Long Valley Scientific Drilling Program (Nielson, 2001). The hybrid approach uses a conventional rotary rig to drill and emplace large diameter casing to the reservoir cap. Then a high-speed coring head is attached to the rotary rig and continuous core is collected through the cap and into the reservoir. This phase may involve multiple directional core holes to provide a greater understanding of the reservoir character. Following the completion of the coring, the coring head is removed and the well can be completed at production size using the rotary rig. The disadvantage of this scenario is that the operator is essentially paying for two drilling systems during the coring phase. With improvements in coring equipment in the last decade, it is possible to core and complete deep slim holes without using hybrid rigs.

The high cost of discovering and assessing geothermal resources remains an impediment to the expansion of the geothermal industry. We have recently analyzed the use of slim-hole drilling and testing of production zones and concluded that geological and reservoir data equivalent to that from large-diameter production wells can be collected in slim holes (Nielson and Garg, 2016). In that paper, we advocate for the use of slim holes to provide a comprehensive assessment of a geothermal reservoir and illustrate not only cost savings, but also risk reduction.

SLIM HOLE DRILLING METHODOLOGY

Slim holes can be drilled using different techniques: rotary, diamond coring or mud motors. Rotary drilling uses high weight on bit and low rpm to crush rock, and the only recovered samples are rock fragments (cuttings). Once major lost circulation zones (LCZ) are encountered, it may be impossible to recover cuttings and the well is drilled without obtaining subsurface geologic data. In addition, the loss of circulation increases mud costs and can lead to the loss of the well due to plugging of permeable formations. Diamond coring uses high rpm and low weight on bit to cut rock and recover a core sample. Lost circulation generally does not impact core collection, and because of the small cutting size along with small mud circulation volumes, plugging of productive formations and possible loss of the well is avoided. Rotary drilling is normally faster whereas diamond coring produces a straighter hole, superior lithologic samples and less thermal and chemical disturbance.

Slim-hole drilling has been applied to geothermal directly from the mining industry, and there has been little effort to optimize the technology for geothermal applications. Most core rigs drill to depths of 1000 m. Rigs that will core to 2000 m or more are not as common, but they are available and can be adapted to geothermal service. Several rig manufactures offer multipurpose rigs that can drill the upper part of the hole with air hammers or rotary tri-cone drill bits, and following emplacement of casing, complete the hole using core drilling. The geothermal industry needs multipurpose slim hole rigs with a minimum drilling capacity of 31,750 kg (70,000 pounds). This provides the capacity to establish casing above the reservoir for pressure control, and will allow the drilling of HQ core into the reservoir to nominal depths of 2000 m. This size hole give us the option of reducing to NQ should hole conditions dictate. Since most geothermal fluid production is found in steeply inclined faults and fractures, it is often advantageous to drill holes perpendicular to the trend of the fractures. Core rigs commonly drill angle holes by tilting the derrick. Mud motors can also be used in slim holes and can directionally drill from a vertical casing or perform multilateral completions. Mud motors can also be used to drill ahead without core sampling above the cap and then transition to coring once the reservoir is intersected.

A significant advantage of slim hole drilling equipment over production well equipment is its smaller size and greater mobility. This translates into smaller well pads and less environmental disturbance as well as lower daily costs for crews, fuel and consumables. For remote locations, the savings in road construction and transportation costs can also be significant.

Fluid Circulation

The fluid circulation system pumps drilling fluid (mud) down the hole through the center of the drill pipe or drill rod, past the cutting surface of the bit and returns the mud and entrained cuttings to the surface through the annular area. The purpose is to cool and lubricate the bit, remove cuttings and stabilize the hole. The cost of mud can be a significant component of the overall drilling costs (Silverman *et al.*, 2014). Diamond coring typically circulates at a rate of about 40 liters per minute. This contrasts with production well (rotary) methods that circulate more than 3000 liters per minute. Another important point is that rotary drilling crushes rock and produces centimeter-size cuttings while core drilling cuts the rock, produces millimeter-size cuttings and essentially mines about 50% of the rock as core. Along with the smaller hole size, this results in much less formation damage compared to rotary drilling.

Recent mud technology developments include centrifuge systems that effectively clean mud for recirculation. This decreases mud cost and is advantageous in many parts of the world because it also decreases water consumption. The oil & gas industry has pioneered underbalanced drilling methods that control well pressure to less than the hydrostatic reducing the likelihood of lost circulation and formation damage.

To-date, geothermal mud-loss data have not been employed to make quantitative determinations of the permeability of natural fractures encountered during drilling. In petroleum drilling, mud losses as small as 3000 liters have been measured and used as permeability indicators (Dyke *et al*., 1995). Also, petroleum industry has developed mathematical models (Huang *et al*., 2011; Akin, 2013) for computing permeability of natural fractures using mud-loss data. We have proposed using this approach to quantify permeability in real time as the drill penetrates a target reservoir.

Tubulars

Drilling rods used in coring operations have flush joints in contrast to the large tool joints on drill pipe used in production well drilling. Standard rod sizes are P (4.5" x 4"), H (3.5" x 3.063") and N (2.75"x 2.375"). In the event of hole problems, drill rod can be left in the hole as casing and the next smaller drill string can be used to continue drilling. The annular space between the rod and the hole is small, typically 63 to 127 mm (0.25 to 0.5 inches). This is adequate to clear the fine-grained cuttings and also helps to prevent the buildup of mud rings that can cause plugging of the annular area. The inner diameter of the drill rods is also flush, and the bits are open at the end. This allows the driller to use the larger size drill rod as casing with the next smaller size drill rod used to drill out the end of the assembly, without pulling it back to the surface, and continue coring operations.

Hole Design

Slim holes should be designed differently than production wells. We often see "slim hole" drilling plans that are similar to production wells, except for casing strings that are one or two sizes smaller. These designs still require large drilling rigs and multiple casing strings that eliminate cost advantages, and drilling using rotary techniques reduces sample quality.

A reference design for a 2000 m slim hole is shown in Figure 1. A 12-1/4 inch diameter hole is drilled to a depth of 30 m and a 9-5/8 inch conductor is cemented in place. Following that, an 8-1/2 inch hole is drilled to 350 m and a 7 inch surface casing is cemented in place and pressure tested. Depending on rig availability, it may be beneficial to drill the upper parts of the hole with small mud rotary or air hammer rigs. Regulatory agencies typically require the surface casing to be 10% of the total depth of the hole. An annular blowout preventer, in contrast to a full BOP stack, is often acceptable. But provision should be made for a full BOP stack. From 350 m to the top of the reservoir, that we are assuming to be at 750 m depth, the hole can be cored PQ or rotary at 6-1/4 inch. Either way, 4-1/2 inch casing is cemented to the top of the reservoir. From that point, HQ core can be collected in the reservoir or to a depth of 2000 m. NQ can be used as a backup should hole conditions dictate. Delahunty *et al*. (2012) describe drilling experience using a similar, but somewhat smaller hole design. Our reference 2000 m slim hole has a cost in the US of about $1.5 million.

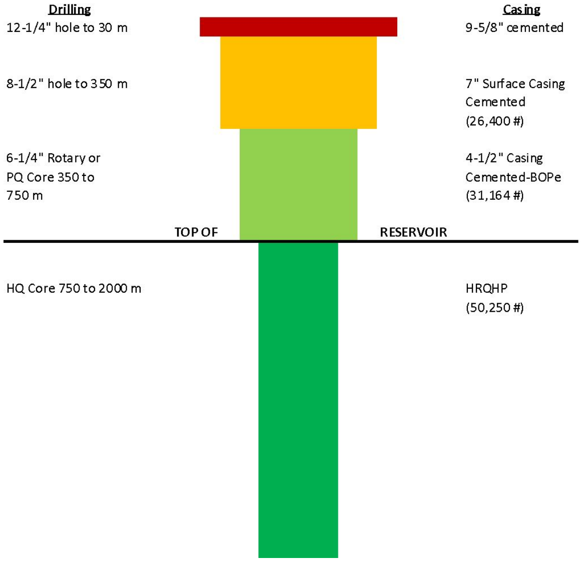


Figure 1: Reference design for a 2000 m geothermal assessment slim hole.

Slim holes are intended for reservoir assessment, investigating the permeability structure and pressures and temperatures as a function of depth in the reservoir. An additional benefit is that this information allows us to better design and budget for the subsequent drilling of production wells. Core material obtained from the slim hole can also be used to determine rock properties of both the geothermal reservoir and the caprock system (Boitnott, 2002). Permeability tests and clay analyses can be performed to better understand reservoir properties. Clay swelling tests can also be performed to determine mud properties needed to reduce clay swelling that can lead to stuck drill pipe and formation damage.

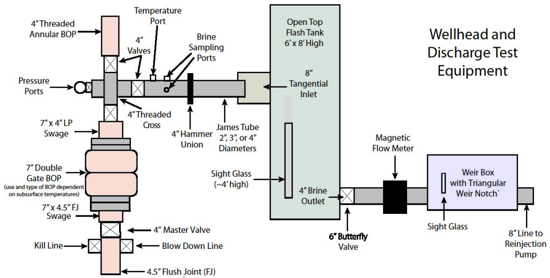
TESTING & ANALYSIS

Slim holes are not normally intended for geothermal production and reservoir engineering data from slim holes are usually obtained through injection testing. However, proper design of the slim hole completion will allow for discharge testing. Standard downhole pressure, temperature and spinner (PTS) survey data can be obtained during both discharge and injection testing. In addition, slim holes can be used in reservoir pressure interference testing (Combs and Goranson, 1995) and used for long-term monitoring of subsurface reservoir pressure and temperature of the geothermal system during long term production and injection operations.

The techniques for slim hole testing and scaling the results to large-diameter holes have been known for many years (Pritchett, 1993, 1996; Combs and Goranson, 1995; Garg and Combs, 1997, 2000, 2015). Our approach to reservoir testing is to characterize permeable zones as drilling advances. This is different than most production well drilling plans that drill the well to a predetermined total depth before performing reservoir tests. We believe that this destroys shallow permeability that may be the most productive component of the geothermal system.

In order to use slim holes for reservoir assessment, it is necessary to be able to predict the discharge characteristics of large-diameter wells based on discharge and/or injection tests on small-diameter boreholes. To compute the probable discharge characteristics of a large-diameter well, a relationship between the injectivity and/or productivity of slim holes and large-diameter production and/or injection wells is required. Garg and Combs (1997) examined production and injection data from slim holes and large-diameter wells at five geothermal fields (Oguni, Sumikawa, Takigami, and Kirishima, Japan; Steamboat Hills, U.S.A.) in order to establish relationships (1) between productivity and injectivity indices, and (2) between discharge capacity of slim holes and large diameter wells. For boreholes with liquid feed zones, the productivity and injectivity indices are more or less equal, and the productivity (or injectivity) index is independent of borehole diameter. It therefore follows that the productivity index of large-diameter production wells can be estimated based on testing of slim holes. If the productivity index is sufficiently large, the discharge rate of the well will not be limited by the formation; in this case, a multi-phase wellbore simulator can be employed to investigate the production characteristics of a well regardless of the borehole diameter. It may also be feasible to predict the performance of wells with two-phase feed zones (Garg and Combs, 2000). Garg and Combs (2015) indicate the importance of data collection for thermal modeling associated with early stages of exploration.

When permeable zones are encountered during drilling, they will be identified by fluid losses during coring. Once there is total mud loss, the drilling will stop to allow testing. Figure 2 shows the surface testing equipment needed to collect flow data from slim holes. In the caprock or other zones with permeability insufficient to maintain continuous fluid discharge, injection tests can be performed. Permeability testing of the caprock, or other low permeability zones, is useful in creating an accurate 3D numerical model of the reservoir system. Production testing is the preferred method in that additional data on fluid and gas geochemistry is also obtained.



Modified after Goranson, 1996

Figure 2: Surface testing equipment for geothermal slim hole assessment.

Below the caprock, production and injection testing can be performed as follows.

1) For flow testing, set up wellhead system, surface flow test equipment and surface measurement equipment (WHP, WHT, James Tube Pressure, Orifice plate pressures, geochemical sample point equipment, etc).
2) Set up test monitor equipment for injection tests.
3) Allow well to heat up for 12-24 hours.
4) Run static pressure-temperature surveys
5) Attempt to flow the well. Pressure up the well with air if it does not self-flow.
6) If the well flows, run the PTS tool and determine the influx zone. Flow the well for 12-24 hours. Run periodic (determined in

the field) PTS surveys to determine subsurface discharge conditions.

7) Set the PTS tool at the main fluid entry zone, shut in the well, measure downhole pressure build-up (or pressure fall-off in the case of injection testing) for 12-24 hours (the actual time will depend on subsurface conditions).
8) If the well does not flow, inject fresh water while monitoring the loss zone using the PTS tool.
9) Inject fresh water for ~12 hours. Run PTS surveys during injection.
10) Identify injection zone from PTS surveys
11) Set PTS tool at main injection zone.
12) Shut off injection and monitor downhole PT for +/- 24 hours.

Development of 3D Numerical Model

In addition to the borehole and well testing data obtained from coring operations, a review of the geology, geophysics, geochemistry, hydrogeology and topography of the surrounding region will provide a basis for establishing geographic relationships of reservoir properties. A preliminary conceptual model including a description of the reservoir volume, heat source, permeability structure, fluid source, *etc*. of the geothermal reservoir is then developed.

A suitable grid for the numerical model in the reservoir simulation software program is developed to encompass the complete geothermal system. The grid should include the entire known permeable region of the geothermal reservoir and lateral boundaries of the system. Based on available data and analyses, preliminary values are assigned for the required formation properties (porosity, density, heat capacity, thermal conductivity, permeability, relative permeability for liquid and vapor phases, *etc*.). Available heat flow data is used to specify preliminary boundary conditions (*i.e.* heat and mass flux) along the bottom boundary of the numerical grid. A natural state model of the geothermal system is created by varying the permeability distribution and boundary conditions. The model is constrained by matching the known information (*e.g.* pressure and temperature distribution, heat flux at the surface, *etc*.) about the geothermal system prior to the initiation of production. The constrained numerical model can then be used to forecast the response of the geothermal reservoir under future production and injection scenarios developed in consultation with the client.

CONCLUSIONS

This paper describes a comprehensive process for the assessment of geothermal resources starting with slim hole drilling and extending through the testing and initiation of numerical modeling. As previously discussed (Nielson and Garg, 2016), slim hole drilling reduces risk and cost in geothermal exploration and development. We believe that this approach has not been more widely applied because developers are unaware of the advantages and history of the approach.

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