DRILLING, COMPLETING, AND MAINTAINING GEOTHERMAL WELLS IN BACA, NEW MEXICO

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ABSTRACT

A 55-MWe power plant is planned for development in the Baca location in the Jemez Mountains of New Mexico. Union Geothermal has contracted to provide the steam for the power plant. This paper uses Baca Well No. 13 as a case history to describe the drilling methods, casing program, cementing program, and completion methods used by Union. The discussion includes aerated-water drilling and the methods of solving corrosion problems in aerated water. Lost circulation control in mud drilling and its effect on the subsequent casing cementing program are discussed.

The paper also includes a case history of scale removal methods used in Baca Well No. 11, including drilling the scale out with a turbo-drill and attempts at chemical inhibition.
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INTRODUCTION

This paper describes the methods that are currently used to drill, complete and maintain geothermal wells in Baca, New Mexico. FIGURE 1 shows the general location of the Baca field [1].

FORMATION CHARACTERISTICS

Some general understanding of the geology and fluid characteristics is required to understand our drilling and completion practices [1]. FIGURE 2 shows a generalized cross section through the Valdez Calera, and FIGURE 3 shows a pressure and temperature versus depth plot [2].

Most wells have casing set into the top of the thermal anomaly in the Bandelier Tuff, and produce from the Bandelier Tuff or a combination of Bandelier Tuff and Andesite. The better wells produce from natural fractures in the Tuff and/or Andesite.

The pressure and temperature versus depth plots show that the reservoir is underpressured, compared to hydrostatic, by 600 to 900 psi (the reservoir pressure is 1206 psi at 4500' above sea level). The underpressured, but water dominated condition of the reservoir results in severe lost circulation problems, which is why we have had to use air assisted drilling fluids.

Fortunately, the produced water is relatively benign chemically. TABLE 1 [2] gives a generalized chemical analysis of the produced water. Produced water is the primary source of water for the drilling rigs, and the only source of water for the drilling muds. The production wells themselves have experienced very few problems, but there has been one instance of calcium carbonate scale buildup.

DRILLING METHODS

The drilling is broken into two parts: I) surface through the last cemented casing, and II) from the last cemented casing to total depth. There is a distinct difference between the drilling practices and the problems in hole sections I and II, due to a change in philosophy about how lost circulation should be handled. In section I, we work toward eliminating lost circulation, while in section II (the production zone), we worry about damage to the lost circulation zones.

I. Surface Through the Last Cemented Casing

FIGURE 4 shows a schematic of the wellbore completion. The wells are usually spudded in rhyolite or caldera fill. A 17½" hole is drilled to 200 to 500 feet with mud, and then opened to 26". After 20" casing is cemented, 17½" hole is drilled to about 1500', where 13-3/8" casing is cemented. 12½" hole is then drilled to the top of the reservoir (2500' to 4000'). This is the basic drilling program for Phase I, which sounds simple, but is associated with many problems.
Mud Program

The mud program is a gel-lime or gel-Ben-X produced water system. An example of the properties are shown in TABLE 2. Drill pipe corrosion is controlled with oxygen scavengers in this part of the hole. The properties are controlled to maintain adequate hole cleaning and sufficient fluid loss control to avoid problems in some of the upper permeable zones. Since there are few hole problems encountered in this part of the hole that are mud related (no swelling clays, etc.), hole cleaning and some fluid loss control at minimum cost are all that is required of the mud. Because of the lost circulation problems, a low cost mud is desirable to keep overall costs down.

Lost Circulation

Lost circulation is the major time consuming and costly problem encountered at Baca. In Baca, as in all geothermal areas, competent cementing of the casing is a prerequisite to having a useable well when we finish drilling the hole. Bitter experiences have taught us that poorly cemented casing cannot survive the thermal stress cycles that a geothermal well must go through, and very poorly cemented casing cannot survive even one thermal shock. This is discussed in more detail later, but for our purposes here, we consider it imperative that all lost circulation be cured before attempting to cement casing in the well.

The usual lost circulation materials are used in the first attempts (mica, walnut hulls, sawdust, etc.). If the loss is occurring to larger fractures (desirable in the production zone, but not here), the common lost circulation materials usually are unsuccessful or only partially successful. Under these circumstances, cementing of the lost circulation intervals has been the only reliable cure we have found so far, although we have experimented with numerous other "cures".

Cementing lost circulation zones is costly, partly because of the cost of the cement, but mostly because of the time consumed in tripping out and back in with open drill pipe, waiting for the cement to harden, and tripping again to pick up a bit to drill out the cement. Frequently, more than one cement plug may be required. Usually this is due to the size and severity of the lost circulation zone, but occasionally one of the following problems contributes to the lack of success.

1. Did not account for where the fluid level was and overdisplaced the cement plug.

2. Pressured up on the cement plug too soon by filling the hole and by pushing all the cement away (this is a problem in severe lost circulation zones).
3. Did not push any cement back into the formation. The only cement was in the wellbore, so circulation was lost when the plug was drilled out (this is usually a problem in seepage zones). As you can see there is a judgement factor between #2 and #3.

4. Did not wait long enough for the cement to harden. This is frequently a problem in geothermal. We retard the cement for the temperature we are "worried" about - the formation temperature which is hot. However, the loss of circulation has cooled the hole enough that the cement then takes longer to set up. Drilling out too soon will frequently result in taking 24 hours to solve the lost circulation problem instead of saving three or four.

The cement used for these plugs is usually a 1:1 perlite-"G" or "H" cement with appropriate retarders. We attempt to drill enough rat hole without returns to assure that we can get back to the lost circulation zone with the cement.

**Directional Drilling**

Due to the steep topography and for environmental considerations, more than one well is drilled from a single location, and the wells are directionally drilled to the targets selected by the geologist. Beside this initial reason for directional drilling, there is a secondary reason. The productive fractures at Baca have proved to be elusive at times, and required that the hole be sidetracked and redrilled toward another likely prospect to obtain a productive well.

Our directional work is done with either mud motors or turbines. We have had both good success and dismal failure with both types of equipment, which may indicate that reliability is more a function of the organization handling the tools than the equipment itself. However, we have tended to stay, and had good success with turbines when the temperatures increased. We do most of our directional work in the 12½" hole, but occasionally we have done directional work in the 8-3/4" hole, either to sidetrack or to make a last minute correction to the holes direction. This has occasionally resulted in doing directional work with aerated water or without returns, but it has been successfully accomplished.

In general, the turbins and mud motors are not as reliable as we would like them to be, and the high rpm of these tools results in a very short bit life. However, these tools have allowed us to successfully complete our directional work. We just feel that there is room for improvement in this area because the costs are high.
Blowout Preventers

The blowout preventer stack is shown in FIGURE 5.

II. From the Last Cemented Casing to T.D.

Various methods have been tried at Baca to drill the productive interval.

Air drilling was tried, but hole stability and large water influxes usually prevented successfully reaching the target, and the combination of air and produced water resulted in rapid drill string and casing corrosion.

Straight mud drilling resulted in serious lost circulation problems and frequently the well had to be drilled without returns. The problems encountered in drilling without returns often prevented the well from reaching the desired location, but more importantly, all the mud and cuttings were lost into the productive fractures where it is believed they seriously impaired the wells productivity.

The current practice at Baca is to drill out of the shoe of the 9-5/8" casing with air until sufficient water influx occurs to require switching to an aerated water system. The well is then drilled to T.D. using an aerated water system.

The major problems with an aerated water system are balancing the air-water ratio and inhibiting the drill pipe corrosion (which also affects the integrity of your casing strings).

Corrosion Inhibition

In the initial aerated water drilling tests, the corrosion rates were unacceptably high, approaching 24#/ft²/yr. We found that combining pH control with a proprietary inhibitor, Unisteam, controlled most of the corrosion problems. The OH⁻ ion is known to be a good oxygen corrosion inhibitor, and we found that if the pH was kept above 10.5 to 11.0, corrosion could be controlled to an acceptable 2#/ft²/yr. or less when used in combination with Unisteam. These corrosion rates are based on corrosion coupons placed in the drill string. The chemical requirements are a function of the chemistry of the produced water (when drilling with an aerated system, you are drilling underbalanced and formation fluids are entering the circulating system, so the chemistry of the circulating fluid rapidly becomes the same as the produced water). At Baca, the produced fluids are relatively benign (see TABLE 1), and inhibition can be obtained with a combination of Unisteam and pH control under most circumstances. However, our attempts to extend this method to other areas with different water chemistries has not always been successful, and we have frequently had to make major changes in the chemistry in order to obtain inhibition.
Even at Baca, the water chemistry will vary slightly from well to well, and occasionally we have high corrosion rates (4-6#/ft²/yr.) for short periods of time because we did not anticipate these changes. The number of times that high corrosion rates have been encountered has been reduced by continuously monitoring pH, bulk mixing caustic, and using chemical pumps to continuously treat the drilling fluid with caustic to maintain the desired pH as indicated by the monitoring system.

While the caustic is added to the circulating fluid (at levels up to 4000#/day), the Unisteam is added to the air stream. The normal Unisteam treatment is to dissolve 30 gallons of Unisteam in 10 bbls of water and inject it into the air stream at a rate of 2 gallons/minute. We have also found it beneficial to add 30 gallons of ammonium hydroxide to this mixture as well.

The ammonium hydroxide was added after we noted that the top 400 to 1000' of the drill pipe appeared corroded on the outside, even though the ring coupons on the inside showed no excessive corrosion. We came up with the following explanation for this external corrosion. As is frequently the case in aerated water drilling, there is a period of time involved in establishing continuous circulation during which there are no returns, except part of the air. This period of non-circulation can be anywhere from 15 minutes to hours in length. During this time, water vapor is carried up the annulus from the surface of the fluid level by the air that is channeling through the water. This warm water vapor condenses on the outside of the pipe which is cooled by the fluids traveling down the inside of the drill pipe. Since this is condensed water vapor, it has a neutral pH and no inhibitive chemicals. Consequently, the air passing by diffuses oxygen into this water layer causing rapid corrosion. With the addition of ammonium hydroxide, some of the ammonia is carried along with the water vapor and air, and when the water vapor condenses on the pipe, the ammonia dissolves in the water providing the necessary corrosion inhibition. The addition of ammonia at Baca has prevented excessive exterior corrosion at the top of the drill pipe.

Balancing the Air-Water System

Balancing an air-water drilling system is at its best an art whose success lies with the experience and dedication of the people at the controls - primarily the driller and the compressor operator. There are no firm fixed air-water ratios, jet sub setting depths or methods of attaining circulation. All I can offer is a review of what we do and why, and the things the driller uses to help him decide the air-water ratios to use.

We have successfully drilled both with and without jet subs. A jet sub is a bit jet nozzle mounted in a drill pipe sub which allows part of the air and water to exit some distance above the
bit to make it easier to establish circulation. When jet subs are used, they are usually placed about 500' below the fluid level. The air exiting the jet sub then helps lift this 500' column of water and establish circulation.

Our normal mode of operation is to use the entire capacity of either one or two compressors, and then adjust the air-water ratio by increasing or decreasing the fluid pump rate. This is the easiest method of operation for the driller, because he has the pump controls at his station, while the air controls are out by the compressors. The compressors we are using put out 1100 to 1200 scfm at the elevations they operate at in Baca. Air-water ratios vary dramatically, but 60:1 is probably a good starting guess. The driller must then adjust this ratio up or down based on how the well performs. If he is having trouble keeping the well circulating, he will increase the air:water ratio (decrease the pump rate), and if circulation becomes too violent, he will decrease the air:water ratio (increase the pump rate).

Since we are basically drilling under blowout conditions, the air:water ratio is a continuously changing quantity. When circulation is initiated, the water is relatively cool, and no production has been encountered. Therefore, a high air:water ratio is required to overcome the underbalanced reservoir condition (see FIGURE 3). As we drill deeper and encounter productive fractures, hot produced fluid enters the wellbore and part of this fluid flashes to steam, which usually increases the gas:liquid ratio in the annulus. The inlet gas:liquid ratio must then be decreased to counteract the increase that occurs in the annulus due to the produced fluid. Since these changes are neither predictable or readily measureable, we must rely on the experience of our personnel to handle the necessary changes in air:water ratios.

Our normal mode of operation involves the use of one compressor (1100 to 1200 scfm), but occasionally two compressors are required (or something between 1100 and 2400 scfm). The extra gas capacity is required to clean the hole because of an incompetent zone or higher gas:liquid ratios are required. We like to keep at least 150 gpm of liquid for carrying capacity, so if gas:liquid ratios need to exceed 60:1, then two compressors are required. We also occasionally encounter an incompetent zone which requires more carrying capacity to keep the hole clean until the zone stabilizes. The extra carrying capacity can be obtained by increasing both the air and liquid injection rates, usually doubling both of them.

Initially it would not appear that air:liquid ratios as high as 60:1 would be required based on the bottom hole pressures. However, since this is an air:water system rather than the more conventional air:mud systems, it is not as efficient. The low
viscosity produced water allows the air to channel through it, so it is not nearly as efficient at removing the liquid as a viscous mud system which will entrain the air and be carried out with the air rather than being bypassed by the air. The use of an air:mud system was considered, but it was discarded for the following reasons:

1. The volume of produced water circulated out of the hole while drilling was large, and a viscosifier would damage the injection wells that had to dispose of the produced water.

2. The viscosifier (clay) could damage the well being drilled during those periods when circulation could not be maintained.

3. The cost of adding a viscosifier to the large part of the circulating system that was only used once was prohibitive.

CEMENTING AND COMPLETION PRACTICES

Since we have just finished drilling the well with aerated water, we will discuss the completion, and then go back to discuss the cementing procedures.

The wells are completed by hanging a 7" preperforated liner from the 9-5/8" casing through the completion interval (see FIGURE 4). A packer is then set in the 9-5/8" casing, and a 9-5/8" tie-back is tied into the 9-5/8" liner and cemented back to the surface. We feel that it is necessary to run this tie-back to provide a string of pipe at the surface that is known to be competent (one that has not been worn by the tool joints or experienced corrosion problems). This competent string of pipe at the surface provides added safety against the shallow casing failures which can cause blowouts.

The surface completion consists of an expansion spool, two full opening valves, a flow tee, a surveying valve, and two wing valves as shown in FIGURE 4.

Our cementing procedures are relatively simple. As discussed previously, it is necessary to fully cement all strings of pipe. The actual cementing is done with a spacer followed by a filler cement of 1 perlite:1 "H" cement with 40% silica flour and the appropriate retarders, friction reducers and gel. The filler cement is followed by a tail-in slurry of "H" cement with 40% silica flour. When cementing the tie-back, no filler cement is used. It is imperative when cementing the tie-back that the cement have 0 free water. Any free water trapped between casing strings will cause the inner casing string to buckle, and while this is a serious problem to watch for when cementing the tie-back, it must also be kept in mind where the 9-5/8" casing laps over the 13-3/8" and where the 13-3/8" laps over the 20" casing.
One horror story should be sufficient to show the necessity of fully cementing casing, and the futility of trying remedial measures after the problem exists.

While drilling Baca #17, lost circulation was encountered at 1090' which resulted in sloughing and a water entry at about 450'. Twenty-inch casing had been set at 247'. After numerous attempts, the lost circulation at 1090' was finally plugged off. The major problem was sloughing at 450' which prevented getting back into the hole to plug the lost circulation zone. The sloughing also was creating a cavity at this depth. The 13-3/8" casing was cemented in place, but there was no cement returns to surface. The annulus was cemented through 1" tubing, and we went on to complete the well. We decided to flow test the well prior to running the tie-back to make sure the well was good before going to that expense. However, when the well was turned on, the casing buckled at 407'. Seven-inch casing was run and cemented back to surface through the collapsed section, the well was turned on, and the 7" casing collapsed at 407'. This horror story has been told to emphasize the need to fully cement the pipe in the hole. We learned our lessons from the failure of Baca #17 and successfully twined this well with Baca #21, which has been completed as a producer.

**LOGGING**

The logging program consists of running a dual induction log in the 17½" hole, a suite of logs in the 12¾" hole consisting of a fracture identification log, compensated formation density, a compensated neutron log, gamma ray log, a dual induction log and a temperature log. The 8-3/4" hole is logged with an induction log, and compensated formation density-compensated neutron-gamma ray log. The large 17½" hole sometimes makes it difficult to obtain a good dual induction log. There are few problems in the logging of the 12¾" hole. The temperature log is run first to assure that we can use low temperature tools, which we have been able to do. High temperature tools must be used in the 8-3/4" hole which limits the tools we can run. We would like to run a fracture identification log in this hole, but they are not available in a high temperature version. High temperature logs are available, but not in New Mexico. We inject water to cool the hole while logging, so we do not have any temperature problems unless the water is not going out the bottom. If the water is exiting high in the hole, the tools usually continue to function, but the logging cable burns up. Consequently, we always log going into the hole so that we have a log if the cable burns up on bottom. Our biggest problems are usually no different than logging normal temperature holes: quality control and people operating the equipment.
REMEDIAL SCALE REMOVAL

Well Baca #11 has had a calcium carbonate scaling problem. The carbonate buildup had curtailed the well's productivity, and was removed in 1976. The scale was removed by drilling it out under flowing conditions with a turbine. The well was kicked off and flowed until the surface temperature reached 320°F, and then the turbine was run with 180 gpm of water while the well continued to flow, bringing the cuttings out of the well.

USING THE DATA DEVELOPED AT BACA IN OTHER GEOTHERMAL AREAS

The methods we use to drill and complete wells in Baca have direct application to most every geothermal area under development. The basic methods of drilling down to the top of the reservoir and installing a competent completion in that hole are the same for every geothermal area we are developing, and, therefore, have wide application. The aerated water method of drilling the producing formation may not have as wide an application, but it does describe one of a number of alternative methods for drilling wells into underpressured geothermal reservoirs.

REFERENCES


AVERAGE PRODUCED FLUID CHEMISTRY

<table>
<thead>
<tr>
<th></th>
<th>BRINE UNCORRECTED FOR FLASH</th>
<th>CONDENSATE</th>
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<tr>
<td></td>
<td>AVG.</td>
<td>(NO. OF SAMPLES)</td>
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<tr>
<td>pH</td>
<td>7.2</td>
<td>(26)</td>
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<tr>
<td>SUSPENDED SOLIDS, mg/l</td>
<td>319</td>
<td>(13)</td>
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<tr>
<td>TOTAL DISSOLVED SOLIDS, mg/l</td>
<td>6093</td>
<td>(24)</td>
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<tr>
<td>SiO₂, mg/l</td>
<td>599</td>
<td>(40)</td>
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<tr>
<td>CO₃⁻</td>
<td>19</td>
<td>(27)</td>
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<tr>
<td>HCO₃⁻</td>
<td>127</td>
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<td>Cl⁻</td>
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<tr>
<td>Mg</td>
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<td>(21)</td>
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<tr>
<td>Ba</td>
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<td>B</td>
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<tr>
<td>F</td>
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**TABLE 1**
(from Reference [2])
AVERAGE NONCONDENSIBLE GAS CHEMISTRY

NONCONDENSIBLE GASES IN STEAM PHASE:
2.51% BY WEIGHT (29 SAMPLES)
1.04% BY VOLUME

<table>
<thead>
<tr>
<th></th>
<th>AVG. PPM BY WT.</th>
<th>AVG. PPM BY VOL.</th>
<th>(SAMPLES)</th>
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<tr>
<td>CO₂</td>
<td>28,254</td>
<td>11,973</td>
<td>(28)</td>
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<tr>
<td>H₂S</td>
<td>204</td>
<td>125</td>
<td>(31)</td>
</tr>
<tr>
<td>N₂</td>
<td>42</td>
<td>28</td>
<td>(26)</td>
</tr>
<tr>
<td>H₂</td>
<td>1.6</td>
<td>14</td>
<td>(31)</td>
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<tr>
<td>CH₄</td>
<td>1.4</td>
<td>1.6</td>
<td>(21)</td>
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</table>

TABLE 1 (Cont'd)
(from Reference [2])

MUD PROPERTIES

Weight - 8.5 to 9.0 #/gallon
Funnel Viscosity - 30 to 38 seconds
Plastic Viscosity - 2 to 8 cp
Yield Point - 1 to 10 #/100ft²
Gel Strength - 10 seconds: 0 to 10 #/100ft²
10 minutes: 4 to 25 #/100ft²
Fluid Loss Control - 10 cc API to no control

TABLE 2
REGIONAL GEOLOGIC SETTING OF VALLES CALDERA, JEMEZ MOUNTAINS, NEW MEXICO.

FIGURE 1
(from Reference [1])
FIGURE 2
(from Reference [2])
FIGURE 3
CURRENT STATIC CONDITIONS AT BACA 13
FIGURE 4
SCHEMATIC DIAGRAM OF BACA COMPLETION

26" HOLE
9 5/8" TIEBACK
20'
17 1/2" HOLE
13 3/8"
12 1/4" HOLE
9 5/8" LINER
8 3/4" HOLE
7" SLOTTED PRODUCTION LINER
FIGURE 5
SCHEMATIC DIGRAM OF B.O.P. STACK
AT BACA