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DRILLING GEOTHERMAL WELLS AT THE GEYSERS FIELD

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ABSTRACT

There are 68 years of drilling history at The Geysers field. During that time, the drilling methods have evolved from cable tool drilling to the current state-of-the-art rotary drilling practices. The tools and practices that were developed during this time form the basis of the technology that is being exported to other geothermal developments worldwide. Since much of the current drilling practice at The Geysers is identical with drilling oil and gas wells, this paper only addresses those drilling practices that differ from petroleum practice. However, the differences are both significant and numerous.

BACKGROUND

Since the first well was drilled at The Geysers in 1922 with a cable tool rig, there have been more than 500 wells drilled. This 68 years of drilling history has continually pushed the technology limits for drilling extremely hard, fractured rock at high temperatures. This technology has evolved to the present state-of-the-art that makes drilling at The Geysers the science that it is today.

The most obvious difficulties in drilling at The Geysers were those associated with high temperatures, since the surface locations for early wells were adjacent to venting steam and boiling mud pots. This led to problems with the muds, cements and tubulars used in the wells. However, temperature is not the only problem — surface stability of locations, difficult drilling formations, abrasion during air drilling, and larger than normal completions are some of the other factors.

During these years, in addition to technology developments that have specific application to The Geysers and geothermal drilling, there have been many developments that have benefited the drilling industry in general. Methods of optimizing bit selection, hydraulics, weight-on-bit, drilling assemblies, and direction control (MWD, motors, etc.) have been developed by the drilling industry. These improvements in general drilling technology are an integral part of the improvements in geothermal drilling, but since they are already well documented in the literature, they are excluded from this discussion.

The drilling at The Geysers is broken down into a discussion of general practices (locations, rigs, hole size), and the two different drilling methods used — mud drilling and air drilling.

GENERAL

Locations

The initial problem to be faced in drilling at The Geysers is the limited number of suitable drilling locations. The field is located in the Mayacmas Mountains east of Healdsburg, California at elevations between 1,500 and 4,000 feet (Figure 1). Steam is produced from wells owned by eight operators for electrical generating facilities owned by seven utility companies, some of which are also field operators (Figure 2). The terrain at The Geysers is extremely rugged and mountainous, which is characteristic of the Franciscan formation. Another characteristic of the Franciscan formation is instability, resulting in numerous landslides (Bedrossian, 1980). Level spots large enough to accommodate a large drilling rig without a lot of earthwork are essentially nonexistent, and much of the surface is rock altered by the presence of fumaroles and mud pots. This is especially true in the areas that were of early interest, those near the thermal features.

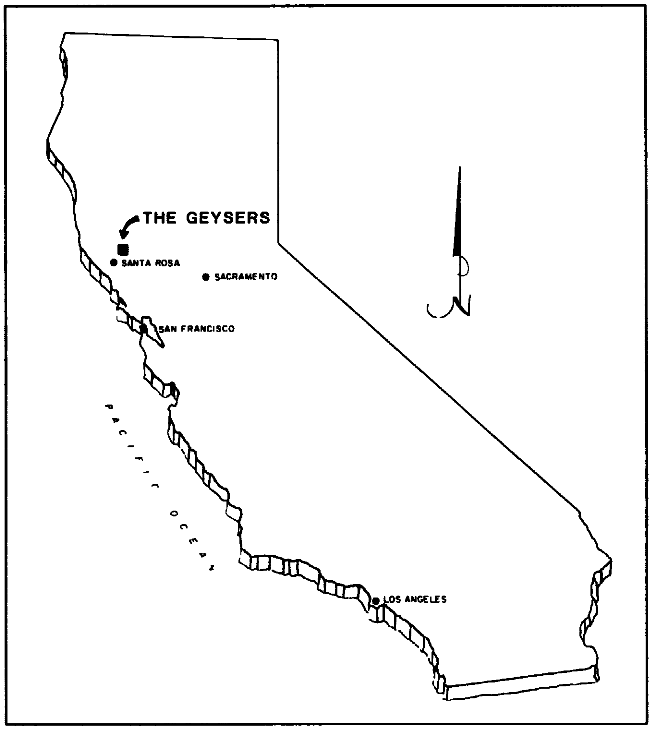

Figure 1. Location of Geysers field.

Early drilling took place very close to surface thermal manifestations. These early wells were hampered by the lack of directional drilling tools suitable for working in the temperatures found in the reservoir rocks at The Geysers, which resulted in the surface locations of the wells being sited directly above the subsurface target. The areas that appeared the most promising had fractures and conduits that permitted reservoir steam to escape at the surface. The heat of the escaping steam degraded the competence of the rock, and when combined with meteoric water, steep terrain and preexisting landslides, active sliding and well failures were inevitable. Several early wells at The Geysers suffered blowouts when landslides sheared the casing within the top 100 feet. A drilling related blowout of Thermal 4 has flowed through a surface muffler since the wellbore could not be found in the landslide where it was drilled. Wells in the last two decades have been sited away from landslide and thermal manifestations and directionally drilled to their subsurface targets. By excavating rock for the drilling rig in areas away from landslides and using the cut material to form the wall of the sump, secure drilling locations have been constructed. The locations are designed so that the subbases for the rig sit on the cut, which results in the wells being spudded into the cut part of the location. Due to the difficulty of building locations, all those built within the last 20 years have been designed to accommodate multiple directional wells.

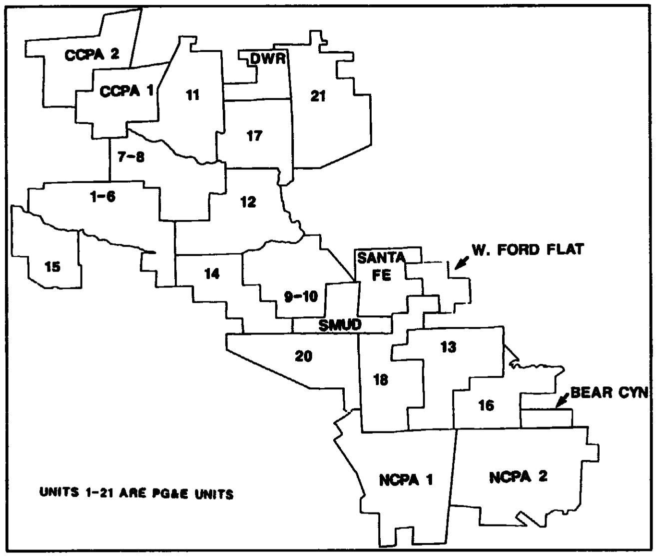

Figure 2. Map of The Geysers area.

Conductors are set as a part of the location construction. A bucket auger is used to excavate a hole 6 to 12 inches larger than the desired conductor size. The annulus between the rock and the conductor is then backfilled with ready-mix concrete. The ability of an auger to penetrate even the surface formations at The Geysers is limited to a maximum of 20 feet. Some conductors have been set as shallow as 3 to 5 feet, but these usually require recementing during the drilling operations.

Rigs

Drilling rigs at The Geysers have evolved far past the tiny cable tool rigs that were used to drill the first wells. In the 1960s and early 1970s, direct diesel powered rigs were common at The Geysers. In more recent years, diesel-electric rigs with silicon cold rectifier (SCR) control systems have become the norm. As development moved from areas where the reservoir was encountered as shallow as 500 feet to areas where the reservoir is below 7,000 feet, increasing depth capabilities have become required. Manufacturers list the depth capabilities of the current Geysers rigs between 15,000 and 25,000 feet. Although wells of that depth have yet to be drilled at The Geysers, the air drilling of the deepest part of the well requires much stronger drilling components, because there is no buoyancy of the

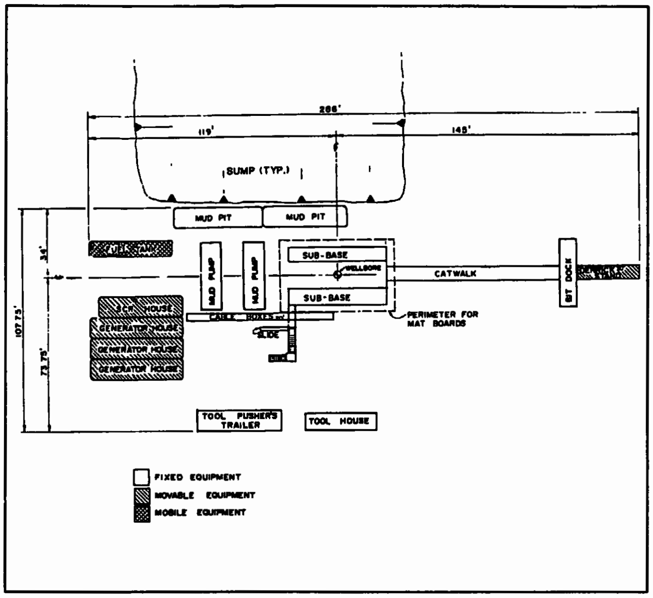

Figure 3. Typical Geysers rig footprint.

drill string as there is when mud is used to total depth. A location plot or "footprint" of a typical Geysers rig is shown in Figure 3.

Hole Size and Casing

With a pre-exploitation reservoir pressure of 500 psi and a very high permeability, engineers decided early in the development of the field that the larger a hole could be completed, the lower the friction losses would be and the higher the flow rates would be during production. Because of the quantity of the steam necessary to make a well commercially valuable, large hole sizes have been a requirement for development. This developer has chosen the casing configuration depicted in Figure 4 with the completion hole of 10-5/8 inch diameter. Other completion hole sizes used in the field are 12-1/4 inch and 8-3/4 inch. The casing design shown in Figure 4 is unusual because of the diameters of the various casing strings. Although all are API listed sizes, most of them are not the sizes most commonly used in oil and gas drilling. The limiting factor in casing design for The Geysers is usually the collapse strength required to place cement. Burst or tensile strengths are usually not the determining factor in casing selection. Fortunately, the relatively shallow setting depths for the various strings limit the required strength to K or N grade casings. The hidden benefit in needing only lower strength casings is that the H_2S contained in the steam would be incompatible with higher strength steels (NACE Standard MR-01-75).

Thermal stress in the casing is a concern (Geysers Environmental Impact Report; Synder, 1980), because the well's temperature is changed over a wide range from initial drilling conditions to the repeated cycling that occurs as a well is produced and shut-in. The casing undergoes compressive yielding on initial heat up, and then cycles within the elastic range, because the temperature variations are small. While Unocal has had failures of 8-round threaded casing, buttress threaded casing has held up well in this service. However, we are still concerned about fatigue failures occurring as the wells get older, but we have not seen any as yet. While the thermal stress problems at The Geysers have been small, other geothermal fields with higher temperatures or wider variations in operating temperatures may experience greater problems.

It was recognized early that setting the casing string that ends immediately above the reservoir as a liner and a tieback instead of a "long string" had two major benefits. Cementing of a "long string" at The Geysers has always been very difficult (see the cementing discussion). The other major benefit was that if the well was tied back after drilling was completed, the surface pipe would not be damaged by drilling. The casing worn by the abrasive drill cuttings and the drill string would be covered by fresh pipe.

Cementing

If one thing, other than the temperatures, separates geothermal drilling from oil and gas drilling, it would be the requirement for a solid column of cement behind every casing string. Two things force complete cementing of casing on The Geysers' driller: (1) the need to limit surface movement of the production equipment and (2) the need to prevent casing failures for the lifetime of the well.

The more limited the vertical movement of the wellhead during thermal cycles, the smaller the forces acting between the casing and the surface production equipment will be. If the casing is moving up and down with thermal cycling of the wellbore, stresses in the casing and the pipeline can reach unacceptable levels. A solid column of cement behind each casing string keeps the movement at the surface within acceptable ranges. The need to prevent casing failures for the lifetime of the well is also obvious. We have found that a full sheath of cement is required around the casing to prevent buckling failures. What was not as obvious during early development at The Geysers was how to cement the casing and keep the cement competent (Carter and Smith, 1958). Thermal degradation of cement was a known phenomenon, but research was necessary to find slurries that would withstand the thermal regimes encountered at The Geysers. Our research showed that slurries with 40 to 60 percent silica flour did not degrade with temperature (Gallus and Pyle, 1978). Recent investigations have indicated that this slurry composition may convert to calcium carbonate with time (Milestone, Kukacka and Carciello, 1986). While we have experienced this problem in other geothermal fields, we have not had this problem at The Geysers (Shen and Pye, 1989).

The other important factor in cementing Geysers wells was the need to keep free water out of the annulus between casing strings. A small amount of water between casings was found to cause the inner string of casing to collapse. Since this could occur very near to the surface of the last cemented string of casing, the potential loss of well control made this a paramount issue.

If for any reason, an incomplete column of cement existed behind a surface casing string, the need to limit trapped water during any type of repair to the cement job made that repair extremely difficult. The most common method used at The Geysers is to run a small pipe into the annulus in question until hard cement is encountered and the small pipe can be lowered no further. Cement is then circulated down the small pipe and the annulus is filled. To avoid having to do such a "top job" or perforating the last cemented surface string for repairs to the cement job, it can be seen that a tieback string was truly a great advantage for well completions. When cementing a tieback string, the liner is plugged and the driller can feel certain that cement can be circulated since the entire job is done inside casing. If a "long string" is used, stage cementing is be necessary to keep the hydrostatic pressure below the fracturing pressure. If there is any cement fallback below the port collar, water will be trapped from the top of the cement to the port collar when doing the second stage, resulting in casing collapse.

Even when cementing a tieback, it is imperative that exact quality control of the slurries and mixing process be maintained to prevent any water from being placed in the annulus.

Drilling Tools

Drilling at The Geysers has continually pushed the limits of downhole tools available both on the basis of size and also durability. As shown in Figure 4, completion holes of this size require starting with a 26-inch hole at the surface. During early exploitation of The Geysers, 26-inch bits, reamers and stabilizers capable of drilling the extremely hard surface formations of The Geysers were not available "off the shelf." The extremely limited life of mill tooth bits and standard stabilization tools at The Geysers frustrated early drilling. As drilling activity expanded in the early 1970s, tools with tungsten carbide inserts became widely available and downhole tool life at The Geysers became more tolerable.

Drilling Methods

Once the obvious problems were evaluated and drilling began, there were many surprises waiting downhole for drillers. The extremely hard rock of the Franciscan formation was severely fractured and had strong directional tendencies. The fractures in the rocks, along with the very low reservoir pressure, made the problem of circulating mud and cement to the surface probably the most difficult of the problems to be faced at The Geysers. The very low reservoir pressures soon led drillers to the use of air as a circulating a medium.

After many different combinations were tried — air, foam and aerated mud both above and within the reservoir — and many failures were experienced, a program was chosen that is in use today. This program was to drill to the top of the reservoir with mud, and then drill the reservoir with air. Since there are no directional tools for use with air, all the directional work is done in the mud drilled hole.

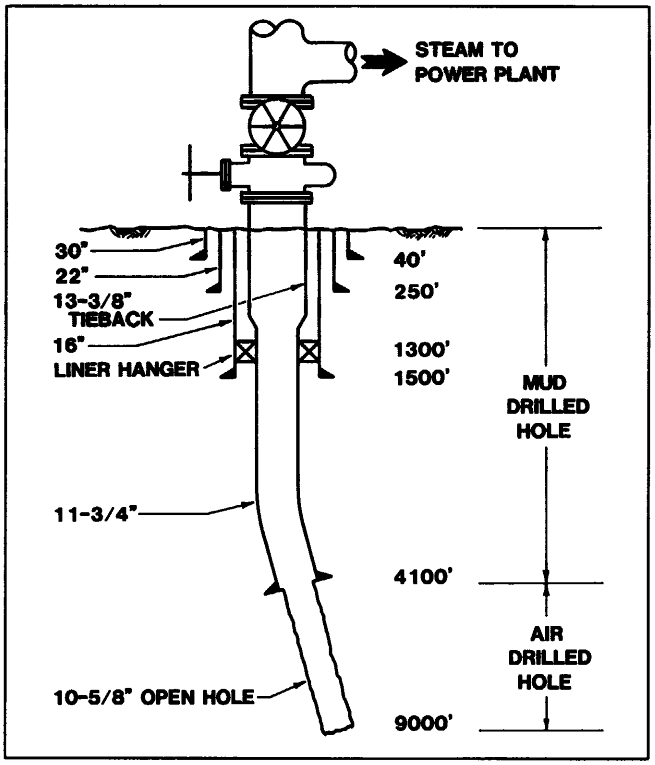

Figure 4. Typical Geysers well plan.

MUD DRILLING

General

It would be a fallacy to believe that Geysers wells could be drilled with water, as hard rock drilling is done in many other areas. The large hole sizes and the presence of some water sensitive formations prohibit such a simple solution. Early attempts to achieve a high enough yield point to clean the large hole sizes by large additions of bentonite led to problems of gelation at circulating temperatures which frequently approached the boiling point. Over the last 25 years, a number of different mud additives have been used to attain high yield point muds with a limited tendency for gelation when static at high temperatures. The system utilized by Unocal at The Geysers for the last 10 years has been the addition of small amounts of lime to the bentonite mud for carrying capacity and inhibition of slightly water-sensitive formations. Polymers are added as necessary to prevent high temperature gelation.

If very water-sensitive formations such as serpentine or argillite are present, then polymeric treatment to reduce fluid loss becomes necessary. Fluid loss control of 20 cc's of filtrate for a high temperature-high pressure test run at the reservoir temperature is considered excellent and is usually sufficient to control formation sensitivities as found at The Geysers. Recently the addition of gilsonite has also proven to be effective in controlling the water sensitivity of serpentine.

Lost Circulation

Lost circulation is the enemy of The Geysers driller. On the one hand, a solid column of cement is required for all casing strings, and on the other hand, the field is highly fractured and the pressure in the fractures is always below the hydrostatic pressure of the column of mud above it. Whenever a fracture is encountered during the mud drilled portion of the hole, total loss of circulation is the usual result. Seepage losses are less common, but do occur. If casing is going to be cemented over the interval where circulation was lost, the cure is to use cement plug(s) to seal off the fracture. Experience has shown that lost circulation material may give the driller a temporary seal, but that seal almost always breaks down under the higher hydrostatic pressure of a column of cement. The difficulties in placing these cement plugs have cost developers at The Geysers tens of millions of dollars. Depending on hole conditions and the suspected geometry of the fracture, different cement slurries are used to plug the fracture. High compressive strength slurries would be the choice if the cement can be placed without losing all the slurry to the fracture. Light weight additives such as perlite are useful if the fracture is larger and a bridging material is necessary. Careful attention to placing a "balanced" cement plug across the fracture has proven to be the most important factor in achieving a solid plug that seals the fracture.

Directional Work

As noted earlier, lack of directional tools suitable for the environment was a handicap to early Geysers drilling efforts and contributed peripherally to several blowouts. For many years the bottom hole location of wells was unknown because a means of surveying the wells did not exist. Development and deployment of heat shielded tools occurred during the late 1960s and early 1970s and allowed accurate surveying of the wells.

Commonly, the surface and intermediate strings at The Geysers are set as nearly vertical as possible. Directional work is usually done in the liner section of the hole. A turbine is usually used rather than a positive displacement motor because the formation temperatures at these depths severely limit the life of the elastomer stator in the positive displacement motors. The directional work required to sidetrack an existing hole is very difficult at The Geysers. The extremely hard formations and the limited choice in cement slurries due to the high temperatures complicates what is a relatively easy task in a sedimentary formation. A densified cement plug is set and allowed to harden for approximately 24 hours. A high offset kick sub is used above the turbine and drilling is done in a manner to limit penetration until a shoulder is established on the borehole wall. Once the shoulder is established, the assembly is tripped and the kick sub is replaced by one with a more conventional angle.

Recently, near surface penetration rates have been increased with the application of steerable systems. These systems are a positive displacement motor with an offset in the housing that is rotated slowly to drill ahead or may be oriented like a conventional directional assembly if the need arises to correct direction or straighten the hole. This system eliminates the need to trip for a directional assembly if a nearby well is approached or if the directional tendency of the formation results in an unacceptable deviation with the current assembly. As departure distances have become larger during more recent drilling, it has also become an advantage to start the well along the desired course closer to the surface. The steerable system has proven ideal for this purpose.

AIR DRILLING

General

When early attempts to drill reservoir rock at The Geysers with mud met with frustration, drilling with air as the circulating medium was attempted. This technology is common to water well and blast hole drillers and used in some areas when drilling for oil or gas.

Difficulties were found in controlling abrasive loss of the tubulars and surface equipment, in controlling noise and particulate pollution and in preventing corrosion of the casing and drill string. Most of the difficulties have been eliminated by improvements developed at The Geysers. The cost of the problems is offset by the vastly improved penetration rate in the hard formations of The Geysers.

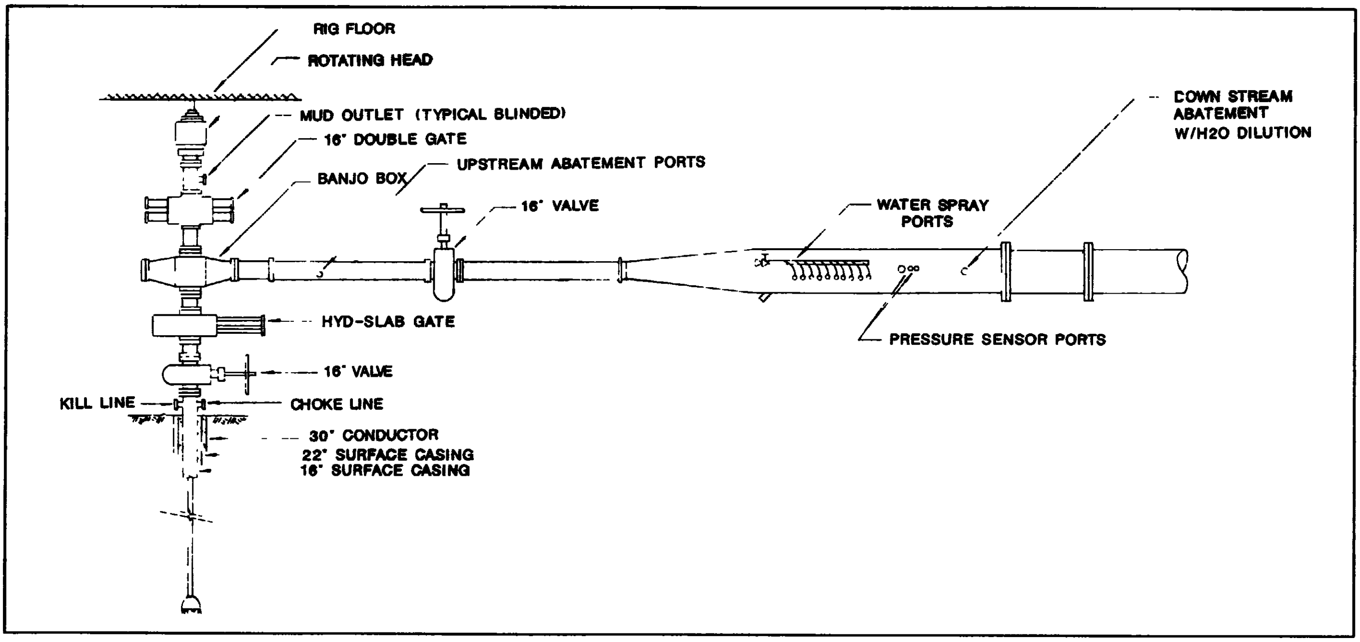

Figure 5. Typical air drilling Blow Out Prevention Equipment (BOPE)

Rig Up

The switch from mud to air drilling is easily accomplished at the supply end by replacing the line from the mud pumps with one from the air compressors. The compressors themselves should be capable of delivering between 2,000 and 4,000 standard cubic feet per minute of air at 1,000 psi. A blow-down line on the standpipe is installed to allow bleeding off the air pressure inside the drill pipe before making a connection. The conversion to air drilling is more complex where the air exits the wellbore. A schematic of a typical air drilling Blow Out Prevention Equipment (BOPE) system is shown in Figure 5. Additions to a typical BOPE stack would be the rotating head, banjo box, blooie line and slab gate. The rotating head is a seal around the drill string to prevent the air, cuttings and steam from getting to the drill floor. The banjo box is the tee where the cuttings are diverted down the blooie line, a specialized flow line, to a cyclonic separator where the steam and air are separated from the cuttings. The slab gate is a specially designed hydraulic valve to minimize the need to operate the master valve. Other items associated with the rig up include a mist pump and a high volume, low pressure pump. The mist pump is a low volume, high pressure pump which injects water and/or chemicals into the air compressor discharge line. The high volume, low pressure pump is to inject water into the blooie line for noise and dust abatement.

Fixtures are welded to the blooie line to allow attachment of various lines for water or chemical injection. The water is injected to separate the cuttings from the air and to reduce the noise of the air and steam when they are in the blooie line and when they exit the muffler. The water clumps the dust like cuttings and allows more efficient separation and by cooling the air and steam reduces the noise by reducing the velocity of the flow stream. The cyclonic separator at the end of the blooie line is at least 10 feet in diameter and is reinforced in the impingement areas to prevent erosion by the flow stream.

In some areas of The Geysers, substantial amounts of hydrogen sulfide gas are included in the steam flow. Local air pollution control districts have limited the amount of this gas which may be emitted during drilling. To comply with these regulations, hydrogen sulfide is removed from the steam by adding caustic soda and hydrogen peroxide to the flow stream in the blooie line.

Abrasion

The largest drawback to air drilling is the abrasive environment created by the near supersonic steam and air flow in the wellbore combined with the drill cuttings that act similarly to the sand in sandblasting. Abrasive attack is most severe on the casing, drill string, and BOPE. With the current design, most of the BOPE wear occurs on the banjo box and the blooie line.

Hardbanding the tool joints of drill pipe is a common technique for dealing with grinding off of the outside of the tool joints during rotary drilling. In a mud hole, hardbanding could be expected to last on the order of a year. In air drilling at The Geysers, hardbanding lasts on the order of days. Each joint of drill pipe is rehardbanded after 50 to 200 rotating hours. The wear rate is sensitive to the steam flow, hence the velocity of the cuttings in the wellbore, and the type of formation being drilled. The felsite that underlies much of The Geysers breaks into highly angular cuttings and is much more abrasive than the greywacke, or "normal" reservoir rock.

While the interruption to the flow stream caused by the tool joints on the drill pipe causes the worst abrasive corrosion, similar abrasion is being undergone by the casing. The casing is also subject to abrasion by the rotary action of the drill string and contact with the hardbanding. For this reason, hardbanding on drill pipe used for air drilling must actually be softer than that used on drill pipe for mud drilling where the mud can be expected to lubricate and cool the contact areas with the casing.

The worst abrasive action, however, takes place in the banjo box. By causing the air stream to expand, the velocity of the air and cuttings is reduced. This partially offsets the abrasion associated with getting the discharge stream to turn a right angle to go out the blooie line to the muffler. Simple heavy-weight tees can suffer wall loss rates as high as 1/2 inch per day. The blooie line spool nearest to the banjo box is prone to wear rates as high as 1/10 inch per day. Lesser rates are observed in the balance of the blooie line and in the muffler.

Corrosion

Injecting air into a steam flow makes an extremely corrosive downhole environment. The water and oxygen in the air act immediately to corrode with drill pipe and casing. To combat this corrosive attack, a chemical is injected into the air stream by the mist pump at the air compressors. This chemical acts to coat the drill pipe at elevated temperatures and prevent corrosive attack by the oxygen in the steam (Fisher and Pyle, 1977).

In a small number of wells, primarily in the northern part of The Geysers, a region of the reservoir is penetrated where the rock temperature is higher than the normal reservoir rock for The Geysers. This high temperature zone (HTZ) may also have a higher chloride level than is associated with the main Geysers reservoir. This more severe environment accelerates corrosive attack on wellbore tubulars. The iron particles can actually cause the steam plume that exists from the muffler to appear red in color. The particles that cause this discoloration are so small that the water injection and the cyclonic separator can not remove them from the flow stream and a "Red Steam" situation may occur. The solution to this problem is of current interest to operators considering drilling into the HTZ at The Geysers.

SUMMARY

Drilling at The Geysers has undergone the same evolution during the last 68 years as the rest of the drilling industry. In addition, the many unique problems outlined have made technology development even more accelerated at The Geysers than for the drilling industry in general. This technology has been exported to essentially all geothermal developments in the world and to a lesser extent to the industry in general where drilling through hot, hard or under-pressured formations is necessary. Despite the many advances made during development at The Geysers, drilling costs there remain significantly higher than drilling oil and gas wells. The challenge for future Geysers drillers will be to bring costs more in line with those elsewhere.

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