# The success of world's first Hybrid PDC and Particle Drilling bit for Geothermal Applications.

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**NOV and Particle Drilling**

**Keywords**

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## ABSTRACT

Geothermal energy is gaining attention worldwide as an attractive and vastly underutilized renewable energy source due to its abundance, baseload capability, resiliency, and reliability.

While there are many types of geothermal energy concepts, the holy grail of geothermal – that would enable geothermal drilling and production in most places in the world – is hard rock or superhot rock concepts. Developing these systems requires drilling into granitic basement formations, often at temperatures exceeding 300º C. There are several technological challenges associated with hard rock concepts. Perhaps the most significant challenge is that very hard rock, such as granite, limits the rate of penetration (ROP) and footage per bottom hole assembly (BHA) due to the limitations of traditional geothermal drill bits.

This abstract summarizes a recent technological development that will significantly impact this challenge. This newly engineered and first of its kind hybrid drill bit cuts through granitic rock by firing steel shot at the rock, while combining PDC cutters to maintain stability and smooth the borehole wall.

Particle Drilling (PD) and NOV's ReedHycalog™ business unit teamed up to design and build a hybrid particle drilling/Polycrystalline Diamond Compact (PDC) bit that could drill rocks of extreme unconfined compressive stress (UCS). These rocks include granite, basalt, and gneiss and are typically associated with the hottest and thus most economically attractive global geothermal opportunities.

Particle drilling is a drilling process whereby steel shot is injected at pressure into the main flowline that runs from a rig's pumps to the drillstring. 3% steel shot is combined with drilling mud and injected into the drillstring, where those steel particles then flow down the drillpipe into the drill bit and accelerate to 500 ft/sec. Where they exit the nozzles of the bit, the steel shot impacts the hard rock two to three inches in front of the bit. The drill bit rotates at roughly 60 to 80 revolutions per minute (RPM), and the particles cut a bottom hole pattern in the granite. The remaining half an inch of de-stressed rock is then removed by the PDC cutters in the reaming section of the bit.

In August 2021, the team rented and deployed a drilling rig to a quarry in Marble Falls Texas, where a well was drilled with two new particle drilling bits. The new bits drilled 990ft of extremely hard (45,000 to 50,000 psi) pink granite at 45 ft/hr., using two bits. After drilling the section with the hybrid bits, a third run was completed with a traditional PDC bit like those used on the Department of Energy's "FORGE" well, and the bit was extremely worn after just 122 ft.

## 1. Introduction

Geothermal energy is being aggressively pursued by national government agencies and startup renewable energy companies but continues to face economic challenges. These challenges stem from three major issues:

1) Very hard rock, such as granite, limits the ROP and footage per BHA due to the limitations of traditional drill bits
2) High bottom-hole temperatures make it difficult for downhole equipment such as measurement while drilling (MWD) to assist in directional work
3) Lack of understanding of the heat reservoir

Particle Drilling (PD) has a significant impact on the first challenge of ROP generation and is unaffected by temperature. Geothermal operators, government agencies, and the academic community are working together to resolve the lack of understanding of the heat reservoir.

Particle drilling is a unique but straightforward technology. To drill hard rock, 2-mm steel shot is injected into the high-pressure lines between the mud pumps and the standpipe manifold. The volume of steel particles required is 2 to 3% of the total volume. The flow rate is adjusted to create a nozzle velocity of 500 ft/sec, impacting the rock at 12 million times per minute.

In January 2021, NOV was invited to visit PD's test rig that was drilling hard sandstones in the Haynesville Shale. NOV provided Blackbox services to evaluate the vibrational environment. It was evident from the vibrational data and damage to the drill bit that the root cause of PD's durability challenges was a lack of lateral stability, erosion, and drill bit body material issues. The particles were drilling an over gauge hole, and the body of the bit was being damaged by the impact of the body with the side of the hole whilst rotating. The secondary and tertiary problems were particles eroding the body of the bit and the nose of the bit being damaged when it met the bottom of the hole.

In March 2021, NOV and PD agreed to partner on rapidly prototyping a particle drilling/PDC hybrid bit. The bit was designed and manufactured quickly and ready to test in July 2021. In August 2021, PD rented a rig and placed the rig in the Coldsprings Granite Quarry near Marble Falls, Texas.

Two bits were used to drill 990 ft at 30 to 45 ft/hr in very hard 45,000 psi UCS pink granite. To get a proper benchmark against traditional PDC bits, we ran a regular ReedHycalog PDC bit (Self and Stevenson 2021) from the Department of Energy (DOE) Forge project, and it drilled 122 ft, coming out heavily worn. This groundbreaking first performance has received significant media attention, including a recent segment on PBS Newshour. Since then, an 8 ½-in version two and a new 12 ¼-in PD/PDC Hybrid have been designed. We are hoping to test version two in April or May 2022.

## 2. Analysis of the performance of Particle Drilling bits from David Cannon Well, Texas

PD invited NOV, other service companies, and other operators to the rig site to witness the drilling using state-of-the-art Particle Drilling bits. These bits drill using particles and have no PDC cutters or reaming sections.

The test drilling at the David Cannon 1 well in January 2021 involved five particle drilling bits (3 PDT33 **(Figure 1.)** and 2 PDT44 (**Figure 2**)). Each bit run increased drilling hours by 2 to 4 times more than the previous best in the Travis Peak formation by a particle drilling bit. Total surface equipment hours exceeded 100 hours, more than double the previous longest run time and the equipment experienced no downtime of consequence.

**Figure 1. New Particle Drilling PDT 33**

**Figure 2. Top View of PDT 44**

The Basin Rig 101 began mobilizing to the location on December 27, 2020, from the yard in Arcadia, Louisiana. Basin 101 was over the hole and went to work for Particle Drilling at midnight on January 8, 2021. After pressure testing the casing and casing shoe and drilling out the cement plug to 11,475 ft, they were ready to begin drilling with particle bits on January 11.

Both initial trips in the hole resulted in PDT44 and PDT44N nozzles being plugged. The initial bit was run without any screen being placed in the drill pipe during fill up. The second bit became plugged by black plastic before getting to bottom. The decision was made to trip back in the hole with a PDC bit and circulate and condition the mud to clean any debris out of the mud system properly.

PDT44C was run in the hole on January 14 and drilled 70 feet in 12.25 hours, averaging 6 ft/hr before the bit washed out internally above the nozzle, which cuts the center of the hole. This bit had previously had 30 hours of shot circulated through it during the test drilling in the yard where it had drilled 473 ft of red granite.

PDT33S was run in the hole on January 16 and drilled 170 feet in 23 hours, averaging more than 7 ft/hr. The bit was pulled when a pressure loss was experienced. This bit failed due to erosion of the bit into a nozzle. After reviewing the damage caused on the previous two runs, it was decided to run in the hole with a near-bit stabilizer above the bit and an additional stand of drill collars. The first two bits were run with a BHA of 3 drill collars. It appeared that the bit was having vibration problems and that lateral vibration was causing accelerated wear of the carbide tiles on the side of the bit.

PDT33N was run on January 18, and the rig washed through a couple of tight spots for five hours and then drilled an additional 32 feet of hole in 5 hours. The bit was intentionally pulled after ten hours to evaluate the wear going on downhole. A review of the bit showed that carbide tiles had been rubbed off on either side of the junk slot. After discussion, it was decided that the stabilizer was hurting bit performance.

PDT33C was run in the hole January 21 to coincide with a visit from Halliburton. This bit drilled 126 feet in 16 hours, at an average ROP of 8 ft/hr. This bit washed out in a similar fashion to the previous PDT33S, which had lasted 23 hours. This bit had previously drilled for 15 hours and 200 feet of red granite in the lab.

PDT44N was run in the hole on January 25 and drilled 142 feet in 28.5 hours, averaging 5 ft/hr. This bit established a new record for total time drilling in the field for PD, but failed with a similar issue as the other PDT 44, a washout above the center nozzle. The belief , at that time, was this nozzle required the flowpath to make a hard turn to get back to the nozzle and the shot was rebounding off the carbide puck and into the bit wall, where the failure was occurring. Minimal damage to the bottom carbide tiles was noted, similar to what was seen with the first PDT44 bit. Both PDT44 bits experienced significantly less damage to the carbide tiles on the face of the bit when compared to the PDT33 bits.

After discussions, Particle Drilling wanted to run the NOV Blackbox HF ™ tool (a high frequency, downhole drilling dynamics tool, that measures torsional, lateral and axial vibration at a rate up to 1800 hz, the tool also measures downhole weight on bit (DWOB) and downhole torque (DTOR) to gather downhole data while drilling. The decision was made to run back in the hole with PDT33N, which had 10 hours of downhole drilling and reaming. We were hoping to see an additional couple of drilling hours to capture data on downhole weight, torque, vibration, and pressures. The bit was run back in the hole on January 17 and drilled an additional 105 feet in 18.5 hours, averaging 6 ft/hr. This brought the total for this bit to 137 feet drilled in 23.5 hours, with 5 additional hours of reaming with shot.

Following this final PD bit run, the hole was deepened by 41 feet to enable logging the entire interval drilled by PD bits. Analysis of the open hole logs showed no potential pay zones in the drilled section. The borehole analysis of the wellbore showed a drilled hole averaging slightly over gauged (9 to 9.25 in diameter). Washouts were noted in the shale sections vs. sandstone sections, but nothing significant. The first 700 feet of open hole, which had previously been drilled, showed a hole averaging more than 11 inches in diameter. This was to be expected given the multiple passes through that portion of the wellbore.

Analysis of the Blackbox HF Data showed that there was significant lateral vibration because the particle drilling bits were drilling an over gauge hole and were coliding with  the side of the borehole at high velocity. The downhole weight on bit (DWOB) data showed that the particle drilling bits were coming into contact with the bottom of the hole. This bottom hole contact added to the damage that was occurring from particle ricochets and shortened the life of the bit.

### 3. Design of the first Particle Drilling/PDC Hybrid bit

After analyzing the data from the David Cannon 1 well and having a joint workshop between the particle drilling experts in PD, drill bit experts from NOV, and the drilling dynamics team from NOV, it was decided that particle drilling had huge potential as a method of drilling hard rock, and if we could generate significant ROPs in hard rock, then it would have a significant impact on the economics of oil and gas and geothermal energy. NOV and PD created a partnership and set about creating a hybrid particle drilling/PDC bit. The fundamental idea was for the particles to drill a slightly under gauge hole and then the PDC cutters to ream out the remaining now destressed rock. The reamer section would provide stability, prevent lateral vibration, and indicate on/off bottom status. If the particle drilling nose of the bit touched the bottom of the hole, then the PDC cutters in the reamer would be lifted and disengage with the side of the hole. That disengagement would reduce torque on the gauges on the rig floor, and the driller would understand that the reamer was out drilling the particle drilling part of the bit. The driller could then dial down the autodriller slightly to prevent damage to the nose of the bit.

Testing of the particle drilling bits PDT 33 and PDT 44 in the particle drilling lab and on the David Cannon well demonstrated that any significant angle changes in the flowpath of the particles inside the bit would lead to substantial erosion of the internals, which in severe cases, created washouts right through the body of the bit. NOV ran sophisticated fluid dynamics software to minimize angle changes and internal erosion.

The proposed external design solution would:

1. Provide a design incorporating a particle drilling pilot with a reamer for stabilization
2. Cut the correct outside diameter from a pre-cut hole by the pilot particle bit
3. Reduce lateral and torsional vibration
4. Mitigate the ability of the pilot section to meet the bottom of the hole
5. Create a torque, weight on bit (WOB), and differential pressure signature on the surface gauges on the rig floor

The proposed internal design solution would.

6. Eliminate any sharp changes in fluid direction
7. Open the feedbore to promote flow into the nozzle sleeves
8. Insert a narrow carbide sleeve with an increased taper length than the original PD-designed puck
9. Allow reusability and make the design easier to manufacture

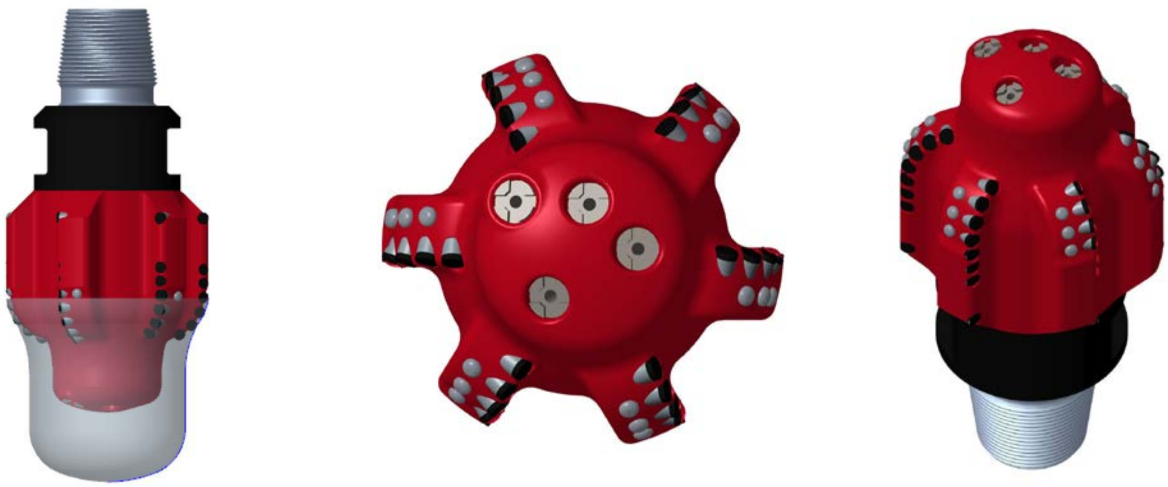

**Figure 3 Image of the external design of 8 ¾" E1429-A1 and the gray area depicting the shot zone**

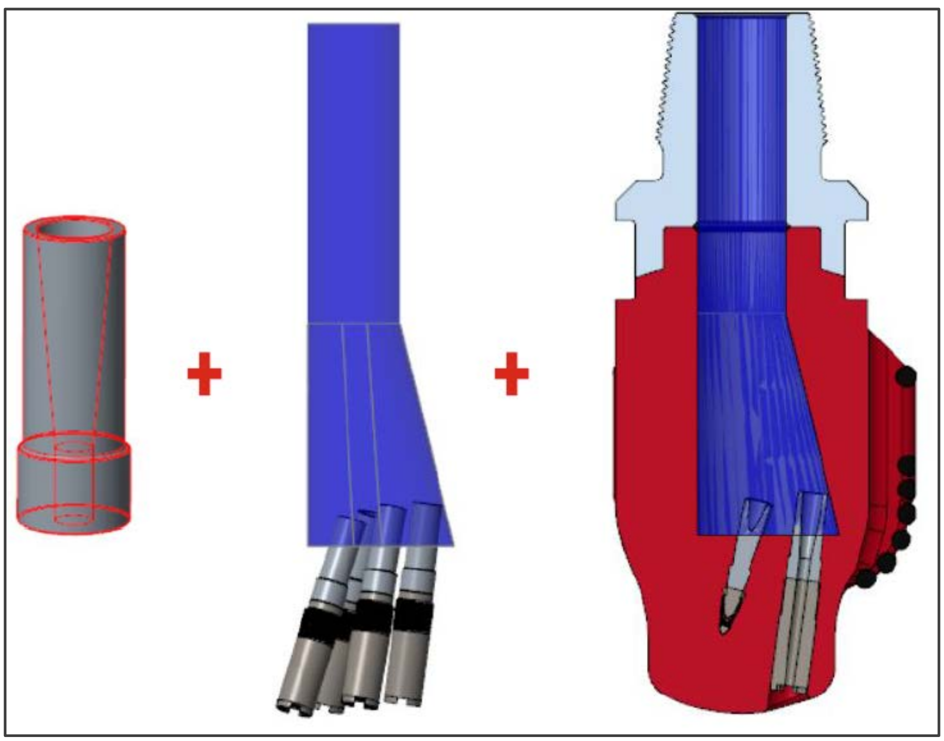

**Figure 4 Image of internal design and the three concepts merged to reduce erosion and make the design easier to manufacture**

The proposed design solution would also:

1. Create a bit where 77 to 85% of the rock would be removed by the particles
2. Create a bottom hole pattern where all particles should be penetrating the formation at a similar point to not over drill a certain ring.

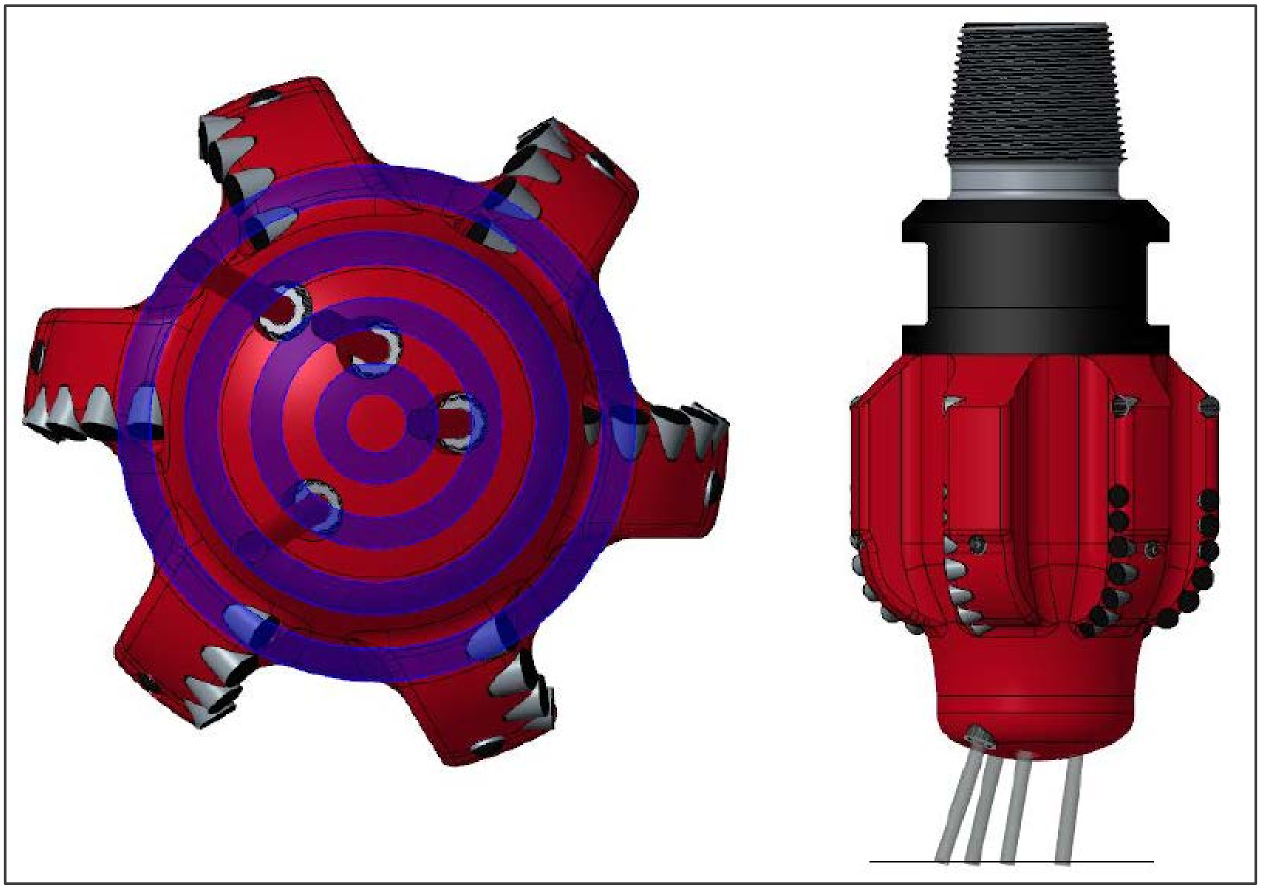

**Figure 5 Image of nozzle placement to create optimum bottom hole pattern.**

## 4. Testing of the first Particle Drilling/PDC Hybrid bit in the ReedHycalog Drilling Lab

Before taking the new particle drilling/PDC hybrid bit to the field, it was decided to test it in the ReedHycalog drilling lab in Conroe, Texas.

The first two tests were run with particles without engaging the reamer, both at 60 RPM and 450 gallons per minute GPM. These two tests established a bottom hole pattern (BHP). The first test was 3 inches off bottom, and the second test was  inch off bottom.

The third test was the first full test with the reamer engaged. Once the reamer engaged rock and established a torque signature, we drilled 8¾ in. with the reamer and 12 ¾ in. with particles and reamer. The RPM was held at 60 and the WOB was kept at 2,000 to 3,000 lb, resulting in a 50 ft/hr average ROP (one section drilled 150 to 170 ft/hr instantaneously). The torque stabilized at around 1,000 to 1,200 ft/lbs The particle bit opened the hole to 6 $^{3/8}$ in. and the rings for the BHP looked like they were spaced correctly. The particles opened the hole to the correct diameter, and rock penetration was at a suitable speed, so the reamer did not out drill the particle drilled pilot section.

On the fourth test, the parameters were increased to four, six and eight thousand pounds WOB while holding the RPM steady at 60. The reamer didn't create the torque needed to start drilling until we got to 6,000 lbs WOB. We were drilling well at 35 ft/hr until near the end, when we saw a torque spike of around 8000 ft/lbs leading us to shut the test down. The ROP had jumped to over 100 ft/hr. The pilot engaged in the bottom of the rock and broke off the outer nozzle, leading us to believe the reamer was out drilling the particle bit once we got to higher weights.

We re-nozzled the bit, changed to a new granite core, and started the fifth test looking for one clean run at 60 RPM, a more consistent torque, and an ROP of around 50 ft/hr. We held the WOB to 4,000 to 5,000 lbs and let it drill the entire core. Once the reamer engaged and the torque increased to 1000 lbf-ft, the ROP started taking off to 50 to 75 ft/hr. This ROP equated to a fluctuation of between 1,500 to 2,500 lbf-ft of torque.

Once removed, the bit looked good and the core had a nice, smooth reamer section, reamer ledge, and the particle pilot diameter drilled was 6.5 inches. Overall, a great run, and and an ideal hole. Photos from test 5 are shown in the figures below.

**Figure 6 Photos of new Particle Drilling PDC Hybrid after test 5**

In conclusion, these atmospheric tests proved that if we can drill with similar parameters downhole, the particle pilot should be able to drill a section around what we need for a diameter of 6.25 to 7 in. for the 8.75-in. reamer to follow. The test results showed the reamer should generally not out-drill the pilot. There was a small amount of scaring on the gauge pad from the particles, but nothing detrimental. Erosion internally looked pretty good, and the body itself did not show any signs of erosion either from particles or fluid. We did have one chipped cutter on one reamer blade, but it did not affect the last test, so it was not significant. The team concluded that we will need more field testing at Marble Falls to better understand how the reamer performs at different parameters in a more realistic system to normal drilling. The results from the initial lab testing were highly positive.

**Figure 7 Photo of the bottom hole pattern in the core after test 5.**

## 5. Summary of Lessons Learned from Field Testing of the first Particle Drilling/PDC Hybrid bit

The field trials on the Coldspring #2 test were designed to test the two PD/NOV newly designed hybrid bits (8 ¾" E1429-A2). The design as shown in section 3 is a combination of the prior particle drilling technology, comprising the lower portion of the bit, and an NOV PDC reamer comprising the upper portion of the bit. The lower portion of the bit is the equivalent of the PDT 33, with 4 focused jets designed to drill a +/- 7-3/4" hole with shot injection. The upper portion consists of 6 PDC set reamer blades designed to open or ream out the remainder of the hole from +/- 7-3/4" to 8-3/4". The design assumes that the particle drilling previously destressed the reamed section.

Several advantages were observed in the field with this bit design. Firstly, the two-stage (or pilot hole then reaming) drilling kept the particle drilling portion of the bit centered and locked in, preventing bit whirl or wobble. This stability was further reinforced with the use of dual roller reamers spaced at 4 feet and 40 feet above the bit. The roller reamer placement created a stable packed hole assembly that would drill in a straight line. Secondly, the two-stage bit assisted in keeping the particle drilling portion of the bit in the prime impact range of 2 inches to 4 inches above the bottom of the hole. All indications from field trials were the particle drilling portion of the bit performed as expected. The testing showed that the reamer section and its positive impact on bottom verification minimized the number of times the bit touched the bottom of the hole. Thirdly, the testing demonstrated a two-stage bit allowed for the concentration of shot in a smaller diameter hole, ensuring 100% shot coverage with appropriate overlap. More specifically, it will enable higher shot concentration per unit of hole area; this probably helped generate higher ROPs.

The particle drilling/PDC Hybrid performance was greatly improved over the previous two particle drilling only field trials. ROPs were initially averaging 40 to 50 ft/hr. However, as the reamer portion cutters began wearing, ROPs slowed to the 25 to 30 ft/hr range, still representing a significant improvement over previous non-hybrid designs. The two 8¾-in. E1429-A2 drilled a combined footage of 980 ft in 23 on bottom hours, at an average of 42.6 ft/hr.

There were no jet washouts or upstream of the jet path washouts, as seen in previous field trials. Jet erosion was not checked on location, but a thorough shop examination showed no significant erosion.

On the downside, the PDC reamer cutters showed significant wear, with chipped and missing cutters. These wear or failure characteristics appeared early in the bit life and were concentrated in the second and third row of cutters, or exactly where the reamer contacted the PD cut portion of the hole. Some of this damage was made worse for two reasons: because we were at shallow depths, meaning we had insufficient WOB to give the bit stability, and because the rig had a bent Kelly, which created a damaging oscillation in the drill string, producing vibration which was exacerbated by the shallow depth. Future designs should consider additional or backup cutters in this area.

Significant facial erosion from shot rebound was seen. Although discussed in the design and building of the bits, NOV believed their proprietary matrix would be sufficient to prevent wear. It is apparent that the particle drilling pilot section, or lower portion of the bit, should be redesigned to incorporate cast carbide or potentially other extremely abrasive/impact-resistant materials.

For comparison, a third NOV-designed bit was run. This bit design had drilled a 2000-ft section of granite on the Forge project in Utah. It was a heavy-set PDC bit, and drilling was done conventionally, without particle shot injection. ROPs were comparable initially, starting at 40 to 50 ft/hr, but the ROP quickly dropped off to below 10 ft/hr. The bit was run for 3.5 hours and pulled after 122 ft in a poor and highly-worn condition with missing, chipped, worn, and broken cutters.

## 6. Conclusions and next steps

The results from the field testing were very promising, with the baseline ROP performance already significantly higher (5x) than the performance of conventional roller cone drill bits in rocks of similar lithology. Performance was also superior to a state-of-the-art PDC (2x). The particle drilling/PDC hybrid design can improve the economics of hard rock drilling. We believe after a few iterations in design, and an improvement in materials, the increase in performance will be even more significant. The potential improvement could help the economic viability of superhot geothermal (SHG), Advanced Geothermal Systems (AGS), and Enhanced Geothermal Systems (EGS) whenever they are targeting igneous and metamorphic rocks as the primary heat source. The ability to drill fast through igneous and metamorphic rocks could also enable well designs to be simplified and optimized for extracting the maximum amount of heat energy.

### *6.1 Conclusions*

The combination of a particle drilling nose and a PDC reamer created a drill bit design that solved several problems seen by either just particle drilling or drilling with conventional PDC bits.

1. The PDC reamer created a particle drilling bit with full borehole contact. That full borehole contact created stability and reduced lateral vibration.
2. Combining the PDC reamer with the particle drilling nose created a surface torque signature that could be used to identify on/off bottom events and optimize ROP.
3. Drilling most brittle rock types with steel particles creates high instantaneous ROPs and destresses the rock enabling the PDC reamer to drill the remaining diameter more easily.
4. The particle drilling/PDC hybrid cutter layout needs to be further optimized to improve the durability of the reamer section. Shaped PDC cutters could be used in future designs.
5. The nose shape needs to be more ballistic to reduce damage from particle ricochets, and the whole body needs to be made from cast carbide to minimize nose and body erosion.
6. Nozzle placement could be further improved to spread out the particle flow over the whole junk slot area of the bit.
7. Need to design a one-piece nozzle and particle accelerator to improve manufacturability.

### *6.2 Next Steps*

When writing this paper, all the recommendations in section 6.1 have been implemented into the second iteration of a hybrid particle drilling/PDC bit, shown in **Figure 8**. The bit body has been changed from TMS matrix to cast carbide, the nozzles and accelerator sleeves are one piece, we have increased the PDC cutters from 39 to 50 and we have placed them on a shoulder radius of 100 mm rather than 55 mm, and the particle section profile has been made more ballistic. We hope to test the new design in the next few months or run in a commercial well before the end of the year.

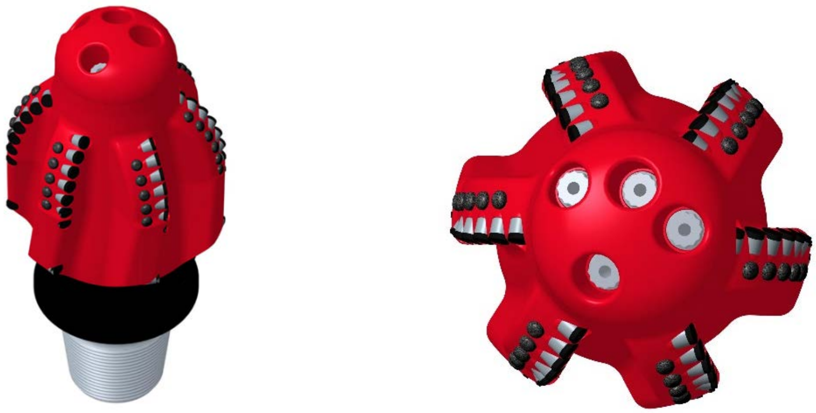

**Figure 8 ½" E1433-A1 Hybrid particle drilling/PDC bit incorporating all the new design features**


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