Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Hard-Rock Field Performance of Drag Bits and a Downhole Diagnostics-While-Drilling (DWD) Tool

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Keywords: geothermal, drilling, hard rock, drag bits, drag cutters, PDC, TSP, abrasion, impact, wear, Diagnostics-While-Drilling, DWD, drilling dynamics.

ABSTRACT

A series of field tests sponsored by Sandia National Laboratories has simultaneously demonstrated the hard-rock drilling performance of different industry-supplied drag bits as well as Sandia's new Diagnostics-While-Drilling (DWD) system, which features a novel downhole tool that monitors dynamic conditions in close proximity to the bit. Drilling with both conventional and advanced ("best effort") drag bits was conducted at the GTI Catoosa Test Facility (near Tulsa, OK) in a well-characterized lithologic column that features an extended hard-rock interval of Mississippi limestone above a layer of highly abrasive Misener sandstone and an underlying section of hard Arbuckle dolomite. Output from the DWD system was closely observed during drilling and was used to make real-time decisions for adjusting the drilling parameters.

This paper summarizes penetration rate and damage results for the various drag bits, shows representative DWD display data, and illustrates the application of these data for optimizing drilling performance and avoiding trouble.

1. INTRODUCTION

The mission of the U. S. Department of Energy (DOE) Geothermal Technologies Program is to satisfy a significant portion of domestic energy demands by promoting the economically competitive exploitation of geothermal resources. This mission is accomplished by supporting both the ***development*** and ***application*** of technologies relevant to geothermal access and utilization.

Sandia National Laboratories has primary responsibility for implementing a major aspect of the DOE Program, namely ***drilling system development***. Sandia's work entails research projects focused on specific topics that, among others, include *hard-rock drill bit technology*, *diagnostics while drilling (DWD)*, and *high-temperature electronics*. The present paper summarizes the results of field tests that benefited from the synergistic linkage of these three particular projects to achieve and demonstrate significant advancements in drilling technology.

With its drill-bit project, Sandia seeks to catalyze the commercialization of next-generation rock cutters and bits that provide improved performance and reduced costs for drilling the hard, hot, abrasive, and fractured formations commonly found at geothermal energy sites. The objective is a combined doubling of penetration rate and bit life compared to current rockbit (*i.e.*, rollerbit) technologies, which will decrease the cost for a typical geothermal well by ~15% (Glowka, 1997). On the basis of their record-breaking runs in soft and medium-hardness formations (*e.g.*, Perdue, 1999), properly designed and controlled drag bits have excellent prospects for meeting this goal. Laboratory results support this premise (Raymond, 2001).

Since the introduction of drag bits in the 1970s, Sandia has worked with DOE funding to develop and apply substantial in-house capabilities and expertise for identifying and analyzing drag-bit failure mechanisms and improving bit designs (Glowka, 1987; Finger and Glowka, 1989). Drag bits are equipped with multiple fixed cutters that break rock with a shearing process that is inherently more efficient than the crushing action applied by a rollercone bit. These cutters typically have ultrahard layers of PDC (polycrystalline diamond compact) or TSP (thermally stable polycrystalline) diamond that are bonded to tungsten carbide substrates. Parametric studies by Sandia and U S Synthetic Corporation (Wise, *et al*., 2002) have examined the influence of geometry and material variations on PDC cutter performance. Joint investigations by Sandia and Technology International, Inc. have validated new brazing methods and fracture-toughness enhancements for TSP cutters (Radtke, 2002).

The DWD project has concurrently aimed to reduce geothermal drilling costs by providing high-speed, real-time downhole data to the surface for interpretation and subsequent utilization in a closed-loop feedback control system. This work stems from research goals defined during a Sandia-sponsored technology workshop (Glowka, 1997). Sandia's high-temperature electronics project lends critical support to the DWD effort by providing the necessary circuitry and packaging for downhole tool components whose construction is mechanically, and ultimately thermally, robust.

The idea of using real-time downhole data while drilling is not new (*e.g*., Pavone and Desplans, 1994). However, past efforts have generally been directed toward occasional use for research purposes and have not aimed at operations in the extreme geothermal environments that are being addressed by Sandia. Progress on development of Sandia's DWD system is summarized in a recent report (Blankenship, *et al*., 2004).

2. TECHNICAL APPROACH

Sandia sponsored a geothermal drilling demonstration in the early 1980s that showed encouraging results with the PDC bit capabilities of that era. While drag-bit designs and materials have evolved dramatically since then, no comparable follow-up demonstration has been carried out to assess the performance of modern drag bits and cutters in hard rock. The present work eliminates this deficiency by means of field-based drilling with conventional (*i.e.*, baseline) and advanced drag bits.

2.1 Drag-Bit CRADA

For the drilling demonstrations discussed in this paper, Sandia collaborated with four bit companies under the terms of a mutually adopted Cooperative Research and Development Agreement (CRADA), which was entitled "Advanced Drag Bits for Hard-Rock Drilling." The industry partners for this work were:

- ReedHycalog, A Grant Prideco Company;
- Security DBS, a Product Service Line of Halliburton Energy Services, Inc.;
- Smith Bits – GeoDiamond; and,

- Technology International, Inc.

These companies are internationally recognized innovators and manufacturers of PDC and/or TSP rock-cutting products. Each of these partners is committed to the continued development and marketing of improved drag-bit materials and designs. Company-specific capabilities include bit and/or cutter modeling, design, and fabrication, as well as laboratory and field testing. The cost-shared CRADA activities very effectively leveraged the respective technical and funding resources of both the public (DOE/Sandia) and private (industry) sectors.

Bit demonstrations stipulated by the CRADA were completed in three phases, which are outlined below. Each phase was accomplished in conjunction with deployment of the DWD system for acquiring and displaying real-time downhole and surface data. Drilling during all three phases was conducted in a common lithologic interval using the same bottomhole assembly (BHA).

2.1.1 CRADA Phases 1 and 2

Sandia collaborated with Security DBS during Phases 1 and 2 of the CRADA to generate baseline hard-rock drilling data for a conventional, widely known drag bit (Security DBS Model PD 5; 8-1/2 inch diameter) that was operated ***without*** DWD feedback to the driller during Phase 1, then ***with*** DWD-based control during Phase 2. These tasks, in combination, satisfied the Proof of Concept (POC) requirements for Sandia's DWD program. Bit performance and wear results from Phases 1 and 2 have been previously reported (Wise, *et al*., 2003), as well as interpretation of the associated DWD dynamic data (Mansure, *et al*., 2003).

2.1.2 CRADA Phase 3

Sandia transferred full data sets from the Phase 1 and Phase 2 tests to each CRADA partner to support its separate development of a "best effort" hard-rock bit design and DWD-based drilling strategy for demonstration during Phase 3 of the CRADA under the same constraints (*i.e.*, lithologic interval and BHA) as the Phase 1 and Phase 2 operations.

During its individual test period, each industry partner supplied a single "best effort" bit and an accompanying team of one or more engineers who continuously monitored the streaming DWD data displays and actively controlled the drilling process. The Phase 3 bit performance results and dull-grade measurements have been documented (Wise, *et al*., 2004) along with comparisons to the Phase 1 and 2 results.

2.2 Test Bits

2.2.1 Conventional Bit (Phases 1 and 2)

Security DBS supplied an 8-1/2 inch drag bit (Model PD 5, manufactured in 1994) and two identical cutter sets for the Phase 1 and Phase 2 drilling. A new cutter set was installed by Security DBS during bit refurbishment prior to each phase. The PD 5 bit is shown in Figure 1.

The PD 5 has a short-taper, concave-profile steel body with erosion-resistant hardfacing. This is a non-bladed bit (IADC Code S873) with a "random set" cutter layout. It was designed to drill a wide range of medium-soft to medium formations with hard stringers. PD 5 bits have been known for directional stability in operations that do not require exceptional cleaning capability at the bit. Three size 15 (*i.e.*, 15/32-inch orifice) interchangeable nozzles were used for Phases 1 and 2. To achieve both durability and rapid penetration, the PD 5 was heavy set with large (19-mm diameter) stud-mounted face (18 each) and gage (6 each) PDC cutters. It was also equipped with smaller (13.3-mm diameter) stud-mounted gage trimmers (9 each).

Figure 1: Security DBS Model PD 5 drag bit used for Phase 1 and Phase 2 testing.

2.2.2 "Best Effort" Bits (Phase 3)

The CRADA specified that each of the four industry partners would provide an 8-1/2 inch diameter "best effort" drag bit, then use that bit to drill a separate borehole to measure its performance relative to the other conventional and advanced ("best effort") bits in the specified lithologic column. No other restrictions were established with regard to cutter size and type, cutter count, cutter density, bit configuration, or bit hydraulics. By agreement among the partners, the "best effort" results were to be reported anonymously for bits identified only as A, B, C, or D.

Specific details of a particular "best effort" bit design are CRADA-protected data that must be obtained directly from the bit manufacturer. However, three of the four CRADA partners have released face views of their bits. A pre-test photograph of the ReedHycalog six-bladed "best effort" bit appears in Figure 2. The worn eight-bladed Smith "best effort" bit and worn seven-bladed Security DBS "best effort" bit are shown, respectively, in Figures 3 and 4.

Figure 2: ReedHycalog™ DSX148 "best effort" drag bit (new).

Figure 3: Smith Bits – GeoDiamond "best effort" drag bit (worn).

Figure 4: Security DBS "best effort" drag bit (worn).

2.3 Bottomhole Assembly (BHA)

The same stiff BHA was used for Phases 1, 2, and 3. The configuration was chosen by consensus among Sandia and the CRADA partners. Table 1 lists the BHA components in order, beginning with the bit.

Table 1. BHA Elements for CRADA Phases 1, 2, and 3.

Component	Length (ft)
Drag Bit (PD 5 or "best effort")	-as received-
Near-Bit Stabilizer (NBS); 1/16-in under gage, hard-faced & ground smooth	4.04
Crossover	0.80
DWD Measurement Sub	7.03
Crossover	1.38
Lower Integral Blade Stabilizer (IBS); at gage diameter	4.18
6-1/4 in Drill Collar (DC)	30.08
Upper IBS; at gage diameter	4.13
6-1/4 in DC; 9 double stands	554.90
4-1/2 in Drill Pipe (DP); 16.6 lb/ft	-as needed-

As shown in Table 1, the BHA incorporated stabilizers immediately below and above the DWD measurement sub. This arrangement was chosen as a precautionary measure to minimize the chances of damaging the DWD tool with large-amplitude lateral vibrations and impact during drilling.

2.4 Test Site and Lithology

All of the combined drag-bit and DWD field operations were conducted at the research site managed by the Gas Technology Institute (GTI) near Catoosa, OK. This site features a well-characterized, laterally uniform lithology and a test-oriented drilling crew. All drilling for CRADA Phases 1, 2, and 3 was done at depths between 1100 and 1913 ft. The geologic formations encountered in this range (Hinch, 1987) are identified in Table 2, where the reported positions of the formation tops have been adjusted to be consistent with a depth of 1274 ft for the top of the Mississippi limestone.

The hard Mississippi limestone is of primary interest for the present study. This interval has rock strengths exceeding 35 kpsi and includes "The Wall," which is a section that has historically been difficult to drill with PDC bits. By comparison, the Sierra White Granite used as a "geothermal" standard for hard-rock testing at Sandia has an unconfined compressive strength of 28.2 kpsi (Pratt and Black, 1980).

Table 2. Formation Depth Intervals for the GTI Catoosa Test Facility.

Adjusted Depth Interval (ft)	Formation Name
901 - 1208	Booch Sandstone
1208 - 1238	Burgess Sandstone
1238 - 1274	Fayetteville Shale
1274 - 1571	Mississippi Limestone
1571 - 1600	Woodford Shale
1600 - 1627	Misener Sandstone
1627 ~ 2942	Arbuckle Group

Security DBS used its GeoMechanics model (Wise, *et al*., 2004) to generate the data shown in Figure 5 for rock strength as a function of depth at the GTI Catoosa Test Facility. Although the strength remains generally high for depths below 1274 ft, substantial variations do occur.

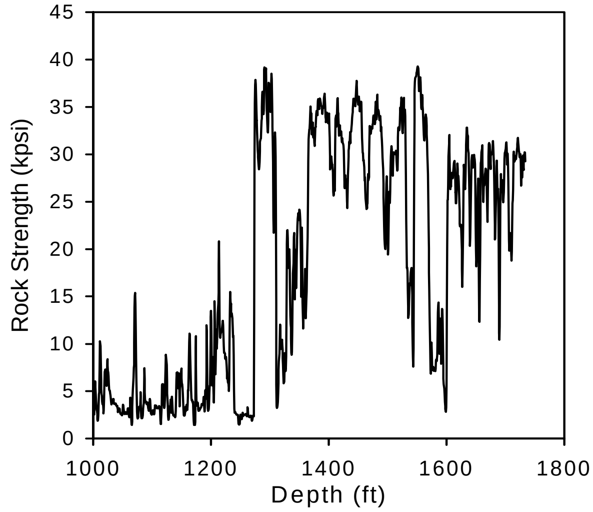

Figure 5: Catoosa rock strength variations derived from the Security DBS GeoMechanics model.

2.5 DWD System

Sandia's DWD system (Finger, *et al*., 2003a and 2003b) provided high-speed, real-time downhole data during Phases 1, 2, and 3. The measurements acquired with the downhole DWD tool and their associated sampling rates are summarized in Table 3. The parameters noted in Table 3 are continuously digitized and multiplexed downhole, then transmitted to the surface through a wet-connect wireline data link at a rate of approximately 200,000 bits per second. The DWD system includes specialized displays of surface ("mud logger") information and downhole data for convenient observation by the driller and/or members of the engineering team.

Table 3. Downhole Measurements and Sampling Rates.

Parameter	Sample Rate (s^{-1})
Weight on Bit (WOB)	1041.67
Torque on Bit (TOB)	1041.67
Lateral (X, Y) Bending Moment	1041.67
Lateral (X, Y) and Axial (Z) Acceleration	1041.67
Broadband Z Acceleration	2083.34
Angular Acceleration	1041.67
X, Y, Z Magnetometer	130.21
Internal/External Pressure and Temperature	65.10

2.6 Testing Protocol

One week (nominally 5 working days) of rig time was reserved for each of the PD 5 bit runs (Phases 1 and 2), and for each of the "best effort" bit demonstrations (Phase 3). Besides several instances where problems arose with the wireline or its connection hardware, DWD data were displayed and recorded almost continuously for all CRADA bit runs. Drilling was interrupted during each run by one or more intermediate trips out of the hole for bit inspection and for maintenance work, as required, on the DWD downhole measurement tool and associated wireline equipment.

All bit runs, except one, began at a nominal starting depth of just over 1100 ft with a specified initial bottomhole inclination of less than 2 degrees from vertical. This starting depth was selected to allow about 170 ft of relatively easy drilling before encountering the top of the Mississippi limestone interval at 1274 ft. The only exception occurred during Phase 3 for "best effort" Bit B, whose run began at a depth of 1166 ft due to the additional footage needed to bring the starting bottomhole inclination back to a value of 2 degrees or less after kicking off the new test hole at a shallower depth.

During Phase 1, drilling with the PD 5 bit proceeded from the starting depth and continued under the direction of an experienced driller until the rate of penetration (ROP) fell essentially to zero due to bit damage and wear.

Phase 2 drilling with the PD 5 bit paralleled that for Phase 1, with the important difference that DWD data were actively monitored by an experienced drilling engineer and used to make recommendations to the driller regarding adjustments in operating parameters for the sake of improved ROP and bit life.

Prior to Phase 3, each industry partner notified Sandia of its preferences for the data display. During drilling, the company teams tracked these displays carefully, interpreted the data, and responded by instructing the driller to change conditions (*e.g*., WOB, RPM, and/or mud flow) or to lift off bottom and restart drilling to mitigate undesirable downhole dynamics.

3. RESULTS

3.1 Bit Penetration Rate (ROP) and Total Run Distance

For each CRADA test, the ROP plotted in Figure 6 was calculated for numerous recording depths using information from the surface-data files.

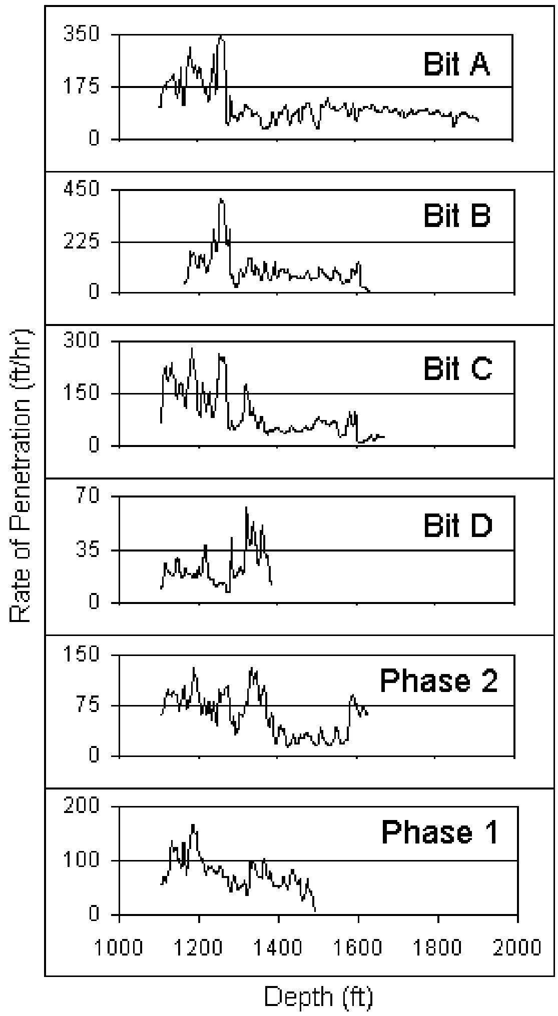

Figure 6: Rate of penetration results for "best effort" Bits A, B, C, and D (Phase 3) and baseline PD 5 bit (Phases 1 and 2).

The ROP value reported for a given depth corresponds to the slope of a linear best fit to the depth-versus-time data available within an interval of 10 ft (*i.e.*, ±5 ft) centered on that depth. The resultant ROP data are plotted separately in Figure 6 for the PD 5 bit runs during Phases 1 and 2, as well as the runs for “best effort” bits (A, B, C, and D) during Phase 3. The same depth scale is used for all of these plots; however, the sensitivity of the ROP scale has been adjusted for each bit to allow higher resolution display of the full range of ROP values achieved by that bit.

For softer formations above the Mississippi limestone, maximum penetration rates of 407, 344, and 278 ft/hr were obtained, respectively, with Bit B (Fayetteville shale, 1259 ft), Bit A (Fayetteville shale, 1259 ft), and Bit C (Booch sandstone, 1182 ft). Bit C exhibited another ROP peak of 263 ft/hr in the Fayetteville shale (1253 ft). By comparison, the PD 5 bit reached a peak soft-formation ROP of 167 ft/hr during Phase 1 (Booch sandstone, 1181 ft), and 131 ft/hr during Phase 2 (Booch sandstone, 1187 ft).

In contrast, Bit D exhibited its initial ROP peak of 43 ft/hr just after entering the Mississippi limestone (1284 ft), and its overall peak ROP of 63 ft/hr at a depth of 1322 ft, which is also within the Mississippi limestone.

The formation-by-formation average ROP for each test bit is reported in Table 4, which also lists total run distances and times together with the corresponding overall ROP averages. Bits A, B, and C fully penetrated the Mississippi limestone formation with average ROPs of 78.2, 76.4, and 54.7 ft/hr, respectively, in this interval. These values are dramatically higher than the Phase 2 average of 33.0 ft/hr for the PD 5 bit, which also survived the Mississippi limestone during drilling with active use of DWD feedback. Offsetting runs for Bit D and the PD 5 (Phase 1) bit ended in the Mississippi limestone at depths of 1386 and 1492 ft, respectively, when these bits were no longer able to advance the hole due to cutting structure damage.

Like the PD 5 bit in Phase 2, “best effort” Bits A, B, and C also successfully transited the hard and abrasive Misener sandstone interval. Bit A maintained a very high (93.8 ft/hr) ROP through this formation, whereas the ROP for Bits B and C dropped to 35.2 and 13.5 ft/hr, respectively, during this portion of the drilling. These results compare to the Phase 2 average of 67.0 ft/hr for the PD 5 bit in Misener sandstone.

Beyond the Misener sandstone, Bit A continued with high average ROP (86.5 ft/hr) in the hard Arbuckle formation, ultimately reaching a final depth of 1913 ft before the available rig time was exhausted. In total, this bit traveled 811.6 ft in 8.535 hr, corresponding to an overall average ROP of 95.1 ft/hr. Bit B progressed only a short distance at low ROP in the Arbuckle before drilling was suspended at 1632 ft due to a washout of the DWD downhole tool. Bit B drilled a total of 465.6 ft in 6.311 hr, achieving an overall average ROP of 73.8 ft/hr. The ROP for Bit C recovered somewhat in the Arbuckle, averaging 24.5 ft/hr from 1627 ft until drilling ended at a final depth of 1670 ft, also due to a DWD downhole tool washout. The overall average ROP for Bit C was 53.0 ft/hr. For comparison, in Phase 2 the PD 5 bit reached a final depth of 1632 ft after making 525.5 ft of hole in 12.029 hr; this translates to 43.7 ft/hr as an overall ROP average.

Table 4. Formation-Specific and Overall ROP Averages.

Formation Name	Average Rate of Penetration (ft/hr)					
	Bit A (starting at 1102 ft)	**Bit B** (starting at 1166 ft)	**Bit C** (starting at 1103 ft)	**Bit D** (starting at 1105 ft)	**Phase 1 PD 5** (starting at 1105 ft)	**Phase 2 PD 5** (starting at 1106 ft)
Booch Sandstone	191.1	105.9	160.9	18.8	104.9	89.2
Burgess Sandstone	178.1	129.3	124.4	21.4	90.7	69.0
Fayetteville Shale	259.7	273.3	194.2	11.9	77.0	84.9
Mississippi Limestone	78.2	76.4	54.7	24.3 (to 1386 ft)	57.8 (to 1492 ft)	33.0
Woodford Shale	103.8	65.4	67.8	–––	–––	53.0
Misener Sandstone	93.8	35.2	13.5	–––	–––	67.0
Arbuckle Group	86.5 (to 1913 ft)	10.1 (to 1632 ft)	24.5 (to 1670 ft)	–––	–––	66.0 (to 1632 ft)
Overall Bit Run	**95.1** (811.6 ft/ 8.535 hr)	**73.8** (465.6 ft/ 6.311 hr)	**53.0** (566.3 ft/ 10.679 hr)	**19.4** (280.4 ft/ 14.480 hr)	**69.6** (386.6 ft/ 5.554 hr)	**43.7** (525.5 ft/ 12.029 hr)

Data for hole depth versus time on bottom (*i.e.*, drilling time) are shown in Figure 7 for all "best effort" and PD 5 bit runs during CRADA Phases 1, 2 and 3. Bit A clearly delivered the greatest total footage while maintaining the highest average ROP.

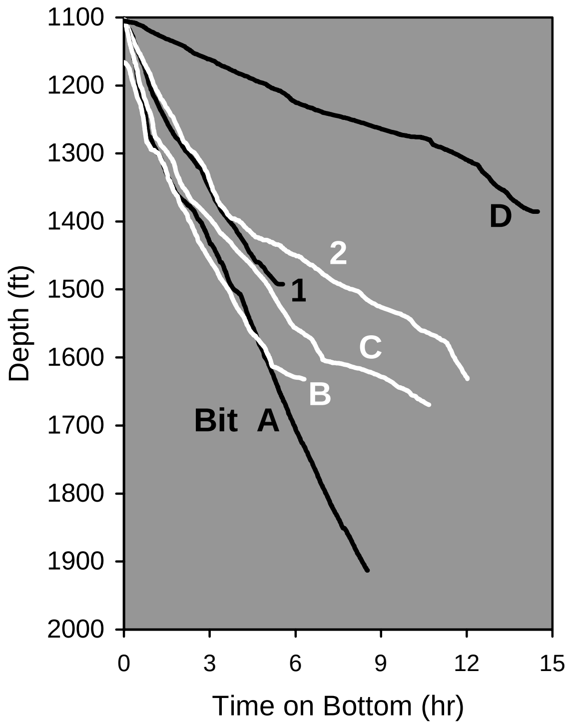

Figure 7: Hole depth as a function of drilling time for "best effort" Bits A, B, C, and D (Phase 3) and baseline PD 5 bit (Phases 1 and 2).

3.2 Bit Damage Assessments

The PD 5 bit dull grade was determined at the end of its Phase 1 and Phase 2 runs. For each of the Phase 3 "best effort" bits, dull grading was done initially during a mid-run trip out of the hole (TOOH), then a final time at the end of its run. The results are summarized in Table 5 using the IADC standard format (Brandon, *et al.*, 1992).

The dull grading inspections confirmed the expected accumulation of additional wear and damage by the cutting structure of each bit as drilling progressed. However, the overall degradation experienced by Bits A, B, and C was low, and these bits could have drilled significantly further than the listed hole termination depths. The run for Bit A ended when the available rig time during its week was spent. The runs for Bits B and C were terminated by the failure (*i.e.*, washout) of the downhole DWD measurement tool. Design deficiencies in the DWD tool housing were subsequently identified, and these deficiencies have been corrected in the latest embodiments of this device.

For Bit D, damage accumulated much more rapidly with depth, and all inner cutters were lost by the time this bit began entering "The Wall." As indicated in Table 5, the second TOOH for Bit D was prompted by low penetration rate. Bit D was not rerunnable after this trip due to the severe damage sustained by its cutting structure.

The cutting structure of the PD 5 bit was generally less damaged at the end of Phase 1 than it was after Phase 2. However, the loss of key cutters during Phase 1 apparently prevented advancement of the hole beyond 1492 ft. The more conservative, DWD-guided control exercised in Phase 2 yielded a 36% increase (525 versus 387 ft) for total footage drilled in Phase 2 as compared to Phase 1. The total footage achieved in Phase 2 would have been even higher if additional rig time had been available to allow continued drilling.

Table 5. Bit Dull Grade Assessments for CRADA Phases 1, 2, and 3.

PHASE	BIT	DEPTH OUT (ft)	CUTTING STRUCTURE				B	G	REMARKS	
			INNER ROWS	OUTER ROWS	DULL CHAR	LOCA-TION	BRNG/ SEALS	GAUGE 1/16 in	OTHER CHAR.	REASON PULLED
1	PD 5	1492	1	0	CT	C + N	X	I	WT	PR
2	PD 5	1632	3	1	WT	A	X	I	CT	TD
3	A	1507	1	0	BT	C	X	I	CT	BHA
		1913	2	0	BT	C	X	I	CT	TD
	B	1484	0	0	CT	S + N	X	I	WT	BHA
		1632	0	1	WT	S + N	X	I	CT	DTF
	C	1544	0	0	CT	S + N	X	I	NO	BHA
		1670	1	1	WT	S + N	X	I	HC	DTF
	D	1316	3	0	LT	C	X	I	WT	BHA
		1386	8	1	NR	C	X	I	WT	PR

Notations: Grade = 0 for no wear, 8 for no usable cutting structure; CT = chipped cutters; WT = worn cutters; BT = broken cutters; LT = lost cutters; NR = not rerunnable; HC = heat checking; NO = no major/other dull characteristics; C = cone; N = nose; S = shoulder; A = All; X = fixed-cutter bit; I = 'in' gauge; PR = penetration rate; TD = total depth; BHA = service bottomhole assembly; DTF = downhole tool failure.

3.3 DWD-Based Observations and Drilling Control

3.3.1 Conventional Bit (Phases 1 and 2)

Representative WOB and TOB (torque on bit) data are shown, respectively, in Figures 8a and 8b for an extended (one hour) period of *smooth drilling* during Phase 1. Over this period, the borehole depth advanced 63 ft (from 1357 to 1420 ft). The overlayed downhole and surface data agree closely in terms of major features. Peak-to-peak fluctuations in the downhole WOB and TOB appear significantly higher than the respective surface fluctuations due (at least in part) to filtering and lower sampling rates for the surface data. The time-dependent mean of the surface torque remains consistently higher than the downhole mean since the applied uphole torque must compensate for both bit torque and the rotational friction between the turning drillstring and the borehole wall.

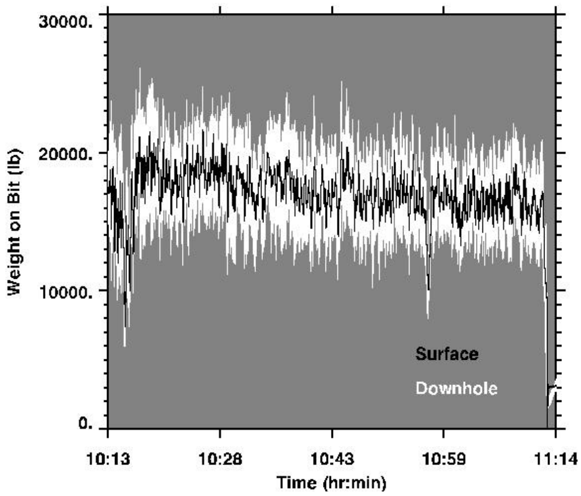

Figure 8(a): Phase 1 downhole and surface WOB data for the interval from 1357 to 1420 ft.

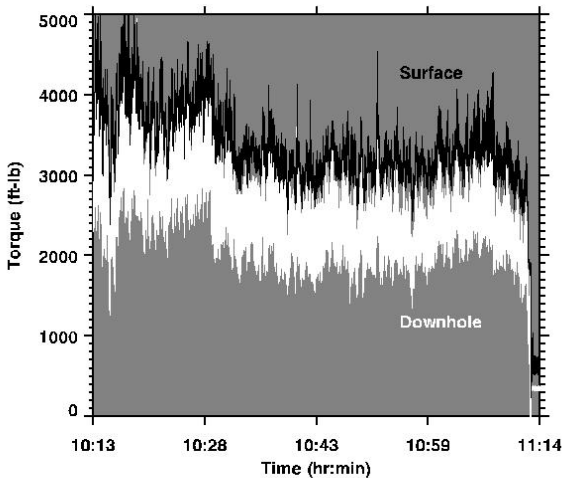

Figure 8(b): Phase 1 downhole and surface TOB data for the interval from 1357 to 1420 ft.

In Figures 9a and 9b, the WOB and TOB are shown, respectively, during the last 40 minutes of Phase 1 drilling. In this time period, the borehole depth only increased from 1480 to 1492 ft despite the application of high (>25,000 lbf) WOB values. In fact, midway through this interval (at a time of 17hr:30min) the hole had already reached 1492 ft; the remaining time (about 20 minutes) was spent in unsuccessful attempts to reestablish forward progress.

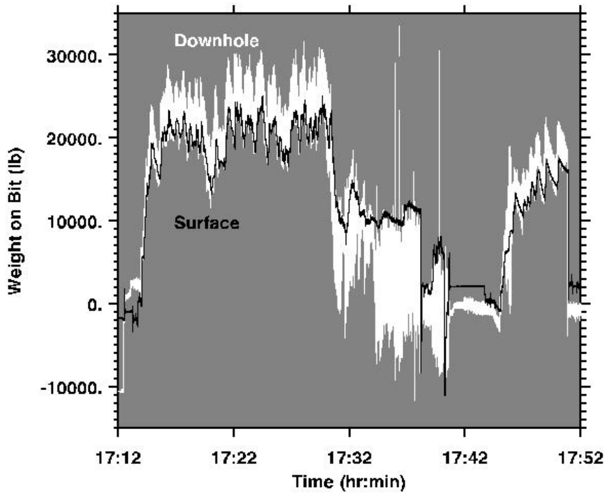

Figure 9(a): Phase 1 downhole and surface WOB data for the interval from 1480 to 1492 ft.

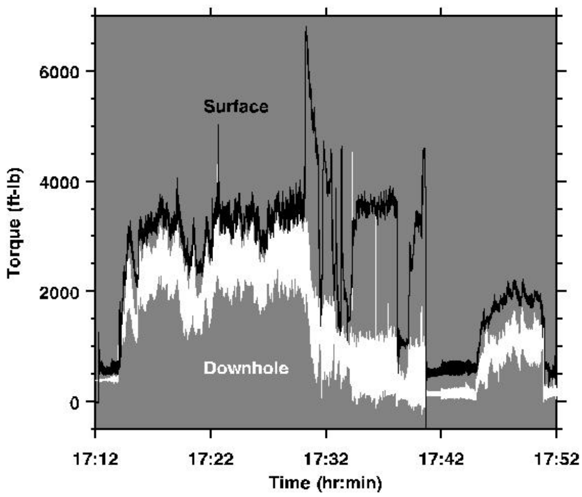

Figure 9(b): Phase 1 downhole and surface TOB data for the interval from 1480 to 1492 ft.

Erratic drilling conditions were noted as the time approached 17hr:30min, including strong vibrations felt at the rig floor, and the driller pulled up off bottom at 17hr:36min to allow vibrations to subside before drilling was started again at a lower WOB. When drilling was resumed during the period from about 17hr:37min to 17hr:40min, the downhole WOB (see Figure 9a) showed the reappearance of large-amplitude fluctuations that were not detected at the surface. Matching fluctuations also were evident on the downhole TOB trace (see Figure 9b).

The driller pulled up off bottom more than once to allow these vibrations to diminish and to adjust drilling conditions, but he was unable to deepen the hole. The observed peak in the frequency spectrum at ~17 Hz for the downhole vibrations indicated BHA whirl since it corresponded to the calculated frequency of the fundamental torsional mode of the BHA. This whirl allowed the bit to drill off and bounce on bottom even though the surface indicator showed reasonable WOB readings.

To illustrate a situation involving *DWD-based intervention*, the WOB and TOB are plotted, respectively, in Figures 10a and 10b for a short (10 minute) period of drilling during Phase 2. Over this period, the borehole was advanced 3 ft (from 1574 to 1577 ft).

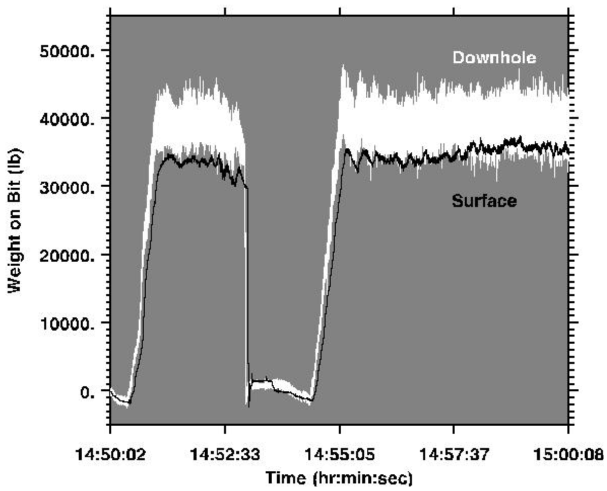

Figure 10(a): Phase 2 downhole and surface WOB data for the interval from 1574 to 1577 ft.

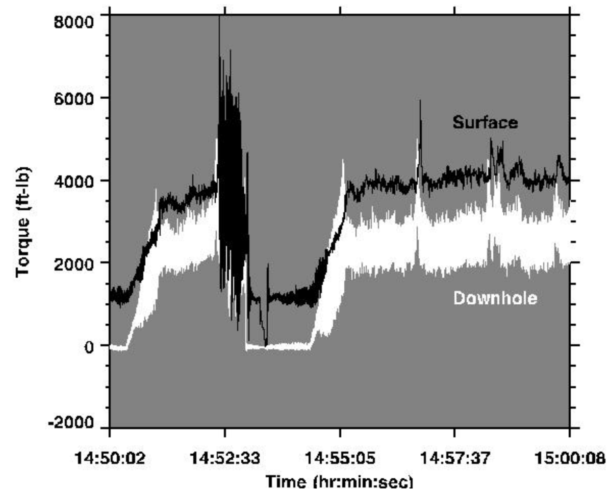

Figure 10(b): Phase 2 downhole and surface TOB data for the interval from 1574 to 1577 ft.

For roughly the first 20 seconds of this period (beginning at 14hr:50min), the bit was rotating off bottom. From Figures 10a and 10b, the bit was then set down on the bottom of the hole, as evidenced by both the downhole and surface data. Large-amplitude fluctuations in the downhole torque appeared almost immediately as drilling resumed, whereas the surface torque readings were initially smooth.

About 100 seconds later, the surface torque readings also began to show very large fluctuations just after an increase in the downhole fluctuation magnitude. Stick/slip motion was evident since the downhole RPM was fluctuating from zero to three times the 70-rpm value being applied by the top drive. The source of this problem was probably the stabilizers above the DWD tool since the mean and peak-to-peak amplitudes of the surface torque exceeded the corresponding downhole values. As a remedy, the bit was pulled up off bottom and drilling was suspended for over a minute. After this, drilling was resumed with no further problems during the sample interval.

3.3.2 “Best Effort” Bit (Phase 3)

As a final DWD example, consider a measurement interval that involved drilling with one of the “best effort” bits in Booch sandstone through a depth range of 1120 to 1160 ft. Figure 11 shows selected channels of downhole and surface data for this interval in strip-chart format.

From Figure 11, four distinct bursts of coupled, large-amplitude fluctuations in the *downhole range* envelopes for WOB and TOB are apparent in the subject interval. The first burst was mitigated by reducing WOB from 22 to 17 klbf at a depth of 1125 ft. With this change, smooth drilling was reestablished, and the ROP increased.

At 1138 ft the driller began building WOB, ramping up to 24 klbf at a depth of 1142.5 ft. However, the WOB and TOB oscillations reappeared, so WOB was decreased momentarily to about 9 klbf at 1142.5 ft, then reset to 17 klbf for about 2 ft of drilling. A third burst of WOB and TOB oscillations persisted through this 2 ft range until the WOB was decreased momentarily to less than 8 kpsi at 1144.5 ft, then was built back up to 17 klbf.

The WOB and TOB oscillations appeared again at 1147.5 ft and continued until 1148.5 ft when the driller dropped the rotation rate from 138 to 117 rpm. In this case, the adjustment of RPM instead of WOB eliminated the WOB and TOB oscillations, yielding an increase in ROP to values as high as 250 ft/hr. The authors of the present paper emphasize that *all of the corrective measures noted above were taken on the basis of undesirable downhole dynamics that were detected by the DWD tool and were not sensed by the conventional surface instrumentation.*

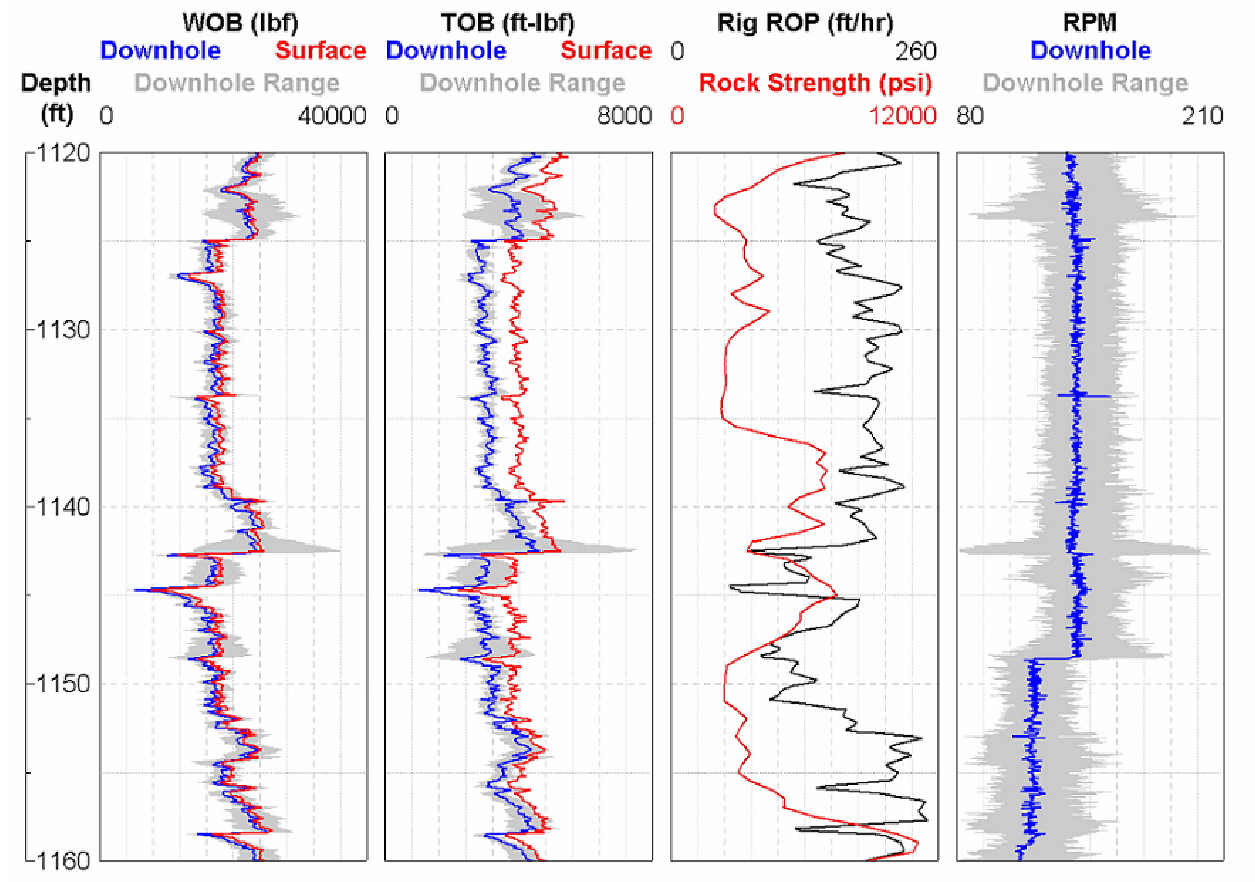

Figure 11: Selected downhole and surface data for a "best effort" bit drilling a section of Booch sandstone.

4. CONCLUSIONS

The present study has established benchmark hard-rock drilling data for conventional and "best effort" drag bits. In addition, the capabilities of a Diagnostics-While-Drilling system have been demonstrated for the acquisition, transmission, display, and application of real-time downhole data for manual control of the drilling process.

As shown during Phases 1 and 2 of the CRADA, the joint use of drag bits and DWD-derived feedback control for the drilling process can yield extended bit life and high penetration rates in hard-rock intervals—even with an older (PD 5) bit design. CRADA Phase 3 results for three out of four state-of-the-art "best effort" drag bits operated with DWD feedback have substantially exceeded the measured ROP and bit life for the baseline PD 5.

Improvements in bit life achieved by active DWD-based intervention in the drilling process may involve some trade-off for penetration rate. The relative impact of bit life and ROP on overall drilling cost per foot must be considered in light of the respective costs for the bit and rig time. Clearly, excessive intervention at dynamic loading levels below minimum damage thresholds may lead to an increase in cost. Unfortunately, these thresholds are difficult to define without a substantial database and associated model for bit and cutter failure. Ultimately, such a database and/or model may be developed and incorporated as part of the DWD system to maximize drilling economy on a real-time basis.

The DWD system is evolving toward high-temperature capabilities for the downhole tool, and the use of wired drillpipe to eliminate the difficulties inherent in a long wireline connection between the tool and the surface (Blankenship, *et al*., 2004). In addition, this system may eventually provide automatic feedback control for a downhole damping mechanism to mitigate damaging axial and torsional bit vibrations (Elsayed and Raymond, 2002).

ACKNOWLEDGEMENTS

Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

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