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Update on a Diagnostics-While-Drilling (DWD) System to Assist in the Development of Geothermal Wells

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ABSTRACT

This paper provides an update on the development of a Diagnostics-While-Drilling (DWD) system at Sandia National Laboratories (SNL). The DWD system provides for real-time, high-speed downhole data while drilling. The first generation of the DWD system was designed and fabricated for low-temperature applications (less than 135 °C). This system has been proof-tested and subsequently used to support Sandia and industry-sponsored drag bit development efforts. A second-generation DWD system is currently being developed to accommodate fielding in geothermal reservoirs, allowing for continuous operating temperatures of 225 °C. This paper provides a background on the DWD system and an update on recent activities, including those related to the fabrication of a high-temperature version of this system. The utility of the DWD system is illustrated with examples of real-time and post-processed data obtained during previous test efforts.

Introduction

While a detailed description of the rationale for and early development of Sandia's Diagnostics-While-Drilling program has previously been reported [Finger, et al., 2003a, 2003b], this section provides a summary of past development efforts.

The DWD project originated from the principle that some of the drilling research funded by the Department of Energy (DOE) should be directed toward high-risk, revolutionary advances in drilling technology. In support of this concept, Sandia National Laboratories organized two workshops directed at defining appropriate research goals [Glowka, 1997]. After considerable discussion, a consensus emerged that the greatest deficit in most drilling functions was the lack of real-time knowledge and control of what was happening downhole. As a result, Sandia National Laboratories, with funding from DOE's Office of Geothermal Technology, is developing a Diagnostics-While-Drilling (DWD) system to provide real-time, high-speed downhole data to the driller. The idea of using real-time downhole data while drilling is not unique [Pavone and Desplans, 1994]; however, past efforts have generally been directed toward occasional use for research purposes and were not directed toward operating in the extreme environments associated with geothermal reservoirs. The premise of the DWD program is that real-time, high-speed information from the downhole environment can reduce the cost of geothermal wells in two ways: (1) by avoiding trouble, such as stuck pipe or twist-offs, and the resulting flat time, and (2) by optimizing drilling performance, such as using PDC bits for faster penetration in hard rock.

The first-generation prototype DWD system was fielded in a series of proof-of-concept tests to validate functionality. Additionally, the DWD project has developed a symbiotic relationship with other projects within Sandia's Geothermal Drilling Program. Of particular note is the use of the DWD system to support a single-laboratory/multiple-partner CRADA (Cooperative Research and Development Agreement) entitled *Advanced Drag Bits for Hard-Rock Drilling*. The drag-bit CRADA was established between Sandia and four bit companies, and involved testing of a PDC bit from each company [Wise, et al., 2004] in the same lithologic interval at the Gas Technology Institute (GTI) test facility near Catoosa, OK. During these CRADA tests, the DWD system provided real-time, high-speed data that was used by the bit-company drilling engineers to monitor and optimize performance of their bits. The first two phases of the drag-bit CRADA effort were linked to Proof-of-Concept tests [Wise, et al., 2003] that compared performance of identical bit/BHA combinations with and without DWD feedback. In addition to proof-of-concept testing and support for the bit CRADA effort, the DWD system has also been fielded in cost-sharing efforts with an industrial partner to support the development of new generation hard-rock drag bits. To date, all field-testing of the DWD system has been performed at the GTI facility, but Sandia's Geothermal Research Department currently seeks an opportunity to field-test the system in an actual geothermal reservoir.

The DWD System

Major components of the DWD system include the downhole measurement sub, the data link between the downhole sub and the surface, and the data display system used at the surface.

Downhole Measurement Sub

Of the many possible downhole measurements, current sub design focuses on measurements of forces and accelerations associated with bit dynamics. The DWD sub measures:

- Three-axis acceleration
- High-frequency axial acceleration
- Angular acceleration
- Rotary speed (by magnetometer)
- Weight on bit (WOB)
- Torque on Bit (TOB)
- Bending moments
- Drill pipe and annulus pressure
- Drill pipe and annulus temperature

The DWD sub is a 7-in outside diameter tubular tool about 85-in long. The WOB, TOB and bending are measured with strain gages bonded to a reduced-diameter section of the outer body of the tool and protected with "clamshell" type covers. Electronics and the remaining sensors are contained in a concentrically located electronics package, with an annular flow path between it and the outer case. The electronics package accepts the analog sensor outputs, provides signal conditioning, converts the signals to a digital format, and transmits the data uphole. A schematic of the DWD sub is shown in Figure 1.

By design, no data processing occurs within the DWD sub. An early development decision was that all data processing would occur uphole on raw, transmitted data, thus avoiding the problems of placing temperature-sensitive computing power downhole, and providing the capability of changing data processing on the fly.

Data Link

A wide range of established data transmission methods was reviewed. Because the digital data rate supplied by the DWD sub is about 200,000 bits per second, standard mud-pulse data transmission was inadequate. Other data transmission methods reviewed by Sandia were either insufficiently developed or inadequate for the required data rates, with the exception of a commercially available data link called wet-connect wireline. For this reason, we chose this technology for the prototype DWD system. The wet-connect wireline is a conventional single-conductor cable with connections that can be made and broken while immersed in drilling fluid. The wireline system also incorporates one or more electrical swivels that allow the lower portion of the wireline to rotate relative to the upper portion while maintaining electrical continuity. This system has several advantages: it is commercially available with a substantial operating history, it allows the measurement sub to be powered from the surface, wireline components are already qualified for operation at over 200 °C and that limit could be raised fairly easily, and it does not significantly alter normal rig operations. There are, however, certain disadvantages: many operators have severe prejudice against having wire in the pipe while drilling (although the system is already used for directional drilling with air), there are additional operations during drillpipe handling (although the wireline added less than five minutes to connection time), data rate may be reduced at long wireline lengths, and there is a rental cost for the equipment.

The eventual solution for a data link may be a concept that several service companies are currently pursuing, namely the development of wired pipe with the data transmission medium incorporated into the drill pipe body. Some of the proposed designs for wired pipe will allow powering the measurement sub from the surface, but for the versions that will not accommodate this, batteries will be added to the sub. Sandia is cooperating through non-disclosure agreements with several manufacturers that are pursuing wired-pipe development and we plan to incorporate this technology into the DWD system when it is available.

Data Display System

The data display system used at the surface not only provides the driller and/or drilling engineer with an integrated, real-time display of surface and downhole data but records and archives all the raw data sent both from downhole and from surface equipment. In addition to these numerical input data, anyone with access to the data system can submit real-time comments about operational conditions, anomalies, and drilling-procedure changes that are entered, displayed, and recorded with the data system. This is a significant task in that the downhole data are transmitted as a digital telemetry stream with most of the individual measurements being sampled about 1000 times/second (some channels have higher rates and some lower). The data from surface equipment, however, can be acquired in many different formats, depending on individual rigs and their instrumentation. At the Catoosa test site, where we have done all the drilling tests to date, surface-equipment data is in analog form sampled at a rate of 10 to 65 samples/second/channel. Although not all the following measurements are taken at Catoosa, the data-display system should be capable of recording and displaying the following measurements:

- WOB
- TOB

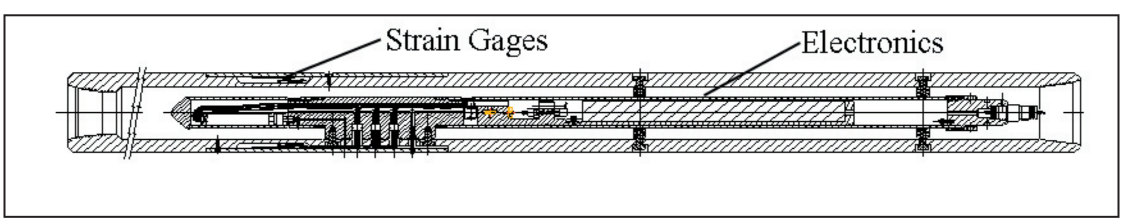

Figure 1. Layout of DWD measurement sub.

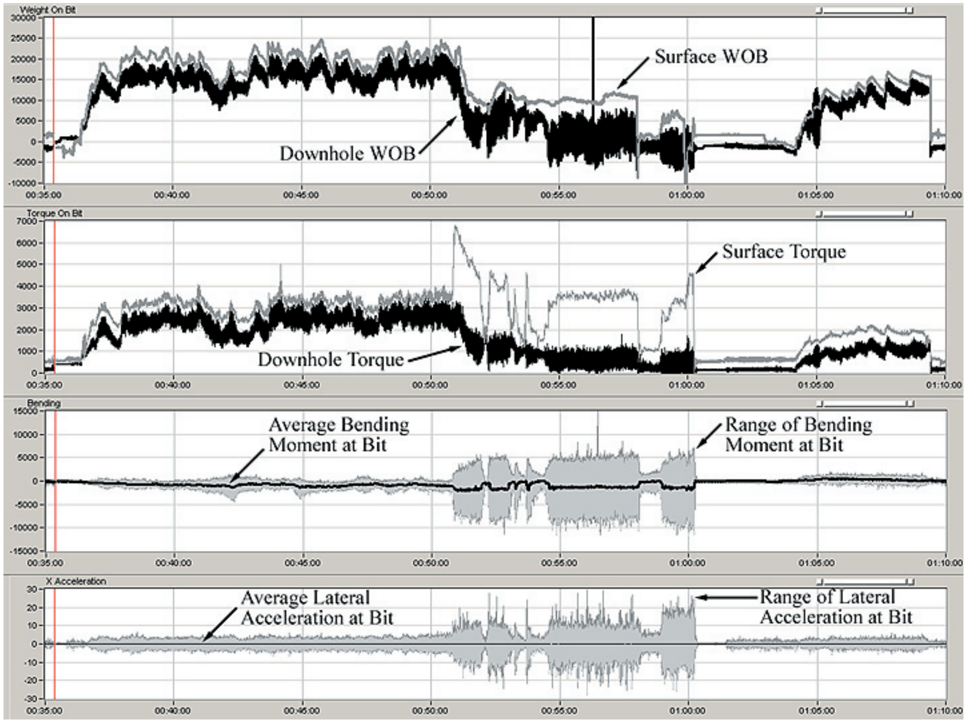

Figure 2. Overlay example of surface and downhole data.

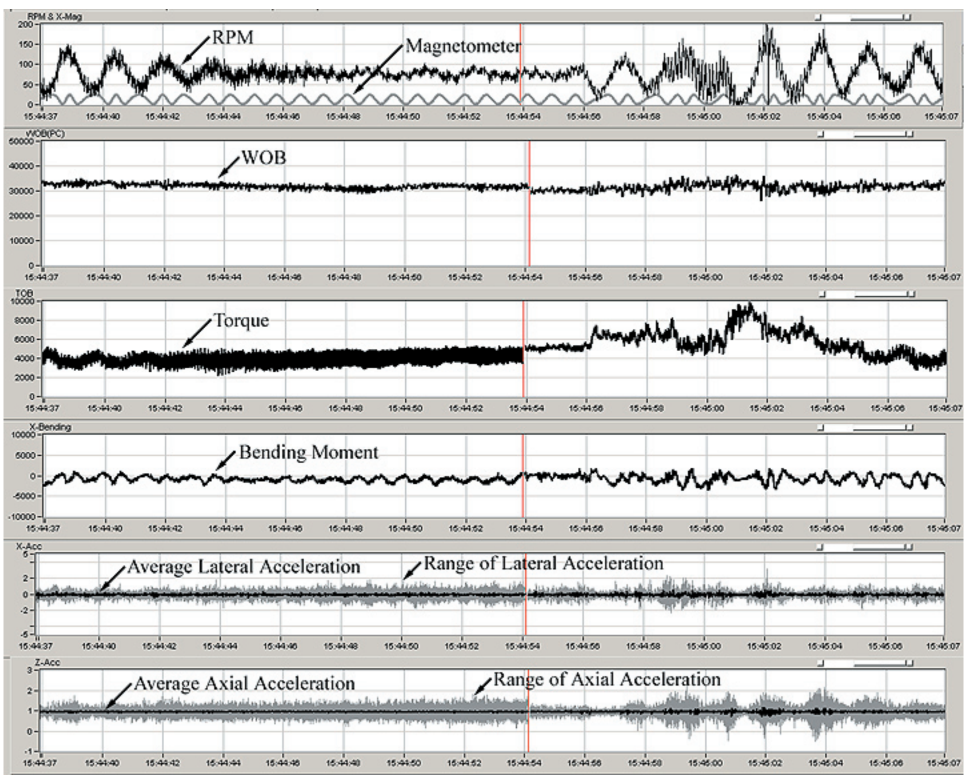

Figure 3. Strip charts of downhole data showing bending in phase with rotation of bit (magnetometer signal).

- Rotary speed
- Depth
- ROP
- Standpipe pressure
- Inflow (magmeter)
- Pump strokes
- Outflow
- Block height
- Pit level(s)
- Mud density
- Flow line temperature
- Hook load

Data acquired from the downhole tool or from the surface equipment can be presented in various user-selected formats to accommodate the driller's preferences. These formats include numeric displays, time-based strip charts, Fast Fourier Transforms of any downhole data channel, and cross plots of different downhole channels (e.g., X-acceleration vs. Y-acceleration). Surface readings can be overlaid on downhole measurements (e.g., surface and downhole WOB readings can be displayed on the same strip chart at the same time, as in Figure 2). This significantly improves our ability to diagnose drag-bit operational problems, such as those arising when significant weight or torque applied at the surface does not reach the bit. A system that requires one to mentally compare separate displays is not practical for the driller who must understand this information at a glance without losing focus on the second-by-second operations of the rig. The data system also allows different displays on different monitors, so that users can select preferred quantities to display at the driller's console, in the doghouse, or in a consultant's trailer.

Discussion of Acquired Data

The basic plan for the DWD Proof-Of-Concept and subsequent bit tests was to use a knowledgeable drilling engineer to interpret the data and make recommendations to the driller. This was always seen as a developmental step, however, because the best use of DWD data is to provide a display directly to the driller, allowing him to avoid drilling problems and maximize performance. Sandia and our industry advisors had considerable debate as to how this should be done, with strong opinions expressed by our advisors that anything more than a "stoplight" system would be unappreciated. Our experience has been to the contrary.

The basic real-time displays developed for the knowledgeable drilling engineer included strip charts of signals vs. time (Figure 3), cross plots, Fast Fourier Transforms (FFTs) dis-

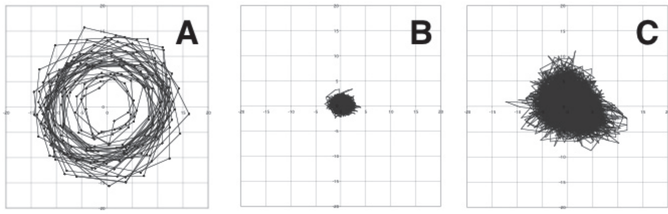

Figure 4. Laboratory accelerations during whirl (A), field accelerations during whirl (B), field accelerations during no whirl (C).

played as magnitude vs. frequency, and cross plots of measured parameters such as X- vs. Y-acceleration (Figure 4) or X- vs. Y-bending. Cross plots are useful for detecting whirl. Two conflicting requirements in displaying the data are the need to see both high-resolution details of current conditions, as well as long-term trends. These requirements were met by simultaneously displaying both 30- and 300-second traces. While the 30-second traces are not fast enough to show every vibration detail, they do allow one to see motion that is in step or phase with the rotation of the bottom-hole assembly (BHA); for example, note the similar shapes of the magnetometer and bending traces on Figure 3. Faster motion is better interpreted not by strip charts of signal vs. time, but by looking at signals that have been Fourier transformed to the frequency domain, where plots of transform amplitude vs. frequency show the spectral content of the signal.

Initially we placed all displays in the doghouse, but at the request of our bit-company partners we placed a monitor with strip chart displays on the rig floor. We found that the driller's intuitive understanding of vibration allowed him to interpret the strip charts without any special training. For example, when the RPM fluctuates, going to zero, one has stick-slip motion (as seen in Figure 3) or high-frequency BHA oscillations (also shown in Figure 3). Not only was the driller able to recognize dysfunction, the driller could differentiate between dysfunctions that were not even detected on the surface. In short, the driller found that DWD strip chart displays improved drilling.

As our ability to display cross plots in real-time improves, we anticipate the same favorable response to cross plots that the strip charts have received. FFTs will be another story. Even to the knowledgeable drilling engineer, a FFT is not intuitive without additional information – the modes of vibration of the system. As such, the proper use of frequency information will probably involve artificial intelligence that recognizes the mode and notifies the driller; e.g., BHA torsional oscillation vs. winding and unwinding of the full drill string.

Further discussions of dysfunctions, including whirl, bending, torsional oscillations, chatter, poor startups (seating the bit in the rock), and drill-offs can be found in Mansure, et al. [2003].

DWD Application Example

One of the driller's major problems is that sometimes surface measurements and "feel" do not give the whole/true picture of what is happening downhole. At the end of the first Proof-Of-Concept test (when the driller did not see the

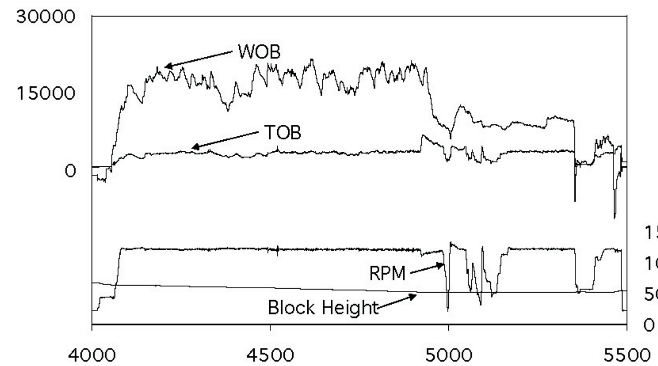

Figure 5. Surface data for the end of first Proof-Of-Concept test.

DWD data) the driller was making good hole -- 48 feet/hour with ~20,000 lbf WOB and ~3,000 ft-lbs TOB -- without the benefit of DWD. The driller was monitoring progress with the traditional console displays of surface WOB, TOB, block height, and ROP. If there had been strip chart displays of these surface-based parameters, he would have seen information like that in Figure 5.

Suddenly, however, the rig started shaking and torque jumped to ~7,000 ft-lbs. The driller let the weight drill off to ~10,000 lbf and ROP dropped to zero. The driller attempted to smooth out the vibrations by adjusting the RPM. After the driller picked up off bottom and the vibrations appeared to smooth out, he re-applied weight; drilling again became rough, and no additional hole was made.

An overlay of DWD data with surface data, during the aforementioned event, clarifies that these effects were caused by whirl (Figure 2). A telltale clue is when the surface torque jumped up, the downhole torque did not increase (the extra torque was absorbed by drag above the DWD tool). While the surface WOB drilled down to ~10,000 lbs, the downhole WOB and TOB drilled off even more with the downhole WOB at times falling to zero. (This "chatter" at very low WOB was likely the cause of cutter damage that ended the test.) Lateral shocks and bending also increased at this time. Rotary speed and axial shock levels, however, did not change significantly.

While the driller followed what was considered good practice for reducing vibrations, namely reducing RPM, picking up off bottom, and restarting drilling, the DWD tool proves these actions were insufficient. Note that when the driller picked up off bottom, the DWD tool showed that the bottom of the BHA was in tension. The tension remained even when the driller attempted to apply weight. Clearly the BHA was in a severe state of "drag" or dynamic sticking. That is, while the driller could pull the BHA off bottom, drag was not eliminated.

Taken together, these data show that the driller could have been guided by DWD to lift off bottom, completely stop drill string rotation and, if necessary, work the drill pipe to free the BHA. Drilling should not have resumed until the BHA could be moved without excessive drag.

Current Development Efforts

The goal for the prototype DWD system was to prove the viability of the concept, while in turn supporting other Sandia research programs. Because this was already a complex development, we elected not to address the even more challenging geothermal application in the prototype. Major updates to the DWD system, directed toward use in the geothermal environment, are under way. These system updates include development of a high-temperature (HT) 225 °C measurement sub and improved integration of the surface display system.

Currently, designs are being refined for a 225 °C measurement sub. The target design temperature for the measurement sub is dictated by the availability of the necessary electronics and sensors. Plans for higher temperature tools will be pursued as components become available. The design temperature for the measurement sub is based on at least three principal components: seals, sensors, and electronics. All seals in the measurement sub are static, and operation at 225 °C does not appear to be a problem. Most of the accelerometer, pressure, and magnetometer requirements for higher temperature can be met, although accuracy may be less than the present system. Details associated with mounting high-temperature strain gages are unclear and this question will be resolved during near-term development. HT electronics for signal conditioning, A-to-D conversion, and data transmission will probably be based on in-house Sandia design and technology, and may require a lower data rate than the present system. If the DWD system eventually uses wired pipe that will not transmit power from the surface, then the sub will also need HT batteries, and this could be a major development effort.

The refined data system, compared to the prototype, allows greater integration of the disparate data streams, and because all raw data are archived, post-processing can be done in any format the analyst wishes. There is an extensive menu of different measurements that can be displayed directly, but we can also display "virtual" channels that are generated by calculation or manipulation of a data channel (e.g., a crude measure of drilling efficiency is to divide rate of penetration by the product of weight-on-bit and rotary speed – this quantity can be displayed, in real time, as one of the virtual channels.) We have spent the bulk of our analytical effort in trying to correlate drilling dysfunctions with the data collected during the field tests, believing that the data signature of these dysfunctions is not always obvious, and that prompt recognition of the problem is crucial.

We believe that the data system is now very near complete as far as what we (Sandia) need for analysis and data playback, but we understand that something different will be more useful for the driller. If the driller has two fundamental questions – "am I drilling efficiently?" and "do I have, or am I about to have, trouble?" – then some other kind of display, almost certainly not a strip chart, will probably answer those questions more quickly and clearly. Further development of a "driller's" display will be an important component of Sandia's effort.

Other development effort is aimed at correcting relatively minor mechanical failures that occurred in the measurement sub during POC and CRADA testing [Finger, et al., 2003b]. The combination of modifications now under way will provide a more reliable system that will make downhole data even more useful and that will operate in a large fraction of current geothermal reservoirs.

Note: Sandia 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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