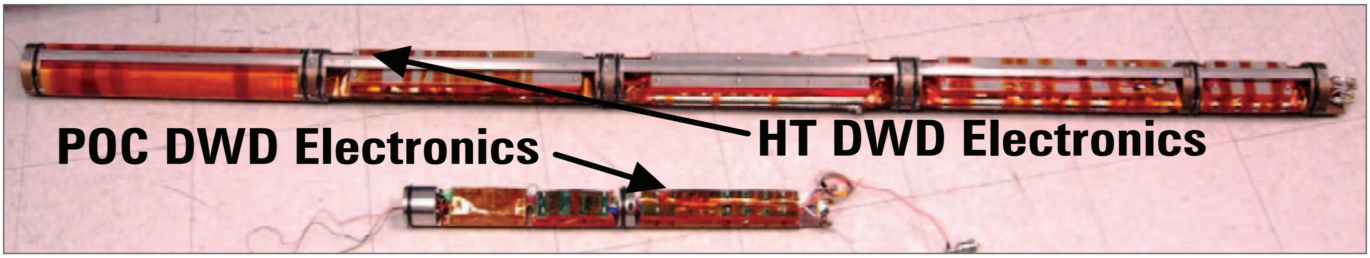

Figure 1: Physical comparison of the HTDWD electronics and the POC DWD electronics.

High-temperature diagnostics-while-drilling system provides data on drilling dynamics

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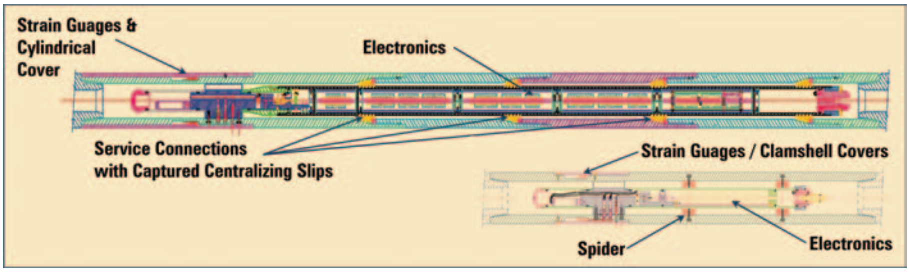

Figure 2: Comparison of the POC DWD tool (bottom) with the HT DWD tool (top). Slightly different scales were used for each drawing.

A HIGH-SPEED DATA link that would provide significantly faster communication from downhole instruments to the surface and back again has the potential to revolutionize deep drilling through Diagnostics-While-Drilling (DWD). Many aspects of the drilling process would significantly improve if downhole and surface data were acquired and processed in real time at the surface and used to guide the drilling operation. Such a closed-loop, driller-in-the-loop DWD system would complete the loop between information and control and greatly improve the performance of drilling systems.

The envisioned benefits of DWD are based on the principle that high-speed, real-time information from the downhole environment will promote better control of the drilling process. Although in practice, a DWD system could provide information related to any aspect of exploration and production of subsurface resources, the current Sandia National Laboratories DWD system provides data on drilling dynamics. This particular set of new tools provided by DWD is expected to enable expedient detection of problems, reduce drilling flat-time and facilitate more efficient drilling with the overarching result of decreased drilling costs. In addition to providing the driller with an improved, real-time picture of downhole conditions, data from DWD systems provide researchers with valuable, high-fidelity data sets necessary for developing and validating enhanced understanding of the drilling process. Toward this end, the availability of DWD creates a synergy with other Sandia drilling programs, such as the hard-rock bit program, where the introduction of alternative hard rock-reduction technologies are contingent on the reduction or elimination of damaging dynamic effects.

Over a number of years, Sandia has evolved the DWD system from a low-temperature (LT) proof-of-concept (POC) tool to a high-temperature (HT) system capable of operation in up to 225°C environments. The system is comprised of the downhole tool, communication link, uphole electronics for decoding the signal and the Integrated Data Display System (IDDS). This article will describe relevant design characteristics and development efforts related to the downhole tool and highlight field experiences that demonstrate the value of DWD technology.

HT TOOL SPECIFICATIONS

Operating specifications:

• OD: 7 in. for use with 8 ½-in. bits

• Collapse/burst pressure: >10,000 psi; differential pressure: <5,000 psi.

• Impacts to ~200g.

• WOB: up to 80,000 lbs.

• Torque: up to 20,000 ft-lb.

• Designed to be powered by cable or separate battery pack.

• Rotary speed: 0-250 RPM and temperature to 225°C.

• Mud: nominally 500 gpm up to 600 gpm.

Measurement specifications:

• 14 channels simultaneous sampling >1,000 samples/second.

• WOB: ± 80,000 lbs; resolution better than 500 lbs.

• Torque: ± 20,000 ft-lb; resolution better than 200 ft-lbs.

• 2-axis bending: ± 20,000 ft-lb; resolution better than 200 ft-lbs.

•3-axis linear acc.: ± 30 g; resolution better than 0.05g.

•3-axis magnetometer: ± 2 Gauss; resolution target 0.001 Gauss.

• Internal and external pressure: internal 0➔5,000 psi; resolution ~1.2 psi.

• Internal and external temperature: 50➔225 °C; resolution better than ½°C.

DESIGN AND DEVELOPMENT

Designing a HT DWD tool with the functionality of a low-temperature tool was and, in many respects, continues to be a major challenge. In general, the design of HT electronics is an "art of compromise" due to the limited availability of

HT components. The HT electronics designer must make do with available components and contend with continuous change in the availability of HT components. In the POC DWD system, several “specialized” integrated circuits (ICs) were used to perform signal conditioning and filtering functions. Using such devices improved performance of the system and minimized the electronic board dimensions. The HT tool design, by contrast, was based on commercially available HT components. Signal conditioning circuits – such as instrumentation amps, charge amps, filters, etc. – were designed using the Honeywell HT1104 operational amplifier. Considerable space reduction could be realized if multichip modules (MCM) were designed and fabricated. For instance, the basic instrumentation amplifier and filter used throughout the tool could have been implemented as an MCM. This would have kept the footprint for this circuit about the same as that of the low-temperature components. However, due to the cost of producing MCMs and project time limitations, discrete components were utilized.

In addition to the paucity of HT electronics, the availability of HT sensors is also limited. With one exception, HT sensors were found and qualified that could replicate the POC sensor capabilities, albeit with some compromises. The missing sensor was an angular accelerometer. This measurement variable was an “extra” in the POC DWD system and therefore not critical to the tool’s functionality. The torque-on-bit (TOB) and magnetometer measurements proved a better way to assess rotational motion.

To provide similar functionality to the POC DWD system, the HT DWD electronics design consists of 7 separate boards, as well as dedicated space for transformers and a prototype HT magnetometer (the magnetometer alone is about 18-in. long). In the HT configuration, available components constrain sensor sampling to a multiplexing arrangement. The boards for the POC DWD tool are supported on one side of a 28-in.-long carrier that is in turn contained within a 2.25-in.-diameter pressure housing. Similarly, the HT DWD boards are supported on 2 sides of a 94-in.-long carrier. The HT carrier is also larger in diameter and housed in a 3.125-in.-diameter pressure housing. Figure 1 compares the sizes of the HT and POC electronics.

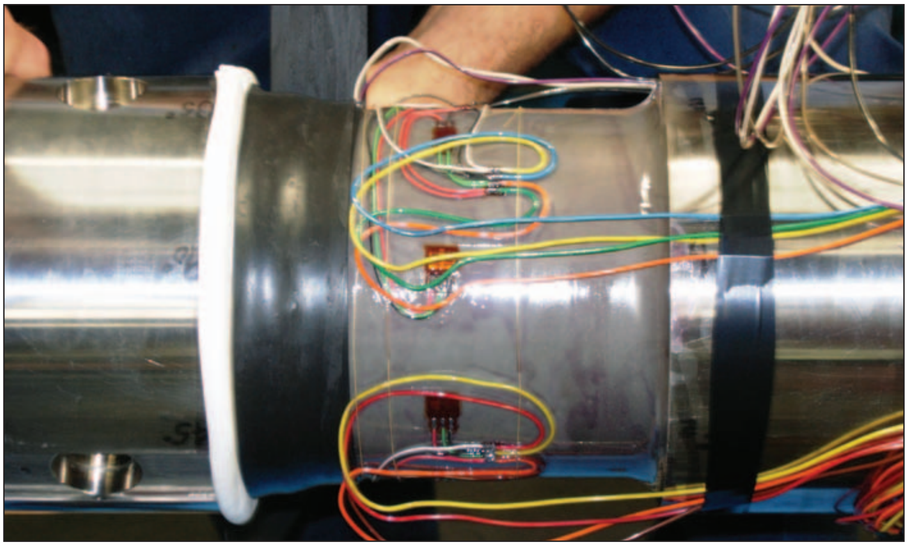

Figure 3: Strain-gauged portion of HT DWD tool gets wrapped with the uncured AFLAS material.

MECHANICAL DESIGN OVERVIEW

Mechanical design of the HT tool focused on 3 primary tasks: accommodating the expanded volume of electronics, hermetically sealing strain-gauged sections of the tool, and selection of elastomeric components suitable for high-temperature operation. The 7-in.-diameter of the POC tool was maintained in the HT tool design, necessitating a significant lengthening of the assembly. The final HT electronics carrier length of 94 in. resulted in a concentric pressure barrel assembly approximately 12-ft long with an associated outside tool body length of nearly 14 ft. Cross sections of the assembly drawings of the POC and HT DWD tools are shown in Figure 2. This tool length was problematic with regard to tool-handling and assembly, as well as stabilization of the internal pressure barrel while drilling. In order to ease the assembly process and to secure the long pressure barrel, a novel solution was developed that addressed both issues and eliminated the need for excess thru-holes used in the POC tool. This solution was to design and fabricate an outer tool body that was an assembly of 5 separate sections connected with 4 service connections. The use of service connections allowed for pressure barrel stabilization via a series of centralizing slips captured at each service connection. The centralizing slips eliminated the need for the bolt-thru "spider" assemblies used in the POC tool. Eliminating the spiders (and associated bolts) reduced the previously observed potential for wash-outs at these locations.

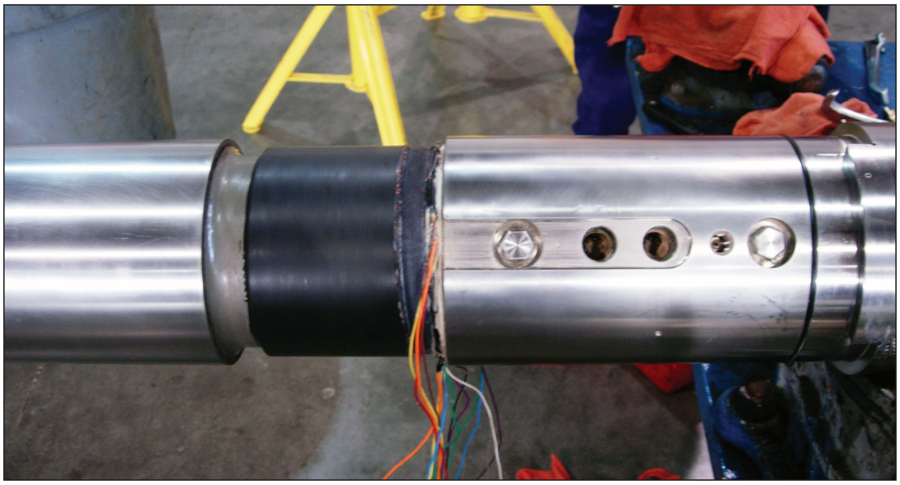

Figure 4: Strain-gauged section of HT DWD after curing of AFLAS encapsulant.

Hermetic sealing of the strain-gauged section of the tool was a significant challenge in the HT tool design and development. The primary seal for the POC tool over the strain gauges was a low-temperature multilayer coating, including various layers of epoxies, SC2000 cement and a Scotchcast 2130 overlay. This encapsulating material provides excellent adhesion to the tool body and is very effective at sealing the strain gauges and pass-thru wiring against fluid intrusion, but cannot perform at the design

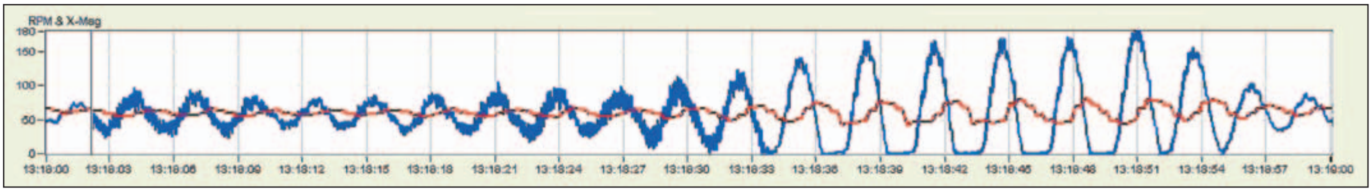

Figure 5: Downhole vs surface RPM showing stick slip.

environment for the HT tool (225 °C with exposure to steam and liquid phase wellbore fluids). An alternative sealing method was therefore required.

The effort to develop a workable encapsulating method for the HT DWD tool involved extensive investigations and testing of candidate materials and application methods. A variety of HT epoxies, silicones, elastomers and other organic materials were investigated for suitability to the required environment. These investigations included reviews of literature, discussions with topical experts, and numerous scoping tests of candidate materials. Associated with each candidate material, specific application methods were required, and these processes were also evaluated. The results of these efforts led to the selection of a process that involved the application of uncured AFLAS (a material similar to Viton but with higher-temperature capabilities) over the strain-gauged portion of the tool. The application process involved wrapping the tool with the AFLAS material followed by a curing sequence in low-pressure (<100 psi) autoclaves and ovens. Sandia worked extensively with a supporting supplier to develop an application methodology suitable for the HT DWD tool. Figure 3 shows the process of applying the uncured AFLAS, and Figure 4 shows the AFLAS encapsulant after the curing process.

While the AFLAS encapsulation method was eventually chosen, it was not an entirely satisfactory solution. Many preliminary tests on reduced- and full-scale samples showed that minor variations in application and curing could result in a substandard seal. While this encapsulation method worked in the recently completed field test, a more robust solution is required.

Another important undertaking in the HT DWD design was to identify and evaluate required elastomeric and non-metallic parts to determine their temperature limitations. Internal non-metallic parts (e.g., circuit boards) were upgraded in conformance with practices developed and proven as part of Sandia's high-temperature electronics program. Elastomeric parts, such as o-rings, exposed to the wellbore environment were identified and tested, not just for decomposition at temperature but also for hydrolysis. These evaluations showed the PEEK cable-head bodies and Viton boots to be adequate. Previously used silicone o-rings were found to be unacceptable; Viton o-rings were found to be marginal. All o-rings were replaced with AFLAS material.

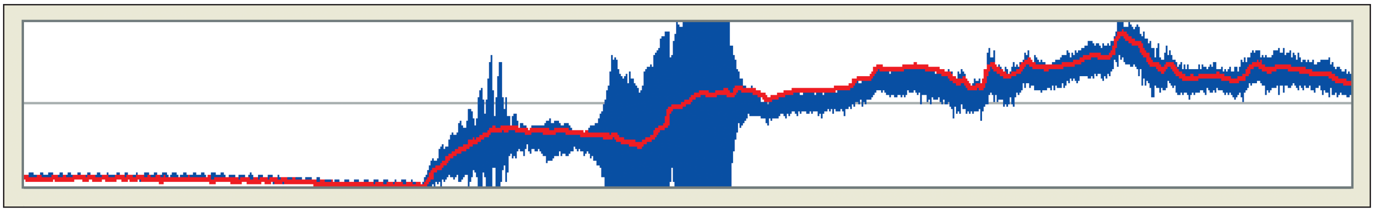

Figure 6: Surface WOB overlaid on top of downhole WOB during start-up.

DWD FIELD EXPERIENCES

The first-generation low-temperature (LT) DWD system was fielded in a series of proof-of-concept tests (POC) to validate functionality by comparing drilling with and without DWD. The LT DWD system was subsequently used to support a Cooperative Research and Development Agreement (CRADA) with 4 bit companies that involved testing of a PDC bit from each company in the same lithologic interval at the Gas Technology Institute (GTI) test facility near Catoosa, Okla. In addition, the LT DWD system has been fielded in cost-sharing efforts with an industrial partner to support the development of new-generation hard-rock drag bits. The HT tool was field-tested in partnership with **Ormat Industries** in a hard-rock geothermal environment at Steamboat, Nev., in 2005. Over the course of the field trials of this technology, numerous instances have emerged that indicate its value as a real-time downhole feedback source to the driller, as well as its enormous potential to further understanding of the drilling process by highlighting the relationship between surface and downhole behaviors.

The obvious benefit of DWD lies in its ability to characterize bit conditions that may be misinformed by surface conditions. In the initial POC tests, DWD proved its value by showing how standard drilling practice – after encountering whirl – can lead to bit damage by allowing the downhole weight to drill off. Without DWD, it is not possible to know if the WOB measured at the surface actually reaches the bit. In the subsequent CRADA, DWD was used to increase drilling performance by drilling to the edge of whirl without allowing bit-damaging axial bounce to occur. In addition to proving itself as a real-time drilling aid, DWD has proved valuable as a means of capturing data that can be used for subsequent analysis by providing an understanding of what can happen when the bit stalls.

Examples have also been found of how DWD can correct the presumption that downhole dysfunctions are present based on visible surface effects. It has long been understood that there can be severe downhole vibrations that dampen out as they travel up the drill string so that they are not felt on the surface. With DWD, it was observed that the opposite can also be true – that there can be severe surface vibrations of the drill string that don't propagate downhole. During one DWD test, surface vibrations were so severe that the driller had to back off to prevent damage to the rig. Downhole, however, the bit / BHA were running very smoothly. Without DWD, one might have been tempted to trip out and change the bit, an action that would have had no beneficial effect.

Driller acceptance and utilization of DWD-generated data have been surprisingly well-received in field trials. Significant effort has been expended over the years in the development of a real-time display system for DWD data. The design of this interface has always been guided by the idea that in order to be utilized effectively, it must be as intuitive as possible. This notion has been validated in field experiences with the rapidly adopted preference of the driller for DWD data for make drilling decisions.

Figure 5 illustrates an intuitive plot of downhole vs. surface RPM. No special training is required for the driller to understand that, downhole, the bit / BHA are in full stick-slip, the RPM coming to a complete stop; whereas, on the surface, the RPM fluctuates but the drill string does not stall. In this case, without DWD, the driller would be concerned about the fluctuating RPM but would believe that the downhole condition was not severe.

DWD has also demonstrated value as a training tool. It was found that even experienced drillers who had been coached had trouble smoothly engaging the bottom of the hole. There are different theories about how to engage the bottom of the hole when starting a new stand. With DWD, results of different start-up approaches can be compared with determine best practices. For example, it was found in field trials that there is a temptation during start-up to pause and check the status of other system components, such as mud pumps. This focus away from the bit can lead to drill off and bouncing if adequate weight has not been applied to keep the bit on bottom. Figure 6 shows that, based on surface data (red line), the driller thinks everything is OK. In reality the bit is bouncing off bottom.

CONCLUSION

In addition to a description of high-temperature tool development considerations, this article presented but a few of the examples of field experiences where DWD has proven its value. It is hoped that the development of DWD systems will continue to evolve and that industry will facilitate finding the appropriate niche for this technology. Early justifications for pursuing the development of a DWD system were based on the belief that the availability of real-time, high-rate data from the downhole environment would provide novel insights that could be used to significantly improve drilling operations and ultimately reduce drilling costs. Current efforts under way at Sandia National Laboratories have demonstrated the feasibility of developing DWD systems and have provided abundant field data demonstrating the potential of DWD data to have tremendous impact on the manner in which drilling operations are performed today.

AFLAS and Viton are registered trademarked terms.

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