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Development of a High-Temperature Diagnostics-While-Drilling Tool

Douglas Blankenship, David Chavira, Joseph Henfling, Chris Hetmaniak, David Huey, Ron Jacobson, Dennis King, Steve Knudsen, A.J. (Chip) Mansure and Yarom Polsky

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ABSTRACT

This report documents work performed in the second phase of the Diagnostics-While-Drilling (DWD) project in which a high-temperature (HT) version of the phase 1 low-temperature (LT) proof-of-concept (POC) DWD tool was built and tested. Descriptions of the design, fabrication and field testing of the HT tool are provided. Background on prior phases of the project can be found in SAND2003-2069 and SAND2000-0239.

ACKNOWLEDGEMENTS

Completion of the DOE JOULE milestone to develop and test a high-temperature DWD tool was possible only through the dedicated efforts of many people. The enthusiasm and support for this research by the Department of Energy has been critical to the success of the program in general. The entire Geothermal Research Department at Sandia contributed to the completion of the Joule milestone. The field tests would not have come to fruition without the support of a large number of suppliers and contractors, and a hearty “thanks” is extended to all those who supported this effort. Lastly, this demonstration would not have been possible without the cooperation of ORMAT, who not only allowed an interruption of their drilling activities but also enthusiastically supported our efforts during the conduct of this test.

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1 INTRODUCTION

The envisioned benefits of Diagnostics-While-Drilling (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 DWD system provides data on drilling dynamics. This particular set of new tools provided by DWD will allow quicker detection of problems, reduce drilling flat-time and facilitate more efficient drilling (drilling optimization) with the overarching result of decreased drilling costs. In addition to providing the driller with an improved, real-time picture of the drilling conditions downhole, data generated from DWD systems provides 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 Geothermal programs, such as the hard-rock bit program, where the introduction of alternative rock-reduction technologies are contingent on the reduction or elimination of damaging dynamic effects. More detailed descriptions of the rationale for the program and early development efforts are described in more detail by others [SAND2003-2069 and SAND2000-0239].

A first-generation low-temperature (LT) DWD system was fielded in a series of proof-of-concept tests (POC) to validate functionality. Using the LT system, DWD was subsequently used 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., 2003, 2004] in the same lithologic interval at the Gas Technology Institute (GTI) test facility near Catoosa, OK. 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.

Following the demonstrated success of the POC DWD system, efforts were initiated in FY05 to design, fabricate and test a high-temperature (HT) capable version of the DWD system. The design temperature for the HT DWD system was 225°C. Programmatic requirements dictated that a HT DWD tool be developed during FY05 and that a working system be demonstrated before the end of FY05.

During initial design discussions regarding a high-temperature system it was decided that, to the extent possible, the HT DWD system would maintain functionality similar to the low temperature system, that is, the HT DWD system would also be designed to provide the driller with real-time information on bit and bottom-hole-assembly (BHA) dynamics while drilling. Additionally, because of time and fiscal constraints associated with the HT system development, the design of the HT DWD tool would follow that of the LT tool. The downhole electronics package would be contained in a concentrically located pressure barrel and the use of externally applied strain gages with thru-tool connectors would also be used in the new design. Also, in order to maximize the potential wells available for the HT DWD system and to allow better comparison with the low-temperature design, the diameter of the tool was maintained at 7". This report discusses the efforts associated with the development of a DWD system capable of sustained operation at 225 °C.

2 SYSTEM SPECIFICATIONS

The system is comprised of the downhole tool, communication link, uphole electronics for decoding the signal and the Integrated Data Display System (IDDS). This report focuses on the downhole package.

As stated previously, the HT tool was developed with the intention of maintaining the same functionality as the LT tool. The tool is therefore instrumented to measure the loads and motions characteristic of drilling dynamics. Detailed operating and measurement specifications are provided below.

OPERATING SPECIFICATIONS:

- OD: 7” for use with 8-½” bits
- Collapse/burst pressure: >10,000 psi.; Differential pressure: <5,000 psi.
- Impacts to ~200g.
- WOB: up to 80k lbs.
- Torque: up to 20k ft-lb.
- Designed to be powered either by cable or separate battery pack.
- Rotary speed: 0-250 RPM, & Temperature: <225°C.
- Mud: nominally 500 gpm up to 600 gpm, <10 lb./gal, no barite.

MEASUREMENT SPECIFICATIONS:

- 14 channels simultaneous sampling >1000 samples per second.
- WOB: ±80,000 lbs; resolution better than 500 lbs ($60,000/2^{11} \approx 30$ lb/bit using 12 bit A/D).
- Torque: ±20k ft-lb; resolution better than 200 ft-lbs ($20,000/2^{11} \approx 10$ ft-lb/bit).
- 2-Axis Bending: ±20k ft-lb; resolution better than 200 ft-lbs ($20,000/2^{11} \approx$ 10 ft-lb/bit).
- 3-axis Linear Acc.: ± 30 g; resolution better than 0.05g ($30/2^{11} \approx 0.015$ g/bit).
- 3-axis Magnetometer: ± 2 Gauss; resolution target 0.001 Gauss ($2/2^{11} \approx$ 0.001 Gauss/bit).
- Internal & External Pressure: internal 0 → 5,000; resolution target 1.2 psi ($5000/2^{12} \approx 1.2$ psi/bit)
- Internal & External Temperature: 50 → 225 °C; resolution better than 0.5 °C ($175/2^{12} \approx 0.04$ °C /bit).

With the exception of the magnetometer and pressure sensors, the theoretical resolution, defined as the span divided by the number of bits, was sufficiently less than the desired resolution to allow for significant noise in the circuit. In the case of the magnetometer and pressure sensors, the inherent noise in the circuit was sufficiently low that the A/D was the limiting factor and the system appeared to meet the target resolutions.

3 HT TOOL ELECTRONICS DESIGN AND DEVELOPMENT

3.1 Design Considerations

Designing a HT DWD tool with the functionality of the POC LT DWD system was 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 the continuous change in the availability of HT components. In the POC DWD system, several "specialized" IC were used to perform signal conditioning and filtering functions. Using such devices improves performance of the system and minimizes the electronic board dimensions. The HT design 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. Due to the cost of producing MCM's and project time limitations, it was decided to use discrete components.

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 functionality of the tool. The torque-on-bit (TOB) and magnetometer measurements proved to be a better way to assess rotational motion.

In order to provide similar functionality to the POC DWD system, the HT DWD electronics design consists of seven separate boards as well as dedicated space for transformers and a prototype HT magnetometer (the magnetometer alone is about 18" 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 inch-long carrier that is in turn contained within a 2.25 inch-diameter pressure housing. Similarly, the HT DWD boards are supported on two sides of a 94 inch-long carrier. The HT carrier is also larger in diameter and is housed in a 3.125 inch-diameter pressure housing. A photograph comparing the HT and POC electronics is provided in Figure 1.

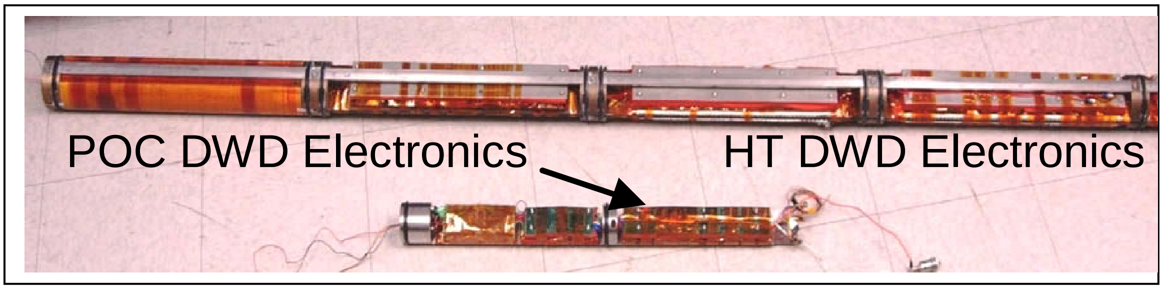

Figure 1 Physical comparison of the HTDWD electronics and the POC DWD electronics.

All electronics and sensors used in the HT DWD system were subjected to extensive testing before selection for use in the tool. Components were subjected to temperatures in excess of 225°C in both static conditions and in combination with vibrational loading. In addition to the testing of individual components, the populated circuit boards were also subjected to vibration and temperature loading to evaluate the completed circuitry and to test all interconnects.

Sandia uses qualified HT components whenever possible for the development of HT tools. In recent years, Sandia HT tools have used the Honeywell HT chipset consisting of the microcontroller (83C51), the Sandia designed ASIC (HT83SNL00), and memory (HT6256) as the heart of the tool [Henfling et al, 2004]. Due to the desired data rate of 200k bits/second, the Honeywell microcontroller was not adequate. Since the operating temperature for this tool was specified as 225°C, it was possible to use a Field Programmable Gate Array (FPGA) to replace the functionality of the Honeywell HT chipset and achieve the desired data rate. The FPGA makes the A/D readings and formats the data for transmission to the surface. While this device is not suited for extended operation at 225°C, it is acceptable for a drilling tool that has a limited exposure to the high temperatures (in contrast to a reservoir monitoring type tool). It does consume approximately twice the current at 225°C that it does at ambient temperatures, but remains stable and is adequate for this application. Actel Corporation manufactures radiation hard and radiation tolerant devices. Unfortunately, Actel only packages these devices in a surface mount flat package with only 0.012” lead spacing. After many tests, it was determined that using these packages with high temperature lead-based solders would not have the reliability needed for a drilling tool. The leads were very susceptible to damage and after temperature cycling, the leads would separate from the pads resulting in unacceptable performance. The only package that was suitable for operation in a drilling environment was a ceramic pin grid array (military temperature range). This 84 pin device proved to be adequate for the tool requirements. It was tested for 300 hours at 225°C with no failure and no increase in current consumption. Another approach would be to have a company such as Texas

Components package the radiation hard (or radiation tolerant devices) into a suitable downhole package. Due to the cost and time constraints, this was not a viable option.

As previously mentioned, one of the challenges of designing the electronics for this tool was the limited selection of high temperature components. A seemingly endless selection of specialized ICs is available to meet the needs of most applications when designing circuits using conventional electronics. HT circuit design requires "getting back to the basics" and designing circuits using discrete components. For example, the only qualified op amp at the time this tool was designed was the Honeywell HT1104. Many circuits were designed using this device including: 1) instrumentation amplifier (strain gage, temperature and pressure), 2) charge amplifier (HT accelerometers), 3) level shifting (strain gages) and 4) low pass 4 pole filter (all measurements). Although compromises are inevitable, all of the requirements for this tool could be met using HT qualified SOI (Silicon on Insulator) components (with the exception of the FPGA).

3.2 Electronic Boards

The electronic boards were fabricated using polyimide (Arlon 45) with nickel followed by gold plating over the copper traces. Multilayer Prototypes Inc. was selected to manufacture the boards. The fabrication process and board materials used in this tool were successfully used by Sandia for logging tools built in recent years. Unfortunately, an anomaly was experienced late in the testing phase of this tool. During one of the test sequences, a faulty circuit was discovered and its cause was identified as a fractured trace in one of the inner layers of the board. The reason for this failure was not apparent. After the initial anomaly, a few additional failures surfaced on the aforementioned board and later on four other boards that were manufactured at the same time (using the same material "batch"). It does not appear the trace failures can be attributed to environmental factors. The same environmental testing procedure was performed on many preceding boards without trace failures. The faulty boards were dissected and examined, however, no definitive cause was found. Unfortunately, this anomaly did not surface until the planned field deployment was only a few weeks away. Due to time constraints, a complete set of new boards could not be assembled, tested and installed in the tool in time to meet programmatic milestones. Of the seven required electronic boards, one of the more crucial boards was reordered and installed in the tool. To date, this newly fabricated board does not exhibit these anomalies. Four of the six remaining electronic boards required the implementation of in-house "3-D" fixes on the offending parts. The fifth and sixth boards were manufactured in a separate fabrication run and did not exhibit this anomaly. While the trace failures were limited and rare, they did cause a significant concern during the testing phase of the project. To date, it is believed the trace failure may be attributed to the particular "batch" of boards, but the exact cause is still unknown.

After discussions with Multilayer Prototypes Inc., the board manufacturing procedures have been modified by changing the amount of copper from 1 oz to 2 oz finished copper weight for the outer layers, thereby increasing the amount of copper in the thru holes. 1 oz of copper was maintained for the inner traces. A pre-bake procedure has also been implemented prior to board assembly. The procedure consists of heating the unassembled boards at 125°C for a minimum of 8 hours just prior to board assembly. Although not likely, a possible cause for the trace breakage could have been linked to “trapped” moisture in the boards.

The electronic package for the DWD tool consists of seven boards plus room for transformers used in the DC-to-DC converter and in the data transmission circuits. A brief description of the boards and their function follows:

Strain-gage signal conditioning board (2 required)
This board has an instrumentation amplifier, 4-pole Sallen-Key Butterworth filter and level shifter circuits for the weight-on-bit (WOB), torque-on-bit (TOB), X bending and Y bending strain gage measurements. These high gain boards were physically located as close to the strain gages as physically possible.

Sensor conditioning board (2 required).
This board has circuits that include instrumentation amplifiers, filters, charge amplifier, and level shifters. The bulk of the measurements are conditioned using this board.

Analog/Digital board – Primary measurements
This board consists of the Honeywell 12 bit A/D converter, Honeywell HT506 multiplexer, and the FPGA. All of the 21 measured parameters are made using the A/D on this board. The 10 primary channels are connected to the multiplexer on this board and include the following measurements: WOB, TOB, X bending, Y bending, pressure outside the drill pipe, X and Y magnetometers, and X, Y and Z accelerometers. The data sampling rate for the primary channels is 1040 Hz.

Multiplexer board – secondary measurements
This board consists of a multiplexer that is controlled by the FPGA located on the analog/digital board. All of the secondary measurements are taken on this board and the output signal is routed to a channel on the analog/digital board. A measurement from this board is taken before every data set of the primary channels. In other words, the secondary measurements are sampled approximately 1/16 the rate of the primary channels (65 Hz). The exception is the secondary accelerometer channels which are sampled at twice the rate of the secondary channels (130 Hz). The secondary channels consist of: temperature inside and outside the drill pipe, board temperature, pressure inside the drill pipe, temperature measurements for both pressure transducers, Z magnetometer, and the X,Y, and Z “over range indicator” accelerometers.

Power supply board
This board contains the circuits to generate the negative 5 volt supply required for the magnetometer, and the positive 5 and 12 volts used throughout the tool. It also contains the drive circuit for transmitting the data signal to the surface (The transmitted data signal originated in the FPGA).

3.3 Sensors

The following is a list of sensors used in this tool. With the exception of the strain gages, all were tested and qualified as outlined above. The strain gages were evaluated during the mechanical system tests described in the mechanical design section of this report.

Pressure – Paine Inc. pressure transducers.
Pressure measurements were taken both inside and outside the drill pipe. Paine has designed a pressure transducer for continuous operation up to 275°C. The part number for the transducer is 211-50-050-01-S. These units were tested with favorable results. Figure 2 shows the output drift vs. time data from a month-long oven test at 225°C.

Temperature – RDF Corporation.
A Resistive Temperature Devices (RTD) was used to measure temperature both inside and outside of the drill pipe. These devices were successfully tested for continuous operation over a period of years.

Magnetometer, 3-axis – Diamond Research Company.
The gated integration fluxgate high temperature magnetometer was designed using primarily HT components and was lab tested to 225°C. It was designed for MWD tool applications and is well suited to meet the tool requirements. The main function for this sensor is to determine the downhole rotational speed of the drill pipe. This sensor performed very well both in lab and the field tests.

Accelerometers, 3-axis – Endevco Corp.
Three single axis accelerometers, model number 7401-100, were used for the primary accelerometer measurements. A 3-axis accelerometer, part number 2230E, (with considerably less sensitivity) was also used to determine an “over range” condition. Due to the limited sensitivity of the 12 bit AD converter, the gains for the primary accelerometer channels were optimized for the expected drilling accelerations that are normally encountered downhole. The addition of the 3-axis accelerometer enabled a means to provide accelerometer data in the event the expected accelerations were exceeded. Figure 3 shows the output of one of the primary accelerometers during a test where the electronics and the sensor were operating under vibrational accelerations of ± 8 g at 225°C.

Strain gages – MicroMeasurements.

Strain gages are used to measure downhole weight-on-bit (WOB), torque-on-bit (TOB), X bending and Y bending. The gages worked well both in the lab and during the field test. The difficulties encountered with sealing the strain gages from the wellbore fluids are covered under the mechanical system details.

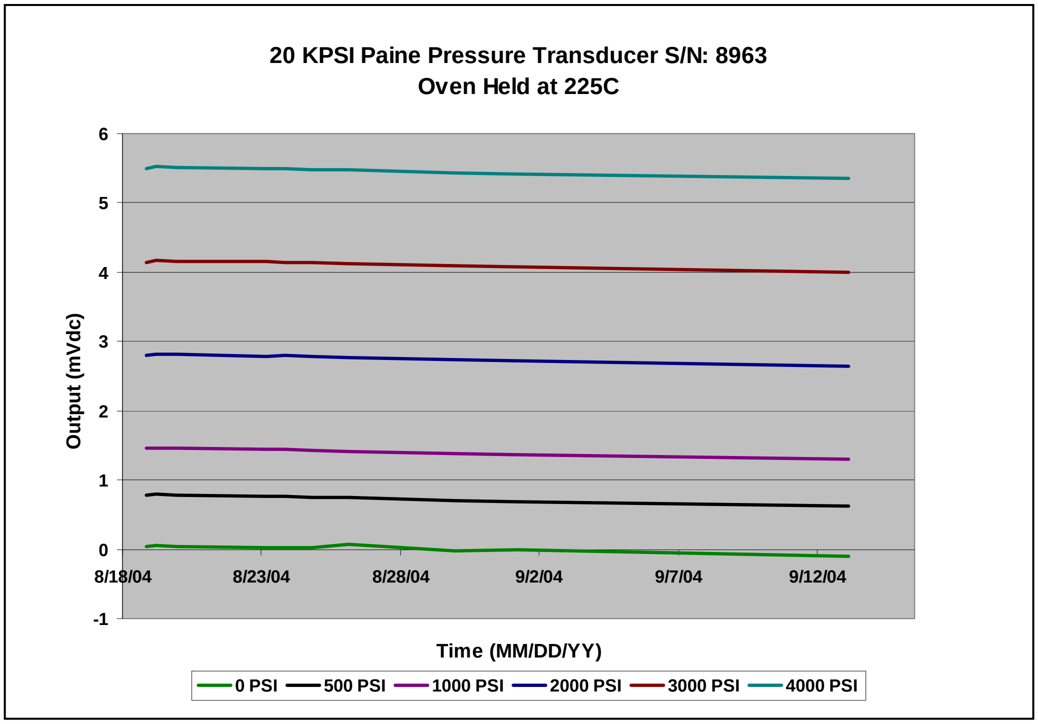

Figure 2 Test results depicting the output voltage drift vs. time of the Paine pressure transducer.

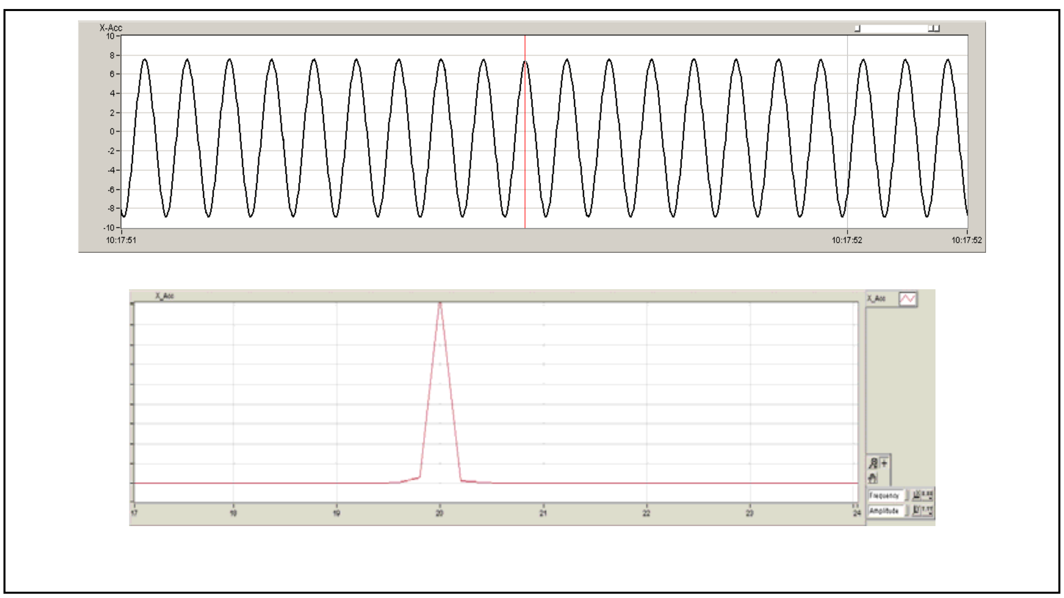

Figure 3 Test data results while both the electronics and the sensor were at 225°C under vibrational accelerations of ±8 g's at 20 Hz.

3.4 High Temperature Soldering and Soldering Techniques

The solder utilized for all of the electronic assembly has a melting point (solidus temperature) of 298 °C, a diameter of 0.025”, and has an activated rosin flux core. It contains 93.5% lead, 5% tin, and 1.5% silver. The part number for the solder is 570-25R and is available from MicroMeasurements.

Two fluxes were used with this solder. Nickel plated copper wires such as the board interconnect wiring and the strain gages required a highly active acid flux. The MicroMeasurements M-Flux SS worked very well for this application. It is worth noting that flux residue can cause degradation of the solder joint. Also, flux residues that are not cleaned from surfaces near the soldering process can cause degradation of protective coatings (i.e. strain gages) or corrosion of metals near the solder points. In addition to the corrosiveness, the conductive flux can also cause circuit errors if not carefully cleaned. The remainder of the soldering utilized MicroMeasurements M_Flux AR flux, an active but non-corrosive flux. This flux worked fairly well, but also required immediate cleaning to avoid degradation of the solder joint at elevated temperatures.

Soldering techniques used during assembly of the electronic boards involved heating the boards while assembling them in order to reduce the thermal stresses induced both during the soldering process and following the tools excursion from ambient to application operating temperature. A pre-heat temperature of 125°C was selected as an approximate mid-point between ambient and the intended operating temperature of the boards (225°C). A hot plate with a custom-built board-holding fixture was used to keep the board as close as possible to the heated surface without making direct contact in order to ensure an even heating pattern.

3.5 Board Testing

All boards were evaluated for adequate performance prior to the final assembly of the complete electronic package. An example depicting the low pass filter response versus temperature is shown in Figure 4 and its characteristics at 230°C are shown in Figure 5. The qualifying of the electronic boards consisted of performing the following tasks: 1) perform the initial bake out of the board at an oven temperature of 150°C for a minimum of 12 hours, 2) identify any defects and perform burn-in tests for the board and components by heating it from ambient to 230°C while monitoring the circuits on the board for proper operation for a minimum of 12 hours, and 3) simulate the drilling environment by heating the board from ambient to 225°C and then subjecting it to vibrational loads consisting of a random shake test of ± 2 g from 10 to 500 Hz for a minimum of 1 hour and a constant frequency shake test at set frequencies of 2, 5, 17, 20 Hz with a vibrational load between ± 5-8 g’s. The duration at the set frequencies was approximately 15 minutes. An argon gas flow across the board under test was used in all of the above tests. The “shaker” oven with one of the signal conditioning boards is shown in Figure 6.

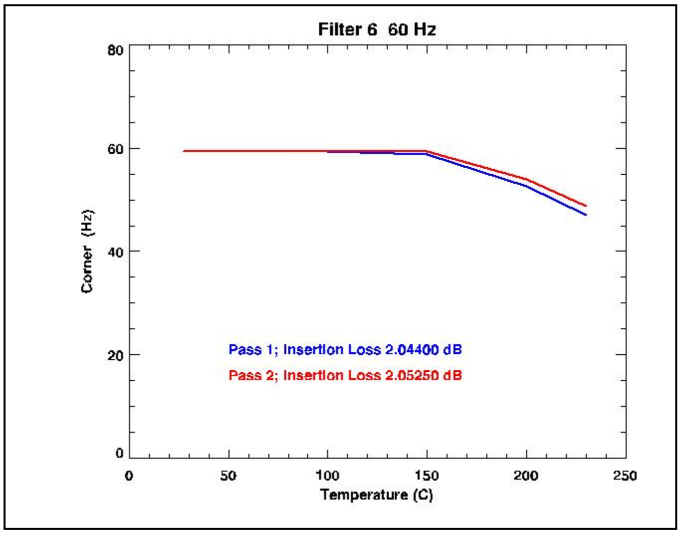

Figure 4 4-pole filter response vs. temperature.

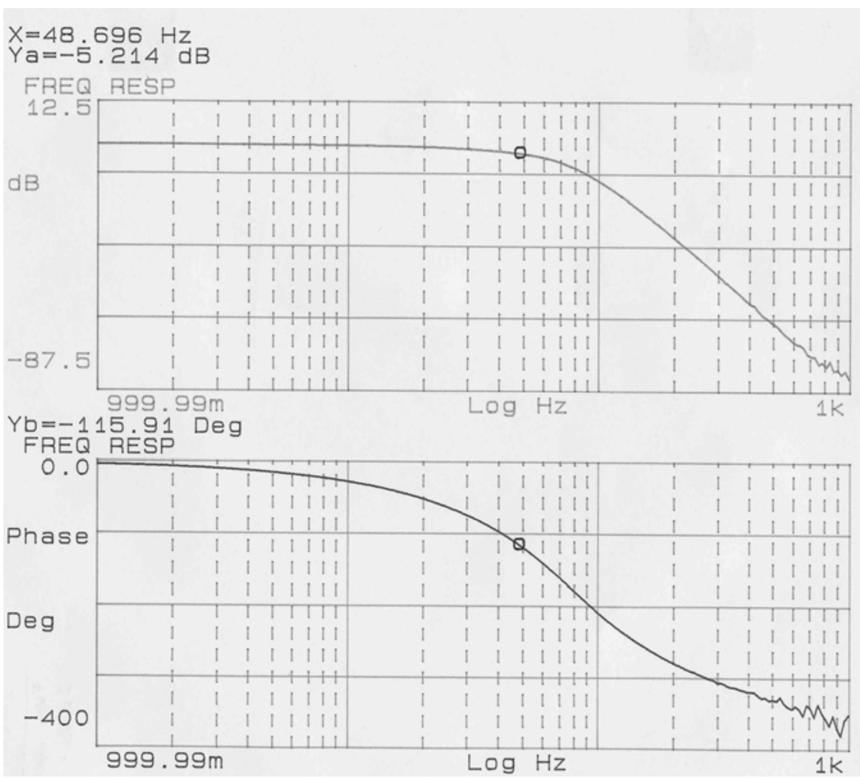

Figure 5 4-pole filter characteristics while operating at 225˚C.

Figure 6 Oven used to qualify the assembled boards at 225°C.

4 HT TOOL MECHANICAL DESIGN AND DEVELOPMENT

4.1 Mechanical Design Overview and Summary

As described above, the plan for the HT DWD tool was to provide similar functionality to that of the POC tool, that is, the tool design was directed at measuring bit and BHA drilling dynamics. Given that a significantly larger volume of electronics was required for the HT tool, a new mechanical design was necessary. This required redesign effort also provided the opportunity to address design issues identified with previous field activities involving the POC tool. However, the time constraints associated with developing the HT DWD system required the redesign be limited to system components that were either absolutely required or could reasonably be completed in FY05.

A major change in the HT tool design was required to accommodate the expanded volume of electronics. Since the 7-inch-diameter of the POC tool was maintained in the HT tool design, this required a significant lengthening of the tool. The final HT electronics carrier length of 94 inches resulted in a concentric pressure barrel assembly about 12-feet-long with an associated outside tool body length of nearly 14 feet. Cross sections of the assembly drawings of the POC and HT DWD tools are shown in Figure 7. 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 secure the long pressure barrel, a novel solution was developed that addressed both issues and also 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 five separate sections connected together with four 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.

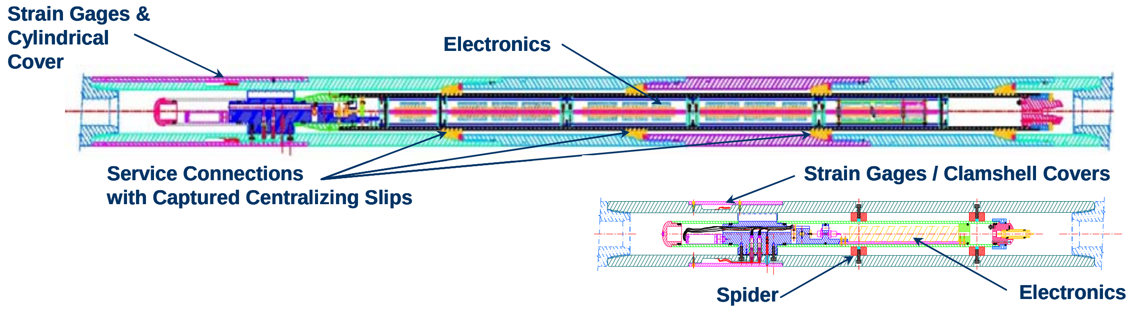

Figure 7 Comparison of the POC DWD tool (bottom) with the HT DWD tool (top), scale between drawings is relative.

A second fundamental design change addressed eliminated the clamshell covers used to protect the strain gage assembly in the POC tool. In a previous POC test, one of the clamshell covers came loose resulting in a catastrophic tool failure. In a production environment, this failure could have resulted in the loss of the hole. In the HT tool, a removable cylindrical cover was designed to replace the clamshells. The cylindrical cover was captured by the shoulder of a cross-over connection below the HT tool. The cylindrical cover was intended to serve the same function as the clamshell covers while eliminating the risk of becoming detached from the tool during drilling. As with the clamshell covers in the LT tool, the cylindrical cover was simply a physical barrier between the strain gaged section of the HT DWD tool and the wellbore. The cylindrical cover does not seal the gaged section of the tool or the pass-thru connections into the electronics pressure barrel thereby permitting exposure to well bore pressures and fluids. Although metallic sealing of the gaged section from wellbore fluids and pressures was on the "wish-list" of design changes, neither funding nor time was available to do the development required for such a change.

The primary strain gauge seal for the LT POC tool 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 gages and pass-thru wiring against fluid intrusion, but cannot perform at the design 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-gaged 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 8 shows the process of applying the uncured AFLAS® and Figure 9 shows the AFLAS® encapsulant after the curing process. While the AFLAS® encapsulation method was eventually chosen, it is 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 to this issue is required. The elastomeric sealing method and installation details are described in detail in the subsequent sections. Efforts to improve the strain-gage sealing method will be pursued in the future.

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 (e.g. o-rings) exposed to the wellbore environment were identified and tested, not just for decomposition at temperature, but also for hydrolysis. These evaluations showed that the PEEK cable-head bodies and Viton®® boots were adequate. Previously used silicone o-rings were found to be totally unacceptable; Viton®® o-rings were found to be marginal. All o-rings were replaced with AFLAS®® materials.

Following the design and review process, the HT DWD tool was fabricated and subassemblies were proof tested. Critical components were pressure tested (e.g., the concentric pressure barrel for the electronics, the strain-gage encapsulant, and the service connections) and the calibration of the HT DWD tool was performed. (It should be noted that two separate sections of the outer barrel to which strain-gages are affixed were fabricated and calibrated, but only one was required for the field test). Final tool assembly was performed and the tool was readied for testing in the field.

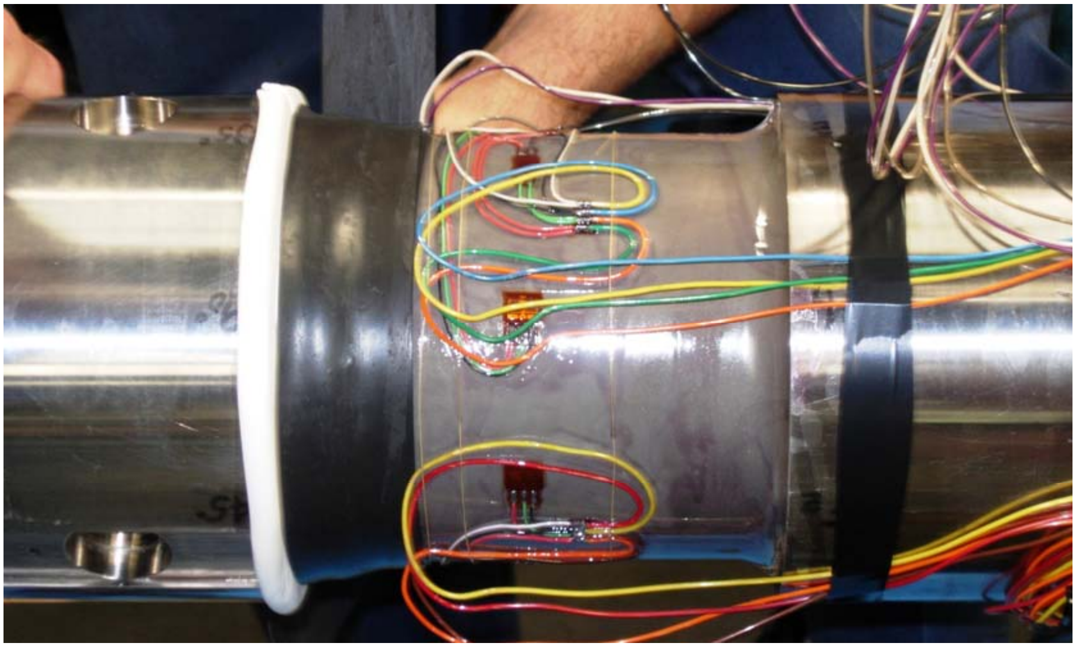

Figure 8 Strain-Gaged portion of HT DWD tool being wrapped with the uncured AFLAS® material.

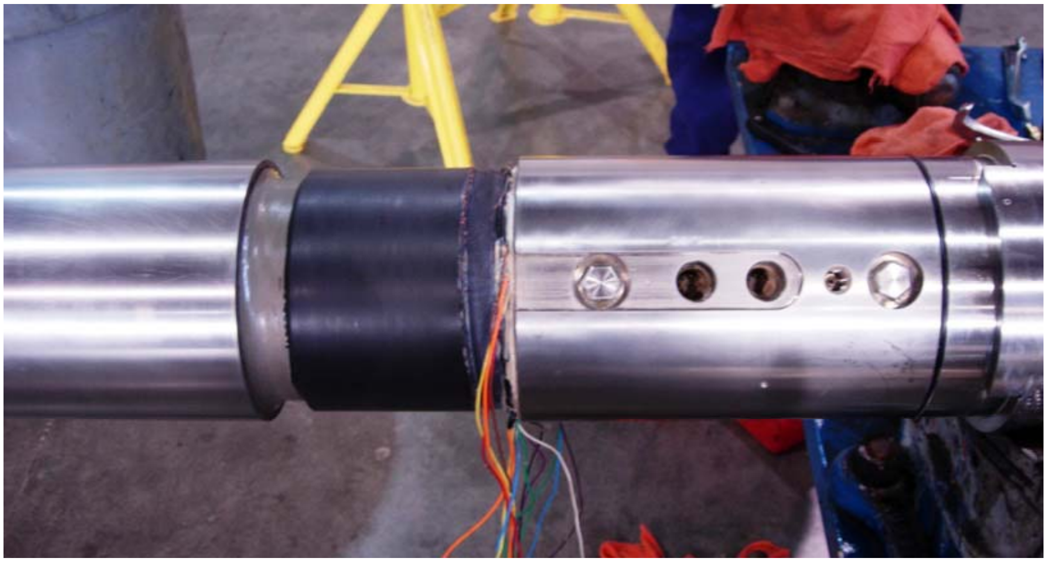

Figure 9 Strain-gaged section of HT DWD after curing of AFLAS® encapsulant.

4.2 Strain Gage Installation and Protection Details

4.2.1 Potting Materials used in 135ºC LT DWD Tool

The LT DWD tool encapsulated the strain gages with multiple layers designed to provide multiple moisture barriers as well as physical protection of the strain gages. Physical protection included stabilizing the wires so that the solder joints and wires leading to the solder joints would not be subject to fatigue failure as the tool vibrates. Flexible rather than stiff materials were used so that the encapsulant would not crack under hydrostatic load. The material had to be able to bond to the tool body steel, strain gages themselves, as well as the Teflon® wires.

Starting from the strain gages the encapsulant was composed of the following layers: 1) Gage Kote #8, 2) SC 2000 Black Cement, 3) F-Kit, 4) SC 2000 Black Cement, and 5) Scotchcast 2130. These materials were applied as per manufacture specifications. This process for encapsulating the strain gages is a standard process used by Stress Engineering Services.

4.2.2 Motivation for 225°C Strain Gage Sealing Approach

Although the long-term vision for a HT DWD tool design targeted an operating temperature on the order of 300ºC, DOE programmatic requirements dictated that a demonstrated HT DWD tool be designed and field tested in a year. The LT tool, starting from scratch, took more than two years to design, fabricate, and test. It was assumed that a similar time-scale would be required for a completely new HT tool design. It was therefore decided to use the existing LT tool design as much a possible to meet the project timeline. The electronic components and sensors available at that time would not support building a fully functioning HT tool to operate at more than 225ºC. An upper limit of 225ºC was therefore selected to permit upgrading of the LT tool features. This allowed the use of elastomeric parts like o-rings for sealing.

One of the primary challenges to upgrading the LT tool to 225ºC was the potting of the strain gages. The 225ºC operating temperature was known to be near the published operating limits of elastomeric materials that could reasonably be considered for strain gage encapsulation. In addition to the strain gage potting, the DWD tool contains various o-rings, rubber boots, and electrical connectors. Test procedures and lessons learned in selecting the high temperature strain gage potting material were applied to these other parts. The COTS boots and electrical feed through connectors being used in the LT tool were found to be adequate for 225ºC. The o-rings used in the LT tool were replaced with AFLAS®, the elastomer chosen for potting the strain gages.

Beneficial features of LT DWD tool design

Design of the WOB (weight-on-bit), TOB (torque-on-bit), and bending measurement function of the DWD tool was of necessity an exercise in compromise. To get the necessary resolution with low signal noise and high fidelity, it was necessary to mount the strain gages on a thinned section of the body (see Figure 10). Thinning of the strain-gaged cross-section raised the strain level sufficiently to produce an adequate signal. The strain gages were mounted on the outside of the tool “exposed” to the drilling mud, but protected with “clam shell” covers. This approach allowed for easy access to and retrofit of the strain gages.

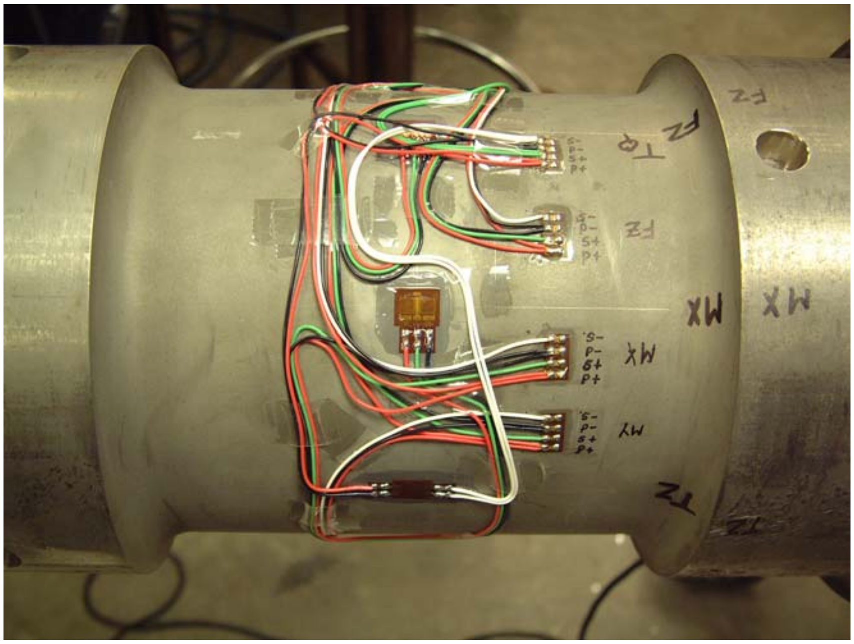

Figure 10 Strain gage section of the DWD tool.

The LT design allowed interchangeable electronics and strain gage sections of the tool allowing the tool to be rebuilt in the field. The strain gages were connected to the electronics by electrical connectors that provided a hermetic seal. By design, the failure of one set of strain gages did not result in failure of all the gages nor did it result in damage to the electronics.

The design of the strain gage section of the LT tool used features, including potting of the gages, that had been proven in prior downhole tools. This minimized risk in the design allowing emphasis to be placed on the other functions that required novel features.

Impact of time table for development of options investigated
Once the commitment was made to have a field tested HT tool in one year, it was decided to limit redesign to tool issues most in need of attention, The basic strain gage section proved acceptable in the LT tool and was considered adequate for use in the HT tool. However it was also recognized that significant challenges lay ahead in developing strain gage potting, sealing (o-rings) and interconnection methods that would withstand the 225ºC drilling environment.

The specification of the electrical connector that feeds the electrical wiring attached to the strain gages into the electronics package and the wireline connector at the top of the tool indicated that these parts should be satisfactory for 225ºC service. However, past experience with unexpected failures of elastomeric parts in geothermal wells motivated independent testing of these parts. This was accomplished by pressure cooking these parts as well as TGA (thermo-gravimetric analysis – sensitive weight analysis as a function of temperature) both exposed to oxygen and water vapor. The tests were done to check for thermal decomposition, oxygen attack, and, most importantly, hydrolysis. The tests confirmed the suitability of these parts. That left investigation of the o-rings and strain gage potting material. Review of the data sheets of LT potting material revealed that there was no chance it would remain serviceable at 225ºC. Thus the major problem became finding a suitable replacement for the LT potting material.

4.2.3 Concepts rejected for elastomeric sealing of the 225ºC tool

Unsuitable Candidates
Many concepts or materials were considered and dismissed as unsuitable and are not worth further discussion, i.e., the Scotchcast 2130 and silicone o-rings used in the LT DWD tool. Others are discussed below, for example, flame spray coating epoxy to form a vapor barrier to protect the epoxy from attack. Some of the concepts explored, but not ultimately used, which merit further consideration are presented in this section.

Rigid materials were only considered as a strain gauge protector (see discussion of epoxy below) and not for the overall “potting” (that is as a replacement for the AFLAS®), because it was believed that under hydrostatic load any bond between the Teflon® wires and a rigid material would fail and leak.

There are a number of readily curable rigid polymeric materials that will withstand 225ºC, for example, the HT polyurethane lost circulation material developed by Sandia [SAND2003-3178C] and conformal coatings used to protect circuit boards. Materials of this type investigated were found to be brittle and subject to cracking in conditions of high vibration.

There are polymeric materials like Teflon® that are suitable for high temperature performance, but require special curing. As discussed below, Teflon® shrink tubing is available for joining Teflon® wires. Such shrink tubing is not available COTS in the diameter needed to surround the DWD tool. However, the individual materials composing Teflon® shrink tubing can be purchased in large diameters. Tests were run to determine if homemade Teflon® shrink tubing could be used to replace both the epoxy and AFLAS®. While successful in achieving the desired shrinkage, bonding to the steel was weak and air pockets could not be eliminated. Also it was difficult to get a complete seal where the wires lay next to the tool body. Thus while this concept was not a failure, it was concluded it would be better to work with a shop that did custom Teflon® processing, see section below.

Note: The term “Teflon®” will be used throughout this report to describe the fluorocarbon based polymer polytetrafluoroethylene or PTFE. Teflon® is the brand of PTFE manufactured by DuPont. Many manufacturers use PTFE to make seals, wire insulation, and other parts. There are many grades of PTFE available for different purposes, and often, the specifics of an actual grade are difficult to identify. A vendor may not wish for their specific formulation to be known by competition, for example. Therefore, while Teflon® insulated wire and heat shrink tubing was used in this project, specific grade information is not available.

Concepts that did not fit the time-table constraint

The size and weight of the DWD tool does not prohibit application of the strain gauges at one location followed by shipping the part to a shop that does custom Teflon® applications. This concept involves performing the entire encapsulation with Teflon® only. Unfortunately it was only late in the project that facilities were identified with the capability to handle parts of the required size and process Teflon® at temperatures that would not destroy the solder, gage adhesive, strain gages, and wires. Unknowns are what preparation work would have to be done (cleanup of solder flux residue, surface roughing, etc.) and if adequate bonding could be achieved. Furthermore it was unclear how thick a layer of Teflon® would be needed and how thick a layer could be applied and was there a risk of a pinhole.

There are other Teflon®-like materials that could similarly be applied in specialty processing shops. One of particular interest is a material that was developed by Brookhaven as a potential corrosion resistant coating for geothermal tubulars. This material is currently being commercialized as a boiler tube coating material. Its unknowns are the same as Teflon®.

4.2.4 Wire selection

In addition to strain gage protection, numerous mechanical issues were considered in the design of the tool. Wire insulation was one of these issues. Criteria were developed in the selection of the wire insulation materials including: 1) The wires to the strain gage circuits had to exit the encapsulation (or “potting”) material. Good bonding between the wire insulation and the encapsulation material was therefore required to prevent wellbore fluid migration through the interface between the wire insulation and the encapsulation material to avoid electrical problems at the strain gage or solder tab connections. 2) The wire had to be reasonably flexible. The DWD tool’s design, specifically around the strain gage area and the channel going to the through-tool Greene Tweed connectors, required that the wires be subjected to fairly tortuous paths. This geometry, coupled with the fact that there would be sixteen wires that had to be routed, required that the wires be of a manageable diameter. 3) Finally, the ductility of the insulation material had to be adequate. Some high temperature wire insulations employ ceramics or fiberglass materials that cannot be flexed appreciably without cracking.

After investigating various types of high temperature wire insulation, it was decided that Teflon® insulation would be the best choice, primarily due to its temperature tolerance, toughness and flexibility. It could be obtained in numerous diameters and insulation thicknesses suitable for the HT DWD application. The main challenge to be addressed was that of bonding between the Teflon® and the encapsulating elastomer because Teflon® is typically resistant to bonding. However, there is an “etching” process that can be used to make the Teflon® surface more readily accept adhesives.

There are two options for obtaining wire with etched Teflon® insulation: purchasing pre-etched wire or etching non-etched wire. Pre-etched wire was purchased for evaluation from MicroMeasurements. The MicroMeasurements 330-FTE Teflon® insulated wire is rated for service up to 260 °C. The first generation DWD tool, while not rated for high temperature operation, also employed a Teflon® insulated wire for its gage circuits. The wire for LT DWD tools was etched by Sandia and Stress Engineering Services personnel using an Acton Technologies product called FluoroEtch. This approach was also undertaken for HT tool evaluation purposes. Acton Technologies also offers an etching service where they use their product to etch wire for customers. They have an established process system, including recommended exposure times and temperatures, to achieve the best etching results using their etchant. They also use the freshest etchant. This chemical solution has a limited shelf life, and its effectiveness is reduced as time passes. Acton Technologies etching service was used as the third candidate for evaluation of wire with etched Teflon® insulation.

Wires etched using the three different approaches were used during a potting material trial so that the wire bonding to elastomer could be evaluated. Qualitative evaluations showed that the candidate etching methods resulted in inconsistent or typically poor bonds between the wire insulation and encapsulant materials. Of the three etching methods, the pre-etched wire from MicroMeasurements was the poorest performer. Based on sample testing, the wire etched by Acton Technologies did not always accept a good bond, but it was generally successful. The Stress Engineering Services etched wire using the Acton technologies product was also able to obtain good results most of the time. Based on a visual and tactile inspection, it was not possible to determine if a particular section of etched wire was going to be a good performer. The etching always roughened the wire insulation surface. It also darkened its color to a brownish hue. Wire that had a rougher texture or a darker color did not necessarily exhibit better bonding. The conclusion was that it was prudent to follow the manufacturer's instructions closely to achieve the best performance. However, the uncertainty of not achieving a good bond on the actual drilling tool was a source of concern throughout the development of the HT DWD tool.

4.2.5 Strain gage attachment to tool

The WK series of strain gages from MicroMeasurements used in the first generation DWD tool were rated for the upper temperature limit of the HT DWD application (225 °C). However, the recommended adhesives used to bond the gages and solder tabs to the host metal had temperature limits close to the HT DWD temperature limit. Initial investigation focused on a P.D. George adhesive from their "Epoxylite" line of products. GA-61 is a two-part, elevated-temperature cure product. The manufacturer was contacted to discuss issues related to use of their adhesive near the specified upper operational limit. These issues included: the presence of significant dynamic and reversing strains in the measurement application; literature advertised "short term" and "long term" temperature limits (315 °C and 260 °C, respectively) without quantitative time definitions of "short" and "long" term; any additional guidance that might be relevant. The manufacturer was in general noncommittal and recommended testing to address any concerns.

Weld-on gages were considered as an alternative to adhesive attached gages. Although they eliminate temperature-related adhesion performance as a risk, they are not without concerns. Foremost was their propensity for initial bias voltage offset which would make HT electronics fabrication more difficult. There was also a lack of experience of welding strain gages to the Carpenter 15-15HS material of the tool body. Ultimately, it was decided to pursue the adhesive approach as it was perceived to have lower risk.

Evaluations were conducted where gages were bonded onto flat plate samples and subjected to long-term oven tests. This testing indicated that the adhesives would be suitable as long as the proper curing (to 205 °C) and post-curing (to 235 °C) procedures were followed. Early plate and tube tests involved curing and post-curing the GA-61 in small ovens. As thoughts turned to being able to cure and post cure the GA-61 on the actual tool, no oven was readily available that could handle the DWD tool dimensions. A smaller ceramic radiant heater was used to cure and post cure the GA-61 on tubular samples that were to be subjected to cyclic bending tests. This heater worked reasonably well with a temperature controller using a thermocouple clamped to the sample body. There was concern that the radiant heater was causing the surface temperature of the epoxy (and gages) to be much higher than intended. This concern was reinforced when it was observed that the epoxy turned a dark brown color during cure and post cure whereas its color at room temperature was more like a mustard yellow. While no gage or epoxy failure could ever be traced to this as a root cause, additional heating methods were considered.

Induction heating was eventually employed to heat the DWD tool body for curing and post curing the gage adhesive. This method of heating was initially questioned because the Carpenter 15-15HS was non-magnetic. Trial runs indicated that the control would be acceptable and the induction heating system proved easy to use, had good ramping performance and control, and ultimately did not cause significant discoloration to the GA-61. The decision was made to conduct all cure and post cure heating of the tools using induction heating.

Confirming that the gage adhesive does not experience bond degradation or creep was the last step in adhesive selection (i.e., confirming that the deformation experienced by the measurement sample was equal to the deformation of the strain gage). High temperature bending tests were performed toward this end confirming the suitability of the GA-61 adhesive for this application.

4.2.6 Strain gage encapsulation

Many concepts or materials were considered for use as encapsulants for the strain gaged section of the tool. A number were immediately dismissed because of obvious temperature sensitivities (e.g. Scotchcast 2130). Other encapsulation methods/materials were considered and rejected because of test results (in some cases extensive testing) or because of the perceived development time.

Early investigation into how the encapsulation of the strain gages would be done led to contact with Eutsler Technical Products of Houston, TX. They perform a “mandrel-wrapping” process with Viton® and AFLAS® on many types of downhole tools. Their client list includes many oilfield manufacturers and service companies. Therefore, their experience and knowledge base made them a good candidate with which to start the development of the desired encapsulation process.

Eutsler’s greatest concern from the outset was that the significant movement (i.e. flow) of the elastomer during curing most likely could damage the strain gages and wires. The prototype HT DWD tool was ultimately coated only with AFLAS® to encapsulate the strain gages. No inner encapsulation over the gages, tabs and wires was ultimately used although extensive experimentation was performed to identify inner encapsulation candidates. That work is described in Appendix A.

Eutsler Technical Products and the Mandrel Wrapping Process
As part of the investigation to develop a suitable encapsulant, a series of tests on simple pipe samples were conducted. Eutsler’s mandrel wrapping process involves the wrapping of strips of uncured elastomer around the desired part. This wrapping operation is done on a lathe. A pair of knives is adjusted to set the strip width to the desired amount. The elastomer is pressed and heated as it is rolled through a calender. The resultant strip thickness is approximately 0.030”. Once these parameters are set, the elastomer material is continuously wrapped onto the sample as it is turned on a lathe (see figure 11).

This is a very labor intensive process – it is not automated. Technicians manually guide the elastomer to achieve the desired wrap thickness. They perform a “windlass” function, having to reverse direction as the wrap thickness approaches an end.

Tension is manually maintained in the elastomer strip. The thickness and length are built up to the desired dimensions. Before the wrapped product is cured, it is constrained on its ends and around its circumference. The end wraps are first used to build “dams” on either end of the wrapped elastomer as shown in figure 12. Fiberglass tape strips soaked in water are then wrapped around the sample as shown in figure 13. The tape wrapping confines the elastomer to cure in its desired location and shape. In some cases, a thin Mylar tape wrap was used as well to provide a moisture barrier during the curing process (figure 14).

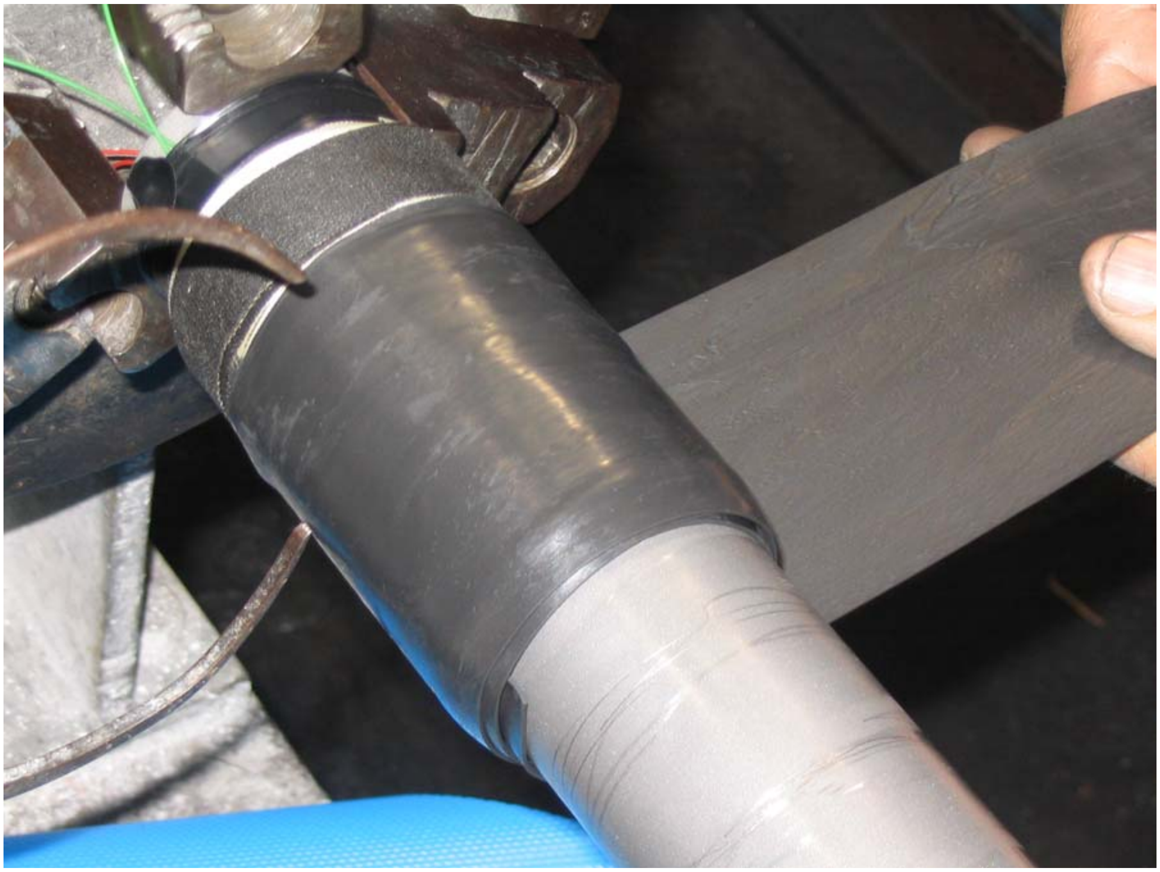

Figure 11 Elastomer winding process

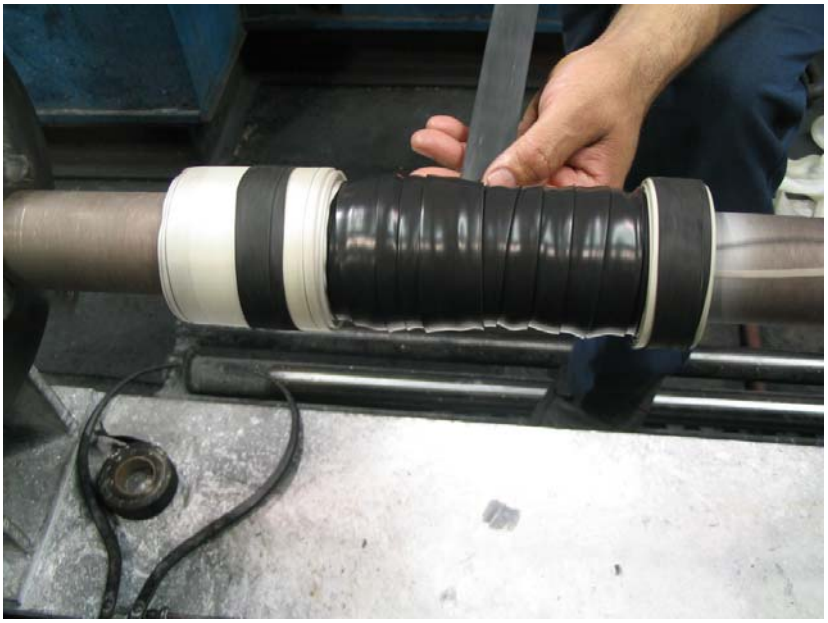

Figure 12 Elastomer winding process showing end dams

Figure 13 Tape wrapping process

Figure 14 Sample wrapping with mylar tape

This wrapped part is then put into a steam autoclave and cured for one hour. The cross-linking of the elastomer ensues in the oven with some off-gassing occurring as the product cures. The steam pressure in the vessel is typically around 90 psig with a corresponding temperature of 160 °C. The steam pressure helps keep the off-gas from forming bubbles or voids in the elastomer. Steam is provided by an on-site boiler. There are several vessels to accommodate various sized parts. The size of the vessel and the load on the boiler at the time can lead to varying rates of pressure and temperature buildup. This was another variable to be addressed as the process at Eutsler was refined.

The combined shrinking of the wrapping as it dries and thermal expansion of the elastomer creates pressure that is critical to obtaining a good cure. The pressure is not as high as one would typically get in an injection molding process. Obtaining a high, uniform, and repeatable confining pressure is difficult and is in part an art. This lack of repeatability can result in an inconsistent final product. A more precise means of controlling the pressure on the curing elastomer would permit optimization of the application process to produce a better performing product.

Viton® versus AFLAS®

Two evaluation criteria were defined once the wrapping process was understood: 1) Which elastomer to use, either Viton® or AFLAS®, and 2) Whether the risk of damage to wires and gages as a result of elastomer flow during curing was excessively high. Laboratory tests and the literature indicated that AFLAS® would be more resistant to decomposition in the geothermal environment, but Eutsler's experience was that Viton® was easier to process. Thus, it was unclear which material would provide the most effective seal. Several tests were conducted by wrapping Viton® and AFLAS® on thin wall 2" pipe. Some of these samples had wires, but no gages inside of the wraps. Some also had individual strands of 24 AWG (7 x 32) wire broken out (stripped of insulation and some conductors cut) to evaluate if an intentionally weakened wire would be damaged by the flowing elastomer.

Subsequent oven tests clearly showed that the AFLAS® demonstrated superior temperature performance. At temperatures of 204 °C and 232 °C, the Viton® exhibited clear signs of charring damage while the AFLAS® appeared unaffected. The decision was consequently made to use only AFLAS® for the remainder of development.

Treatment of Wires

Wire evaluation tests using only elastomer encapsulation were also quite promising. No sample in the group failed wire continuity testing post-curing. There was one case of wire crushing, however. Wires were routed under the fiberglass tape of the end dam where they exited the potting. Following wrapping, curing and post-curing, inspection of the wire insulation on one test revealed that the cross section was no longer round, but a flattened oval. The conductor did not part, but inspection under a microscope clearly showed that the mechanical integrity of the wire was unacceptably compromised. In subsequent testing, a small single-wrap cushion of AFLAS® was placed under the wire and one wrap was continued over the wire to reduce the risk of excessive compression as shown in figure 15.

This approach worked well in subsequent tests, though some flow outward around the wire was always visible. Learning how to protect the exiting wire was a trial and error process. Defining the appropriate protection layer thickness was a trade off between no “compliance” and hence crushing of the wire with too much resulting in leakage, low pressure, and poor curing.

After the product is cured, it goes through a post cure process to a temperature at or above the intended service temperature. Final off-gassing occurs at this stage along with any residual curing/cross-linking. Two approaches to post curing are possible: atmospheric post curing or post curing under pressure. In either case, the post curing must be slow so that there is time for the off-gas to diffuse out of the sample. Time and temperature ramping of the post curing are a function of thickness and thermal history of the AFLAS®. Two HT tool strain gaged sections were eventually fabricated with one post cured using the previously described induction heaters at atmospheric pressure, the other was not post-cured with the intent of letting the post cure occur in the field where wellbore fluids would provide the required temperature and pressure.

Figure 15 AFLAS® protective layers above and below wire exit from encapsulation region

Concerns Regarding the Mandrel Wrapping Process

There were two major concerns with the mandrel wrapping process. First, the manual nature of the process, with its inherent variability from application to application, led to the question of repeatability. For example, specific technicians were typically assigned to specific projects, but if assigned technician was not present that day, the substitute might not be aware of the nuances that the previous tech has identified. Although efforts were made to ensure that the same procedural steps were followed every time, different technicians often employed different techniques. A prime example is the way a wrap is reversed at either end of the sample. Some technicians would fold the AFLAS® strip over when changing directions, while others would not. Also, the width of the strip would be varied sometimes. As experience with the Eutsler process grew, it became clear that a major contributor to sample failure was the occurrence of “frac outs” where entrapped gases (air or other products of off-gassing) rapidly escaped during curing, causing a split, tear, or other fault in the AFLAS®. To minimize frac outs, it was clearly necessary to minimize the presence of air within the AFLAS® strips during the wrapping process. When a “fold-over” was done at the ends, more air was likely to be trapped. Likewise, wherever the strips laid over themselves (as is unavoidable in a continuous mandrel wrap), some air can be trapped in every unit length of overlay. The wider the strip used, the less overlay and therefore the less trapped air. To prove this, tests were carried out to evaluate the susceptibility to frac outs versus AFLAS® strip width. The wider strips were less sensitive to fracing out, but posed more serious problems when nesting wires in the wrapping process.

The second major concern with the Eustler process was inconsistency in the AFLAS® formulation. The AFLAS® used was formulated by an outside source. The formulators are very reluctant to divulge their “recipes” since they often employ subtle variations in the combination of ingredients and consider this knowledge propriety. Because the details of the formulation were not made available by the manufacturer, there is a possibility of variation of elastomer performance if a new tool is built in the future.

AFLAS® protection of wires

Early elastomer wrapping experiments were performed on tubulars without strain gages or solder tabs. Wire management in these areas was a major source of concern given the suspicion that elastomer flow during curing might have adverse mechanical consequences. In addition, Eutsler always used a “bonding agent” to facilitate better adhesion between the AFLAS® and the host metal (or the epoxy). This liquid product was to be applied directly onto the gages, tabs, and solder connections. Discussions with the manufacturer seemed to indicate there would be no material interaction problems. Another surface preparation concern was the need to roughen the areas to which the AFLAS® would bond. Metals were sandblasted and the bonding agent was applied immediately thereafter. Sandblasting of the gages, wires, and solder tabs was not an option as they would not survive sandblasting. Therefore, prior to delivery to Eutsler, but after installation of the gages and wires, an air erase system was used to lightly roughen up the base metal under and around the wires. This process did not yield a high a surface roughness as sandblasting, but it was effective in achieving an acceptable, bondable surface. It also performed the necessary function of removing solder flux residue prior to elastomer application.

Several parts of the process were identified as critical for completing a successful AFLAS® wrap. They were:

1) <u>Slow curing and post curing</u> – It was important for the rate of temperature change to be gradual. This permitted off-gas products of the curing reactions to diffuse out of the rubber, rather than accumulating into bubbles, thereby resulting in a reduced chance of frac outs. A series of temperature ramping tests were performed in an oven to identify critical rates. These rates were followed as closely as possible on subsequent tests. Heating rate was also an issue in Eutsler's steam vessels. Depending on which vessel was used, the loads on their boiler, and resident heat in the boiler from previous work that day, the temperature and pressure could build at different rates when parts were cured.

2) <u>Constraint of the AFLAS® during cure</u> – The off-gas products from the AFLAS® migrate out of the material during cure and post-cure. If gas collects in a closed volume and any rapid pressure release occurred, a frac out results and the run is damaged. If the AFLAS® is constrained well both axially and radially, the enhanced pressure increases the diffusion of off-gas through the AFLAS®, thereby reducing the chance of a frac out. Experiments were done using fiberglass end dams and an adjustable metal sleeve around the outside circumference to hold the AFLAS in the radial direction as shown in the figure below. This experiment proved to be a valuable tool in understanding the curing process and providing a superior product. As the process was improved, successful moldings were achieved with just fiberglass outer wraps. With adequate time the metal sleeve approach would have been pursued further.

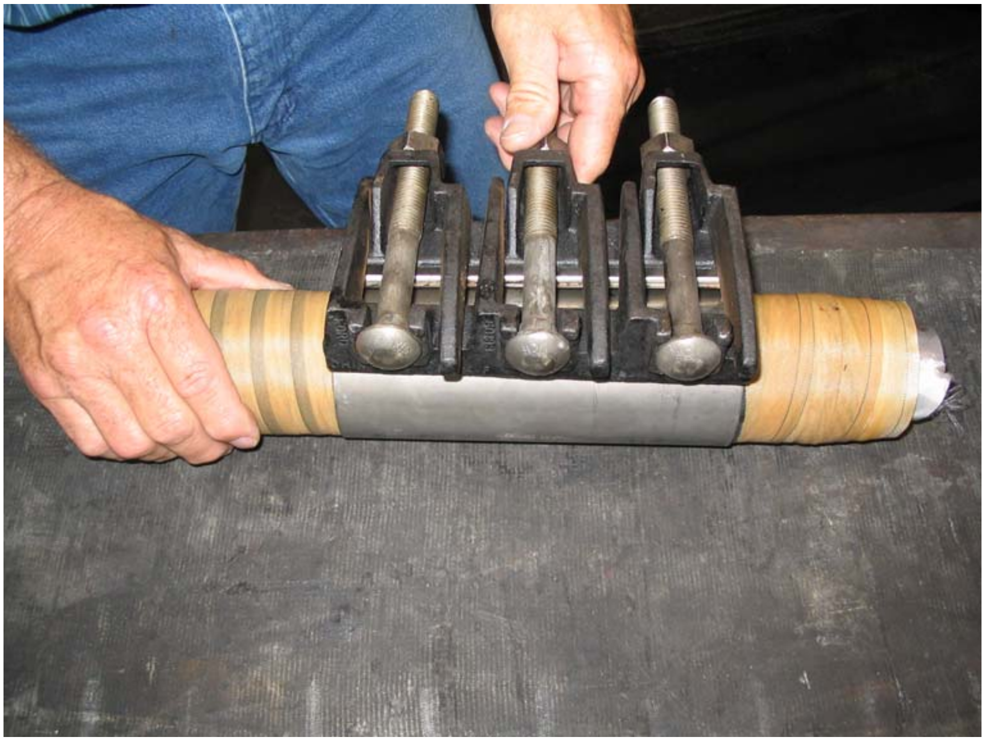

Figure 16 Radial constraint fixture

3) Cushioning of the wires during wrapping – Early tests showed that shrinking of the fiberglass dams could crush the wires. The process of implementing a cushion (i.e. placing the wires between layers of AFLAS® wrap) offers good protection. However, the radial locations of the wire at the solder tabs and the lower protective layer differ. Therefore a smooth transition must be manually formed between the wire and the underlying AFLAS® layer to avoid undue stress of the wire.
4) Minimizing trapped air – The gage section has four full bridge circuits with a number of wires that are routed through the encapsulation material. It is critical to minimize any volumes where entrapped air or off-gas products might accumulate. This requires minimizing wire crossing and "stacking".
5) Careful Preparation of Surface to Ensure Good AFLAS® Bond – Where AFLAS® bonds to other materials, the surface has to be roughened using sandblasting (preferably) or air erasing. Also important is the application of the bonding agent as soon as possible after sandblasting or air erasing. This prevents humidity from collecting on the rough surface and guarantees a better bond.
6) As Thin of a Layer of AFLAS® as Possible – Since it is known that AFLAS® produces off-gassing products when it is cured, it is desirable to reduce the wrap thickness as much as possible while still meeting sealing objectives. The thinner the layer of AFLAS®, the easier it is for off-gas products to escape. An AFLAS® encapsulation layer ¼" thick

was settled upon as being the thinnest layer that the project team felt comfortable with as far as being a good protective layer for the wires and gages.

Other noteworthy observations
During test trials, the occurrence of the frac outs was somewhat unpredictable leading to significant repetition in the manufacturing process. A repair or patching method would be beneficial both for manufacturing and field service purposes. Eutsler had, in fact, worked with Viton® cement before, with varying results, to repair defects in Viton® wrapped parts. They had never worked with AFLAS® cement, but a vendor in Ohio, Eagle Elastomer, offers an AFLAS® cement. Some of this was purchased and tested on some of the samples which had frac outs. These cements actually consisted of uncured elastomer saturated with in methyl-ethyl ketone (MEK). Two trials using the Eagle Elastomer product were performed. The results, while never tested in a heated, pressurized environment, appeared to make a serviceable repair.

Another risk during processing and handling of the HT DWD tool was the accidental crushing or nicking of the strain gage wires. Special concentric heat shrink tubing was obtained for repair in such instances. The inner tubing melts at a lower temperature than the outer tubing. During heating, the inner tubing first melts and flows around the spliced conductors. As temperature increases, the outer tubing shrinks to form a rigid outer coating over the inner encapsulation.

4.2.7 Calibration Testing and Qualification of 225°C Tool

The HT DWD tool was calibrated in the same fashion as the first generation tool. The weight-on-bit, torque, and X and Y bending measurements were calibrated in Stress Engineering Services load frames at room temperature. The response of the new tool during load testing was very similar to the old tool as expected given that they used the same strain gage model and had similar tool gage section geometries. The only significant difference between the two was the tool body material for which the elastic modulus value differed only by approximately 1.7%.

5 FIELD TEST

In cooperation with ORMAT Nevada Inc., the HT DWD system was demonstrated in a production well under construction as part of the Galena Geothermal Project. This well was selected for the initial test for a number of reasons. The schedule associated with fielding the HT DWD system required that a well be available in late of FY05. Over this specific time interval, the ORMAT supplied geothermal well was available. Secondly, ORMAT agreed to allow access to their production well and was willing to accommodate the testing efforts associated with the DWD tool. In addition, this was a geothermal production well with anticipated test zone temperatures on the order of 150-175°C at relatively shallow depths. During the planning of the first trial HT DWD system, the shallow depths associated with the Galena Project wells were considered an advantage insofar as the tripping time for anticipated tool repair would be minimized (as discussed in a section below, tripping for tool repair was not required).

The system was mobilized to the ORMAT facility during the week of September 5, 2005. The DWD measurement sub was placed in the drill string, and DWD-guided drilling proceeded below the last casing in the hard granodiorite intrusive reservoir rock. The system test was successful and performed beyond expectations.

During the test with the HT DWD system, the cooling effect of the circulating fluid limited the actual temperatures seen by the tool to about 70 °C while drilling. However, several times drilling was suspended to attend to other issues including the wireline. During these times, the tool soaked and should have warmed up to close to in situ temperature. Since the tool was off at these times there is no recorded data to know what the actual temperature was. While ORMAT was an accommodating host, they did have a tight production schedule and Sandia chose to spend rig time drilling rather than soaking the tool with the data acquisition on. This decision was based on the fact that temperature sensitive components had been subjected to bench top testing and that given the limited time available, the most efficient use of rig time was to evaluate the HT DWD tool performance during actual drilling; an evaluation that could not be performed in the laboratory. The HT DWD tool performed remarkably well and this first demonstration test marks the *successful completion of the FY 2005 Joule Milestone.*

When Sandi arrived on site, Hole SBH 34-32 was cased with 13.375-inch casing to a depth of 745 feet. ORMAT drilled out the cement shoe and extended the hole to 775 feet with a 12.25-inch bit and followed this with the drilling of an 8.5-inch-diameter rat hole to a depth of 805 feet. Several issues regarding a vendor supplied cross-over sub, scale build up in the drill pipe and the wireline pack-off were subsequently addressed. Early the morning of September 8, the bottom-hole-assembly (BHA) for drilling with the HT DWD system was made-up and drilling activities commenced. A description of the BHA is provided in Table 2.

Photographs of the DWD tool ready to be picked-up and during BHA make-up are shown in figures 17 and 18, respectively.

Drilling with the HT DWD guidance proceeded for a full three stands of drill pipe (90 feet) to a depth of 895 feet. Given that this was the first real-world trial of the high-temperature system, the possibility of system failures (both mechanical and electrical) was not only large, but was expected given the real-world rigors of the drilling environment. The DWD team was prepared to perform field repairs and/or replacement of all electrical, data acquisition, and mechanical subsystems. No repairs were required or performed to the HT DWD system during the drilling phase of the test. A wet-connect wireline system, similar to that used with the POC DWD system, was employed for the tool power and data transmission during the drilling tests. The only exceptional operational event occurred at the end of the last drilled stand, where communication with HT DWD tool was lost. This lost data was attributed to a short in the cable head. With drilling completed, the cable head was not repaired. With the exception of the cable head issue, the most sensitive components of the wet-connect wireline system performed flawlessly during the field test.

Tool	Length (ft)
8 ½" Roller Bit	.95
Near-Bit Roller Reamer	7.02
4 ½" X-Hole to 4 ½" IF Cross-Over	1.81
HT DWD Tool	13.71
Roller Reamer	4.75
4 ½" IF to 4 ½" X Hole Cross-Over	1.69
6" Drill Collar	30.59
Wireline Rocket Retainer / Guide Subs	2.8
Roller Reamer	6.61
6"Drill Collars (7)	215.87
Cross-Over	3.6
Heavy Wall Drill Pipe	30.46
Jars	32.88

Table 1. Bottom Hole Assembly for HT DWD Field Test.

Figure 17 HT DWD tool on trailer ready to be picked up for make up in the BHA.

Figure 18 Make up of BHA with the DWD tool (note the roller reamer at top and the HT DWD tool at bottom).

Following the HT DWD drilling test, ORMAT opened the hole to 12.25-inches and continue drilling to a depth of about 1,540 feet. Logs are reported to show the wellbore temperature was highest at a reported depth of between 1,100 and 1,200 feet, with a temperature of about 157°C. During the drilling with the HT DWD tool, high circulation rates resulted in measured temperatures significantly less than those recorded during logging (a maximum temperature of about 71°C).

The high circulation rates were required to ensure the cuttings from the 8.5-inch rat hole being drilled with DWD were adequately flushed through the 13.375-inch casing.

Following the completion of the drilling test, the HT DWD tool was transported to Albuquerque for a post-test evaluation. This evaluation included a complete tear-down of the downhole assembly and inspection of the tool hardware. The electronics were still functioning. The tool was found to have weathered the drilling test with only minor pitting beneath the cylindrical cover and no evidence of washing occurring at any connections. The new centralizing slips used to secure the concentrically located pressure barrel were found to have performed as designed with no signs of differential movement between the slips and the barrel.

One unexpected but added benefit to the fielding of the HT DWD system was development of an interface to the WITS/ML data stream used by the ORMAT contracted mud logging company (Horizons). In previous outings with the DWD system, the analog signals from the individual surface based sensors were interrogated using analog inputs to the DWD integrated data display system. Interrogation of analog signal is time consuming because conductors need to be run to each sensor, and calibrations for each sensor needs to be input in the DWD system. WITS/ML is a distributed digital signal (i.e., one cable) that provides engineering units directly to any computer connected to the network; it is a much more convenient method to gather surface based information. Fortunately, the programmer involved in development of the DWD data display system created a robust data acquisition system that only required a couple hours work on-site to adapt the DWD integrated data display system to accept and integrate this signal into the data display used by the driller.

While ORMAT agreed to allow the testing of High-Temperature DWD system, the individual drillers involved in the process were initially reluctant participants. During the test, the driller was supplied with a monitor displaying real-time DWD-generated data and provided a brief explanation of the data being displayed. In normal operations, the drillers use a highly damped, low-accuracy analog gage to control the weight applied to the drill bit; DWD supplies the same data, but with much greater fidelity. While drilling with DWD, the drillers remarked that it was easier to control the weight-on-bit with DWD feedback than with their standard method; they were eventually requesting changes in the monitor displays to accommodate easier viewing of the data in which they were most interested. The drillers' acceptance of the system made it easier for Sandia to implement a series of drilling parameter tests as part of this landmark field test. Figure 19 shows the driller from the rear as he is controlling the brake using the real-time data from the HT DWD system.

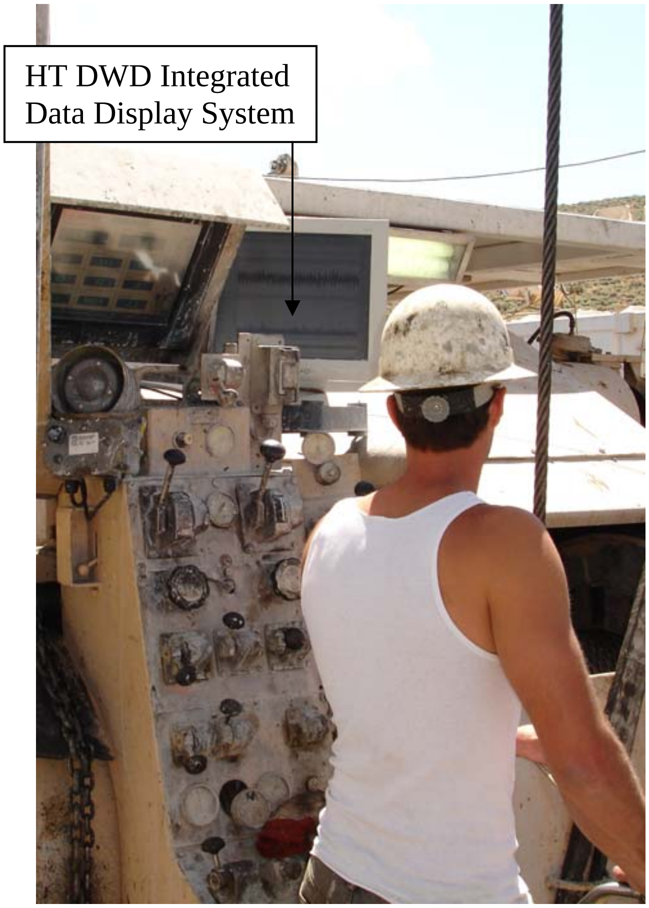

Figure 19 Drilling using the HT DWD data display system to control the weight-on-bit.

6 RECOMMENDATIONS FOR FUTURE DEVELOPMENT

This section defines critical concerns for the development of the next generation of the DWD tool. This tool is expected to target operating temperatures on the order of 300 °C.

Lack of appropriate elastomers

The upgrading of the LT tool to 225ºC was done by selectively screening elastomers to eliminate weak bonds, particularly the bonds that cross-link the polymer. However, that approach is unlikely to work for temperatures near or above 300ºC. The basic bonds that form the backbone of polymers typically begin fail at temperatures well below 300ºC. Polymeric materials that can withstand temperatures around 300ºC, e.g. PEEK, typically do not have the mechanical properties required for o-rings and boots and typically require special application processes that are not practical for downhole tools – e.g. they require sending “small” parts to special fabrication facilities rather than local application to “drill collars.” The previous section notes some exceptional polymeric materials that are worth further consideration. Thus it is anticipated that a 300ºC tool should minimize the need for seals. Seals that can not readily be eliminated should probably be backed up by metallic seals.

Minimization of potential failure points

The original LT tool had a number of bolt penetrations through the “collar” to hold and centralize the electronic package (see figure 9). Bolt penetrations are a potential failure point if bolts vibrate loose or washout. The LT DWD tool had two different types of bolt penetrations: those that held the “spiders” in place and those that held the instrumentation carrier – the central mounting for the accelerometers and other sensors. These latter bolt penetrations are the ones shown in figure 9. During field tests with the LT tool a washout of the spider bolt penetrations did occur. Also there was a problem with the bolts loosening. This was due in part to inadequate curing of the Loctite used. However, even with proper curing of the Loctite, there is concern that vibrations can loosen the bolts. The bolts into the instrumentation carrier appear to be less susceptible to vibrational loosening because they draw it tightly against one side of the collar rather than suspend it in the center, as for the spiders.

The HT DWD tool reduced bolt penetrations by replacing the spiders with a slip type connection. If there had been time for a complete tool redesign, it should have been possible to eliminate the bolt penetrations holding the instrument package. An objective in the design of a 300ºC tool should be to eliminate as many bolt penetrations as possible as well as other connections and holes. For example, the holes shown in figure 9, which are there to contain the electrical feed through connectors and the external temperature sensor, are potential leakage paths that are currently sealed with o-rings.

The internal temperature sensor is housed in a stainless steel (SS) tube that is sealed by welding. The assembly procedures for the LT tool made it difficult to contain the external temperature sensor in a similarly welded SS tube. A design objective of a 300ºC tool should be to contain the external temperature sensor in a similarly welded SS tube. Similarly, the design of a 300ºC tool should minimize the number of connections that require o-rings. One way this can be done is to consider welding such connections, where possible.

Elimination of hinge effect

As discussed above and shown in figure 8, the strain gauge section of the DWD tool is thinner than the rest of the “collar” to improve WOB measurement resolution. Another critical measurement made by the tool is bending strain. Unfortunately the thinning of the strain gauge section results in a significant reduction in bending stiffness. Thus, as currently designed, the DWD tool potentially accentuates some of the drilling dynamic behaviors it is intended to measure (e.g. flexural vibration). Thus a design objective of a 300ºC tool should be to eliminate this “hinge” effect. As noted above, this requires that the problem of space to contain the strain gauges be addressed, as well as the trade off between strain in the steel to which the strain gauges are mounted and resolution of the measurements.

References

Blankenship, D. A., A. J. Mansure, and J. T. Finger, *Update on a Diagnostics-While-Drilling (DWD) System to Assist in the Development of Geothermal Wells*, Geothermal Resources Council Transactions, Vol. 28, August/September 2004

Finger, J. T., A. J. Mansure, S. D. Knudsen and R. D. Jacobson, *Development of a System for Diagnostic-While-Drilling (DWD),* SPE/IADC Paper No. 79884, SPE/IADC Drilling Conference, Amsterdam, The Netherlands, February 2003.

Finger, J., A. J. Mansure, J. Wise, S. Knudsen, and R. Jacobson, 2003(b), *Development of a System to Provide Diagnostics-While-Drilling*, Sandia Report SAND2003-2069, Sandia National Laboratories, 2003.

Henfling, Joseph A and Normann, Randy A., *High Temperature Downhole Monitoring System*, HiTEC 2004.

Mansure, A.J., Bauer, S.J., *Polyurethane Grouting (A Reactive Plug for Cross Flow)*, Sandia Report SAND2003-3178C, Sandia Laboratories, 2003.

Wise, J. L., et al., *Hard-Rock Drilling Performance of a Conventional PDC Drag Bit Operated With, and Without, Benefit of Real-Time Downhole Diagnostics,* Geothermal Resources Council *Transactions*, Vol. 27, pp. 197-205, October 2003.

Wise, J.L., Roberts, T., Schen, A., Matthews, O., Pritchard, W.A., Mensa, G., Ernst, S., Radtke, R., Riedel, R., Hanaway, J., *Hard-Rock Drilling Performance of Advanced Drag Bits,* Geothermal Resources Council Transactions, Vol. 28, August/September 2004

Appendix A
Surface Protection of Gages Ultimately Not Used

This appendix describes the work done to find a rigid encapsulation method to protect the gages, tabs, and wires of the strain-gaged section. Although the described methods were not used in the prototype version of the tool, it is intended to document the lessons learned during the extensive experimentation that accompanied this task.

Search for Candidate High Temperature Epoxies
One failure had occurred in the LT DWD tool due to vibration fatigue of the solder tabs. At the beginning of the development of the HT DWD tool it was felt that some method of stabilizing the solder tabs and lead wires was needed to minimize the potential recurrence of this failure. Initially the idea was to encapsulate the strain gages, solder tabs, and lead wires. Since early tests indicated that the GA-61 would withstand the temperature of 225°C (at least in air), it was decided to try to encapsulate the gages themselves in this compound. Flat plate tests were conducted where the gages were first mounted using the GA-61. After the samples were post cured, a thin layer of GA-61 was spread over the gages and the wires. This sample was then cured and post cured to produce an encapsulation layer. The GA-61 is very thick and is applied with a spatula – it does not "run" when applied. Therefore, neither "dams" nor "forms" were used to restrict flow around the gages for these initial tests.

Encapsulating tests with the GA-61 were not successful. For thin applications, such as used when bonding gages, its performance proved suitable. However the thicker layering required for encapsulation likely led to non-uniform curing through the thickness of the layer. In combination with the high coefficient of thermal expansion of the adhesive, this likely resulted in cracking and chipping during the oven tests as shown in the figure below.

Further studies of higher temperature encapsulating materials have been made by Sandia and are documented in "Conformal Coatings for 225° C Applications" by S. D. Knudsen which was presented at The international conference on high temperature electronics. This conference was held in Santa-Fe New Mexico may 15 through 18 2006.

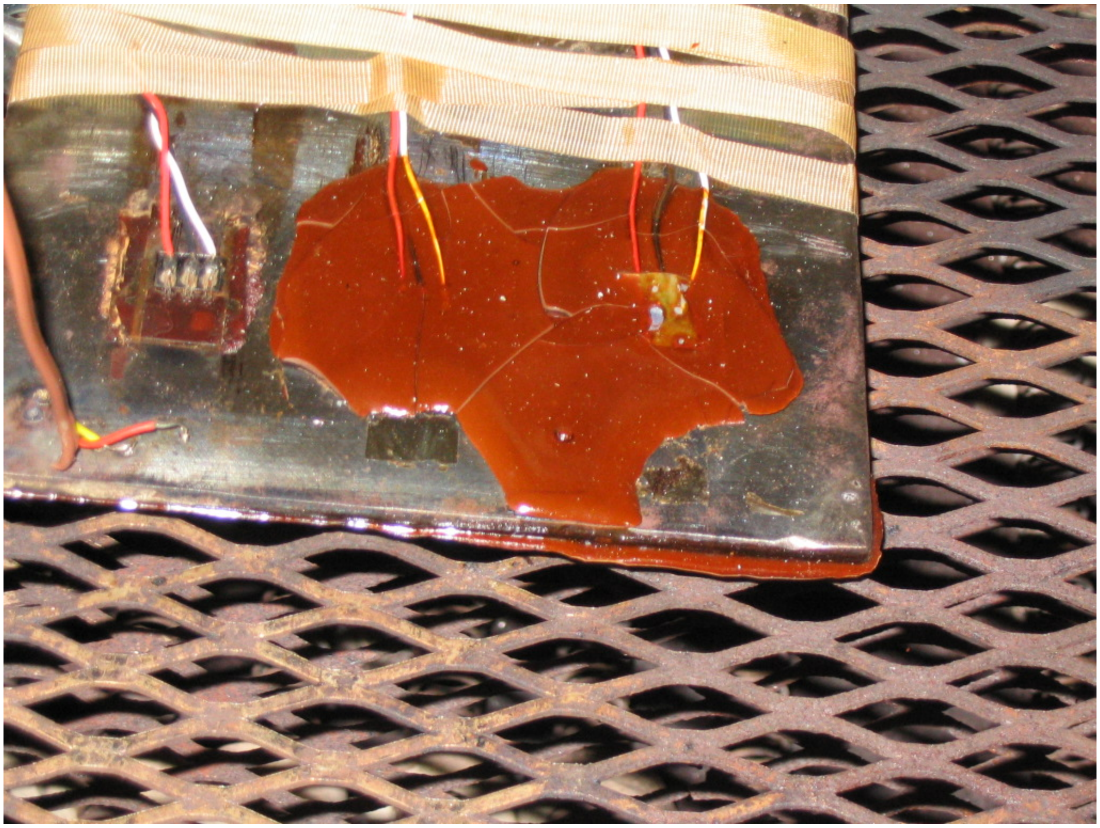

Figure 20 Flat plate epoxy (GA-61) encapsulation test photo

The project team consulted with Mat Celina, a polymer chemist at Sandia with extensive experience related to high temperature epoxies and their reliability, to address this problem. Mat recommended examining products by Huntsman, specifically their 229 and 9029 epoxies. In his experience, these products had very favorable performance at elevated temperature. Both were two-part elevated-temperature cure products which were pourable with good wicking action. Both had favorable qualities for filling crevices and small volumes around the wires and solder connections, thereby achieving a high-integrity encapsulation.

A series of trials was run to test the acceptability of these epoxies using strain gages applied to 4" x 4" x ¼" thick steel plates. Again the gages were bonded down with the GA-61. A small "dam" was built around each gage and solder tab using 1/8" thick silicone sheet. The epoxy was poured into this volume and cured and subsequently post cured.

The 229 product was tested first. It was easy to process and it formed a very nicely-cured block around the gages and wires. The results seemed to indicate that this product might be a good candidate for encapsulation material. For reference, on all steel plate tests, the MicroMeasurements pre-etched Teflon®-insulated wire was used.

During this phase of the effort, it was found that the basic chemistry of these types of epoxy systems (both the Huntsman and P.D. George products) caused the bulk resistivity of the cured product to drop with elevated temperature. At room temperatures, the resistivity was approximately 10^{12} ohms. But, at temperatures over 200 C, the bulk resistivity would drop allowing for a resistance (based on geometry around solder tabs) to be on the order of 10^{6} ohms. Such a resistance, if shunted across solder tabs in a strain gage circuit could potentially cause erroneous readings. Since the intention at this time in project was to consider such an epoxy for a direct gage potting, trials were run to evaluate the effect of the variation of bulk resistivity with temperature.

A split mold was designed and fabricated for application of the epoxy to tubular test samples. This mold was sized to fit a 2" OD tube. It clamped to the sample using bolts. The small gaps at the part lines were filled with silicon sheet to keep the epoxy from extruding out of the mold as it was poured. An annular gap of 0.25" was used to produce the desired epoxy thickness. The mold used for the bending samples is shown in figure 21, clamped in place and ready for the epoxy to be poured.

Figure 21 Epoxy mold

A silicone-based mold release agent was used to prevent the epoxy from adhering to the mold itself. This mold release agent was in contact with the outer cured surface of the epoxy. Since silicone must be mechanically removed (i.e. no solvents for it exist), there was some concern for subsequent operations where elastomer material would be bonded to the epoxy. In early tests, sandpaper was used to roughen up the surface and remove the thin outer layer of epoxy exposed to the silicone. In later tests where elastomers were “mandrel wrapped” over the epoxy, air erasing or light sandblasting was used. The toughness of the epoxy allowed for it to hold up well to this process.

This smaller mold for use with the bending samples had part lines gasketed with 0.062” form cut silicon sheets. As such, the resultant molded epoxy has some flash which had to be dressed with a Dremel tool or equivalent. At this time, a larger mold was made, sized to fit the actual DWD tool’s gage section. It was designed so that it would not have any part lines – i.e. its ID wall was smooth and no gaskets were required.

The 229 was evaluated first, because it was the first product delivered. Both of these Huntsman products were two-part elevated temperature cure high temperature epoxies. The two parts required heating at 50 to 65 ° C prior to mixing to reduce their viscosity sufficiently to pour easily. The mold and the sample were also preheated to this temperature to ensure the best bonding. The 229 mixture was much more viscous than the 9029 mixture, raising concerns about the ability of entrained air to escape prior to, and during, pouring. It was feared that this could ultimately lead to some porosity in the cured epoxy. A vacuum was pulled on the mixtures prior to pouring to accelerate the escape of air entrained during the mixing process. This was effective in achieving a cured sample with minor porosity. The 9029, being thinner (i.e. lower viscosity) was less prone to porosity. It poured easily. Thorough encapsulation of the gages and wires and achieving a ¼” thick encapsulation layer was easily accomplished. Cured molded sample of the 229 and 9029 products are shown in figure 22 and 23.

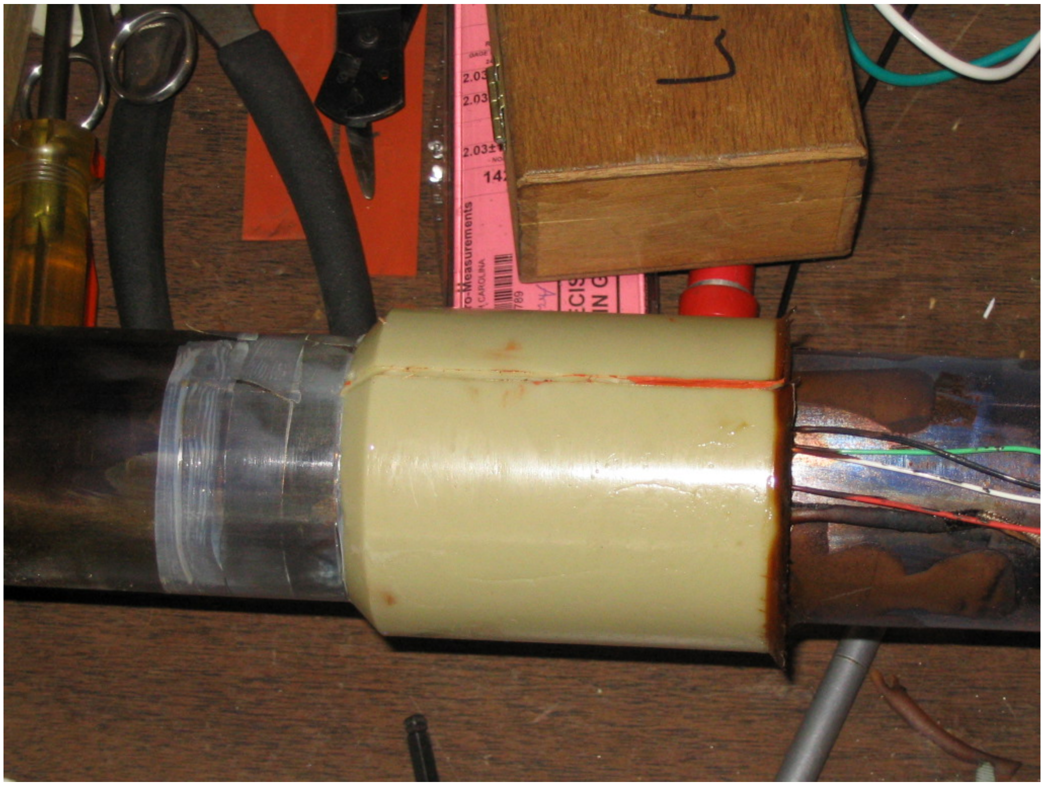

Figure 22 Cured and molded 229 sample

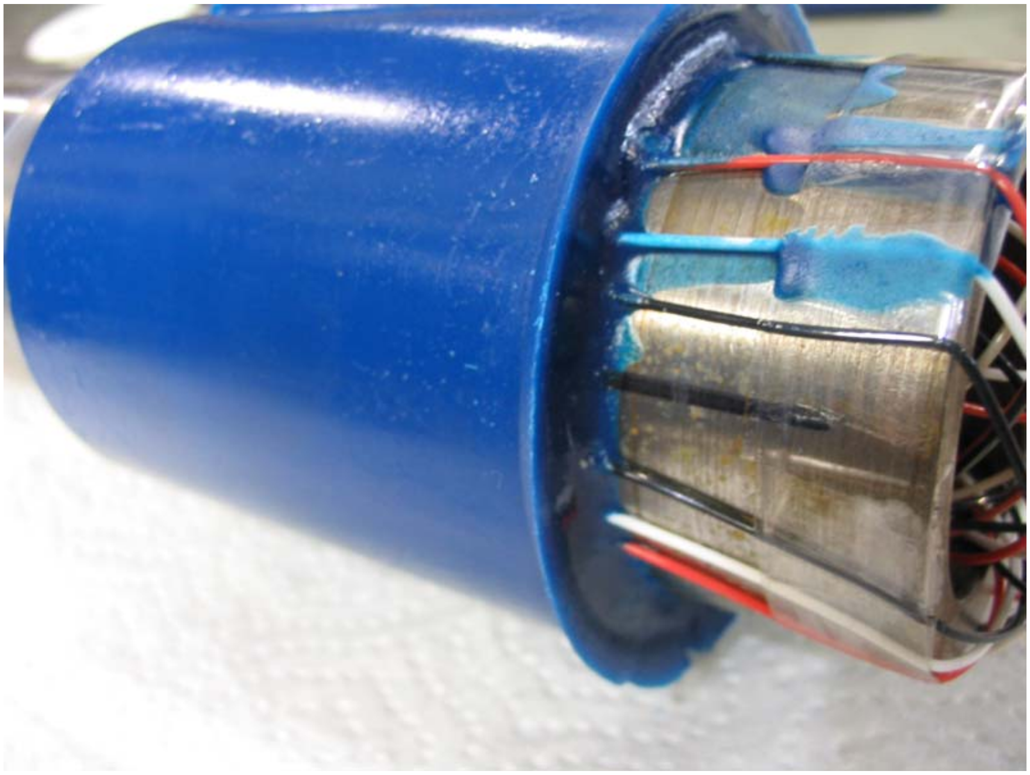

Figure 23 Cured and molded 9029 sample

Mechanical Testing of High Temperature Epoxies

To evaluate the ability of these epoxies to withstand the strain of cyclic bending loads as would be experienced in a drilling tool, a bending frame was designed and fabricated. This frame applied reverse bending loads to a cantilevered test sample. The fixed end of the sample was clamped to the frame with a series of bolts. The other end had transverse “up-down” loads applied with a hydraulic cylinder and a pivoting clamp. The hydraulic pump and valving were controlled by a computer. The computer also recorded data to count cycles and record maximum and minimum outputs from the strain gage circuits. In this way, the gage output could be verified against theoretical calculations to verify nominal performance. The flexure rate was approximately one cycle per second. The bending frame is shown in the figure below. The fixed clamp end is on the left and the loaded end is on the right. The white cylindrical device over the sample in the middle is a ceramic heater which is discussed below.

Figure 24 Strain gage bending test frame

The samples were steel tubes made from 4140 CHT. A 2” OD and 1.5” ID was used in order to generate reverse bending stresses close to the levels that the actual DWD tool would experience. A bending sample with its gages and wiring visible is depicted in figures 25 and 26.

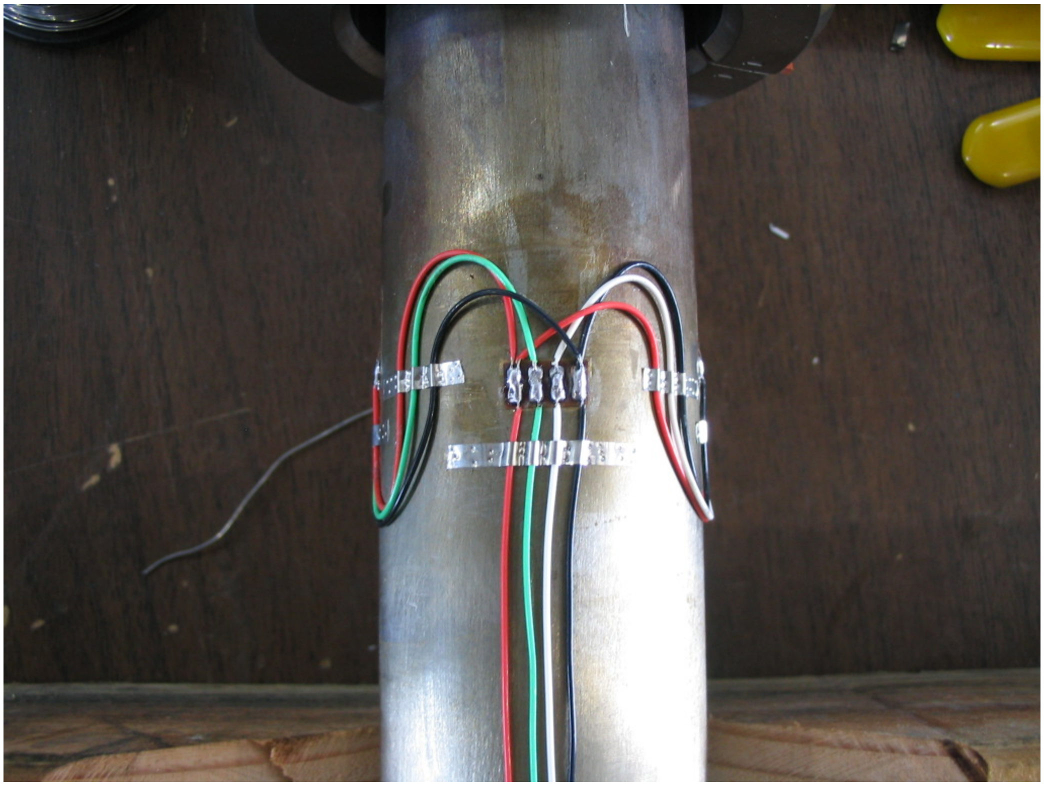

Figure 25 Bending sample view 1

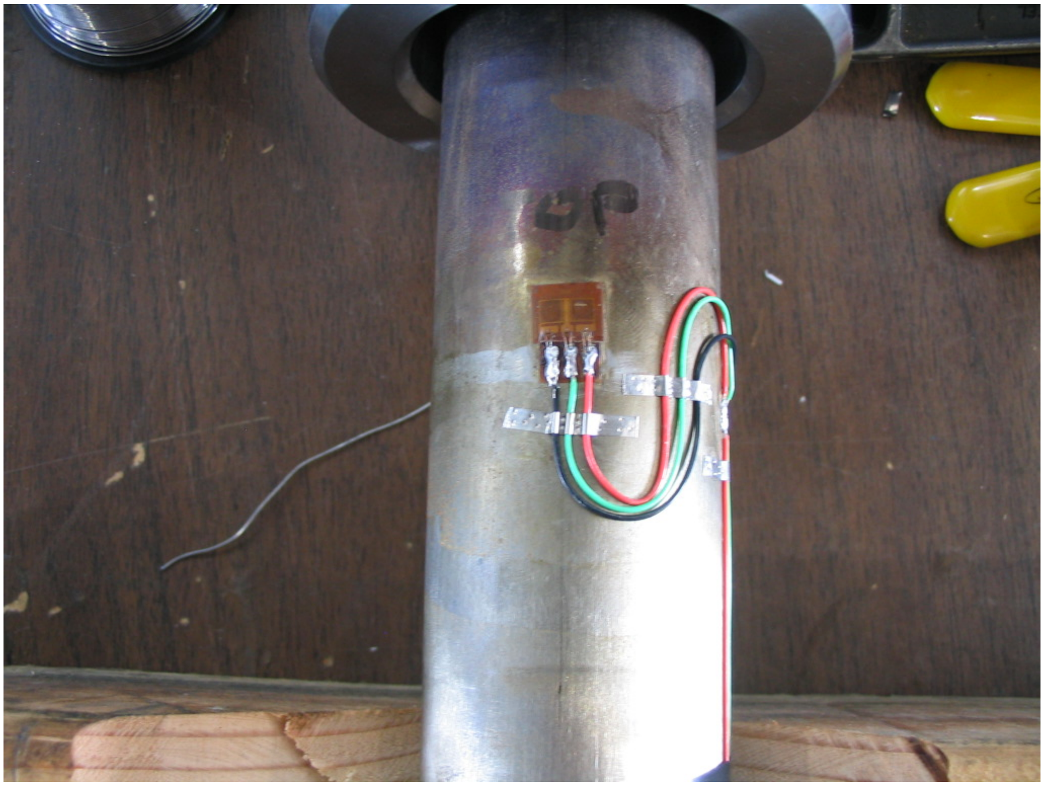

Figure 26 Bending sample view 2

Heat was applied using a radial ceramic radiant heater so the sample could be tested at elevated temperatures. The heater was clamped in a position which centered it with respect to the sample. It had a 6" internal length and a 6" internal diameter with a 1350 watt capacity at 240 VAC. The cylindrical shape provided focused, rapid surface heating and consequently there was concern that the heater would produce excessively high surface temperatures. The heater was driven with 120 VAC to reduce surface temperature overshoot, reducing power consumption by a factor of four to 338 watts. Samples were wrapped in K-wool, a glass-based thermal insulation to promote a slower, more uniform heating of the samples.

The mechanical integrity of the high temperature epoxies and/or the elastomer samples were studied to determine if they cracked or separated from the bending sample. Testing results were used to determine if the processing methodology should be revisited or exclude epoxy candidates from consideration. A base-line metric was established using strain gaged tubes without protective epoxy coatings.

Gages were wired into a full-bridge configuration. Samples were first heated with no applied mechanical load and the bridge output monitored through temperature variations to determine if the circuit output drifted with time and temperature. This effect was insignificant. The temperature variations between ambient and 225 °C never caused a drift of more than several microstrain on each sample. This was deemed negligible and it was concluded that the change in bulk resistivity was not a concern in this application.

Bending frame tests indicated that the gages responded in accordance with calculated predictions, even at temperature, when coated with the Huntsman epoxies. In addition, the epoxies exhibited very good mechanical performance during testing with no observed de-bonding or fracture.

High Temperature Hydrostatic Testing of Samples with AFLAS® over Epoxy Encapsulation

The next step in the process of evaluating the encapsulated gaged samples required the application of heat and fluid pressure. The first test sample to be subjected to this environment was a gaged bending sample where the gages had been encapsulated in Huntsman 229. The encapsulated section was then mandrel-wrapped with a ¼" thick layer of AFLAS® at Eutsler Technical Products. This sample was tested in Mohr Engineering's Lab to 5,000 psig and 232 °C in a 1% brine solution for a period of approximately 12 hours.

Upon removal of the sample after the test, it was observed that the AFLAS® had "ballooned up" over the epoxy as shown in the figure below. (The residue in the photo is a peanut oil residue unknowingly left in the vessel from a prior test. It did not influence the test and was easily removed with a solvent.)

Figure 27 Test sample condition following exposure to 232 °C 1% brine solution at 5,000 psig

Initial observations, along with consultations with the elastomer and epoxy suppliers, were not conclusive. It was unclear whether the AFLAS® or the epoxy (or both) had off-gassed and caused a subsequent “inflation” under the AFLAS®. The off-gassing of the AFLAS® would pose challenges later in the project, but after sectioning of this sample, it was clear that something significant had changed within the epoxy. It was very white and crumbly, almost like chalk, exhibiting none of its previous mechanical integrity. The pressure loading caused this structure to crumble somewhat as well. The AFLAS® appeared to be unaffected, tough and well-bonded to the steel pipe sample. The gages had lost their continuity but it was impossible to tell where the break(s) had occurred.

To better understand the chemical transformation of the 229 epoxy, a series of Fourier Transform Infrared Spectroscopy (FTIR) lab tests were conducted by Analyze Inc. of Chandler, AZ to study the differences in composition between the affected and unaffected epoxy samples. The lab results clearly showed the presence of hydroxyl groups in the “chalky”, compromised epoxy samples. This was indicative of water coming in contact with the epoxy under the AFLAS®.

Careful visual inspection revealed no obvious leak paths within the AFLAS® (no obvious presence of water droplets or wetness was detected). However, further investigation brought to light the knowledge that elastomers can allow diffusion migration on a molecular level. This fact, coupled with the discovery that the fundamental chemistry used in these epoxy products is VERY susceptible to damage by water at elevated temperature, seemed to explain the observations. Therefore, the project team concluded that molecular migration of water through the AFLAS® was degrading the epoxy. It is believed that off-gassing of the epoxy as it underwent this transformation led to the “ballooning effect” of the AFLAS®.

Vapor Barriers

Still believing that application of the AFLAS® directly over the gages and wires would damage these components, a series of tests was undertaken to implement a vapor barrier between the AFLAS® and epoxy. Various attempts were made using: 1) aluminum shim stock in the epoxy molds, 2) polyimide coatings which were dissolved in methyl ethyl ketone (MEK), 3) various fitted shapes of heavy aluminum foil, 4) Kapton tape, 5) Teflon®, and 6) flame sprayed on aluminum. An example is shown in the figure below.

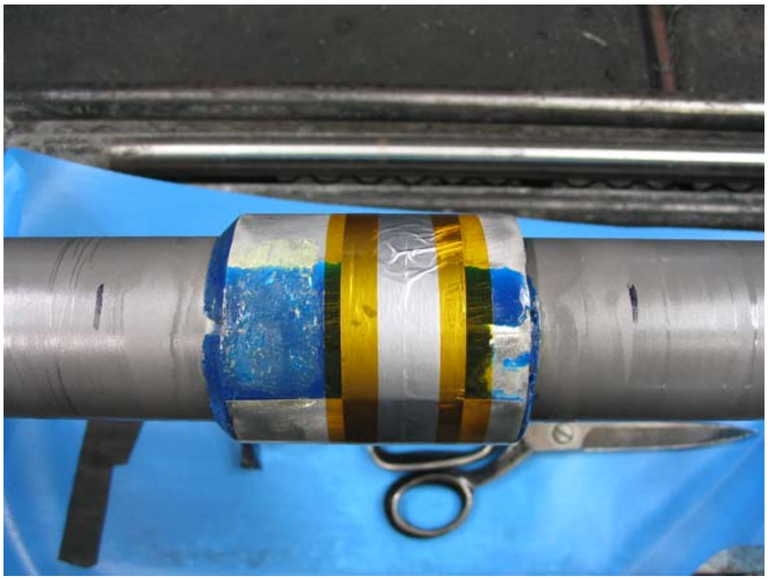

Figure 28 Example barrier designed to prevent steam diffusion through elastomer during curing

The polyimide compound proved ineffective since it was significantly affected by the hot water itself. In addition, the high percentage of MEK solvent in the mixture (which is highly volatile), proved unacceptable for good coverage because the solvent would evolve off leaving “holes” in the polyimide coverage.

The Kapton tape was also unsuitable in that it exhibited significant cracking under the high temperature and high pressure conditions.

The aluminum barriers were marginally effective. They did “slow down” and/or reduce the effect of degradation of the epoxy, but never eliminated it totally. This is due to the difficulty of achieving 100% surface area coverage. The areas around the ends of the cured epoxy and in particular, where the wires exited the epoxy, were always partially exposed. The bottom of the mold was tapered to cover end regions, however, achieving a perfect seal proved impossible.

Both flame sprayed on aluminum and Teflon® also proved too porous. The latter was a surprise. Epoxy was encapusulated in Teflon® and then autoclaved. While the diffusion migration of water was much lower (probably as much as two orders of magnitude lower than AFLAS®) there was still degradation of the epoxy. The water appeared to enter though the bulk Teflon®, not the joint, but there was no way of verifying this. Material specification sheets on Teflon® typically lists its resistance to water migration at the limits of ASTM testing procedures leading to confusion if it is truly negligible or is it too low to test. In any case, inclusion of a Teflon® vapor barrier would have only slowed down the degradation of the epoxy, not stopped it. Also, bonding the AFLAS® to the Teflon® is problematic. Mechanical attempts to reduce the porosity of flame sprayed aluminum were not successful. Trying to seal the pores chemically would have introduced new questions of chemical compatibility. Peening the aluminum reduced the pores and permeability but did not eliminate it.

The use of Teflon® as an encapsulant

Sandia has used several types of high temperature Teflon® heat shrink tubing on past projects. Consequently a series of tests were performed to evaluate its effectiveness as a protective layer over the gages. Again, the issue of the difficulty to bond to Teflon® was a concern. For testing purposes, pre-etched Teflon® heat shrink tubing products were obtained.

Teflon® coated samples wrapped with AFLAS® and subsequently cured and post cured experienced consistent frac outs. The frac out was not always immediately visible after post cure. Sometimes a “skim cut” of the AFLAS® would remove the damaged area. Other times, the skim cut would only reveal deeper defects, in some cases, going all the way to the base metal. Some representative frac outs are shown in the figures below.

Figure 29 Teflon® frac out sample 1

Figure 30 Teflon® frac out sample 2

Initial encounters with these defects during curing involved frac outs that were very small. After the sample was subsequently tested in brine under pressure, the gages were shorted out to each other and to the bending sample steel. Closer inspection detected very small holes on the outside of the AFLAS®. When these holes were probed with small sharp instruments, it was found that these passages led to large voids down in the AFLAS®. These voids appeared to originate near the edge of the Teflon® heat shrink tubing. After inspection and discussion with Eutsler personnel, it was determined that this occurrence of "frac-ing" out was caused by the rapid escape of gas from within or under the Teflon®.

Ordinarily, these gas products migrate through the AFLAS® and escape without causing damage to the curing product. If the gases build up too quickly, from an accelerated curing process, for example, the internal pressure can build too rapidly and a rupture can occur. However, in this case, there was an appreciable amount of empty volume under the Teflon® heat shrink tubing. The tubing was also fairly stiff and did not shrink down perfectly over the wires. So it is likely that air captured under the heat shrink contributed to the frac out. Careful attention to avoiding these frac outs in the AFLAS® continued to be one of the biggest challenges in the remaining efforts to get the HT DWD tool built and fielded.

Given these results, and subsequent testing of this concept using heat shrink Teflon® tubing, it was determined that the tubing could not be used under the AFLAS®. In addition, all of these samples exhibited a poor bonding between the Teflon® and the outside of the tubing. In fact, this poor bond was most likely a contributing factor to the frac outs as well because it gave the evolving gases a place to accumulate rather than migrate out through the AFLAS®. This path of least resistance allowed a large deposit of gas to accumulate which eventually built up enough pressure to rupture the AFLAS®.

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