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An Innovative High-Temperature High-Pressure Measurement While Drilling (MWD) Tool

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Final Technical Report

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ABSTRACT

Measurement while drilling (MWD) tools specified to 150°C (302°F) that provide wellbore surveys, real-time inclination, and natural gamma ray detection are a commodity item in the oilfield services industry. MWD tools specified to 175°C (347°F) that routinely demonstrate highly reliable operation are available from only a few service companies. Commercial MWD tools that reliably operate to 200°C (392°F) for extended periods of time and offer features like real-time gamma ray, retrievability, and reseatability are nonexistent. Need for these higher temperature tools will increase as wells become hotter in the search for new oil and gas resources. The goal of this project was to design a retrievable and reseatable high-pressure/high-temperature MWD tool with real-time continuous inclination, vibration detection, annular pressure, and gamma ray detection. This report describes the development of such a tool from concept, through feasibility, and into field testing and preliminary development planning. It describes the challenges encountered in the design of the tool, along with testing results and decisions about the commercial viability of the tool in the configuration in which it was developed. The decision was made not to commercialize the tool developed under this project because of a combination of battery technology problems and modulation power consumption at the required depths.

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3 Executive Summary

The objective of this project was to design and commercialize a retrievable and reseatable high-pressure/high-temperature (HPHT) measurement while drilling (MWD) tool with real-time continuous inclination, vibration, annular pressure, and natural gamma ray measurements. This tool was designed to improve the economics of deep well drilling by improving overall rate of penetration (ROP) and accurate well placement in deep, hostile environments. Specific research was required in the areas of high-temperature [150°C (302°F) to 200°C (392°F)] and high-pressure [>138 MPa (20,000 psi)] sensors, materials, electronics, packaging, and pressure housings. The project was divided into three phases: Phase I—Feasibility Study, Phase II—Prototype Development, and Phase III—Field Testing and Commercialization.

In Phase I, a market, environmental, and economic analysis indicated a need for an HPHT MWD tool in the market. Based on input from potential clients and current market directions, an MWD tool with ratings of 200°C (392°F) and 206MPa (30,000psi) operating with maximum job duration of 150 hours was proposed, and research and development proceeded toward that goal.

With a target specification defined, research into specific components and technologies began. While the recipient already had a relatively complete suite of electronic components tested and qualified to 200°C (392°F), several parts needed to ensure good measurement quality were lacking. These included analog-to-digital converters (ADCs), voltage references, and power supplies. Testing of existing and new parts of these varieties showed that while some available components functioned at elevated temperatures, commercially available solutions for power supplies were inadequate and would require internal development by the recipient. Candidate sensors for the directional, gamma ray, and pressure measurements were identified and tested with sufficient success to allow commitment to prototype tool development. Test results on pressure housing materials were good enough to allow a preliminary study of increasing the pressure rating of the tool to 241 MPa (35,000 psi), which was ultimately done in Phase II.

In Phase II, an experimental prototype (EXP) tool was developed on the basis of the specification listed above. Because the basic mechanical and electrical architecture of this tool was similar to one already in the recipient's commercial fleet, much of the conceptual work at the tool level began at an advanced stage early in the project development. During the prototype development, a complete tool suite of electronics rated to 200°C (392°F) was developed. Testing consisted of proof-of-concept validation of the coupling device for pressure measurement communication in the recipient's on-site test well, extensive oven testing of the tool electronics up to 205°C (401°F), and oven and pressure well testing of the mechanical portions of the tool up to 205°C (401°F) and 241 MPa (35,000 psi) to validate functionality. As expected, several weaknesses in the electrical circuits were identified during the development, testing, and integration stages. Workarounds were identified and implemented for these issues and corrective design changes were implemented when time permitted. Phase II testing concluded with complete system testing in the recipient's on-site test well to validate the total system performance prior to launching field tests.

In Phase III, the prototype tool was tested in a client's well and a decision was taken not to commercialize the tool as it was designed. The field test of the prototype tool went reasonably well, but revealed gaps in the battery technology temperature rating and weaknesses in the materials involved in the pressure subsystem design. Following the field test an extensive testing program began to fully characterize the tool in terms of power consumption, generation, and availability. Extensive lab testing quantified the static (non-flow) characteristics of the modulator at various temperatures, speeds, and torques. In addition, flow loop testing enabled measurement of modulator torque versus angular position, fluid flow rate, and rotational speed. These data were combined to construct a model of the power characteristics of the tool. Coupled with battery testing over a variety of temperatures and loads, this model enabled determination of expected tool life in various downhole operating conditions. With the available batteries for the tool and the power characteristics as measured, even after improving the power consumption of the tool and optimizing the modulator, the tool architecture as designed showed it was only reasonable to project 20 hours life downhole.

The short expected running life estimated from measured performance data and models led to a decision not to commercialize the tool developed under this agreement. Various alternatives using battery power were considered, but these were either too unwieldy or did not meet market requirements. Ultimately, the recipient made the choice to abandon a battery-powered tool design and pursue a turbine/alternator-powered tool with similar electrical architecture, packaging, and measurement functionality.

4 Experimental

A variety of experiments were conducted on prototype parts and tools during the execution of this project to validate operation and specifications. Following are descriptions of equipment used and experimental methods for various tests.

4.1 Temperature

Temperature testing employed various forced-air convection ovens of sizes appropriate to the devices under test. For larger items such as tools in pressure housings, calibrated thermocouples were attached to the devices and insulated from the oven air to ensure an accurate housing-temperature reading. For smaller assemblies and subassemblies, thermocouples were attached to ambient oven temperature heat sinks or locations on the device that were not subject to significant self-heating. Many assemblies also contained integral temperature sensors that were used to monitor ambient temperature and self-heating. Specific tests included functionality at high temperature, long exposure at high temperature, and thermal cycling including both high and low temperatures.

4.2 Shock

Shock testing was performed with the recipient's standard miscellaneous class shock-testing equipment. Accelerometers were placed on the devices under test (DUTs) to verify shock levels during testing. Testing at various shock levels was performed at the subassembly level as well as at the total tool cartridge level.

4.3 Pressure

Combined pressure and temperature testing was conducted in on-site pressure test facilities that simulate downhole pressure and temperature to stress the tool and ensure compliance with specifications. These wells served to qualify and verify specifications of pressure housings, bulkheads, and other mechanical assemblies as well as to test the entire tool assembly at the target temperature with high-temperature batteries installed.

4.4 Drilling Test Rig

Several tests were performed in the recipient's on-site drilling rig. This fully functional drilling rig is used to simulate downhole drilling conditions such as mud flow, pressure, shock, vibration, and rotation of downhole tools while drilling. These tests are run in the same manner as an external field test to ensure the tests are representative of actual field conditions.

4.5 Flow and Erosion

The on-site flow and erosion loops were used extensively to characterize telemetry quality, tool power consumption and generation, and erosion of mechanical parts under mud flow conditions with and without abrasive mud. The setup of this equipment allows instrumentation of the tool hardware that is not feasible on an actual drilling rig.

4.6 Battery life

Battery chemistry characterization was performed at various temperatures and loads to help predict tool life. As testing of lithium batteries can be dangerous, this took place in the recipient's battery testing facility that includes explosion-resistant test bays and ovens with remotely operated and monitored test equipment to measure temperature, excitation loads, voltages, and currents.

5 Results and Discussion

The objective of this project was to design and commercialize a retrievable and reseatable HPHT MWD tool with real-time continuous inclination, vibration detection, annular pressure, and gamma ray detection. Phase I was a feasibility study to determine whether a reliable and economical tool could be developed, the optimal methods of producing such a tool, and its service. From the results of Phase I, an experimental prototype was developed in Phase II. This prototype was tested at temperatures and pressures defined by the identified tool specifications in the recipient's on-site test well and also in a client's high-temperature well. Phase III included modifications to the first experimental prototype based on results of Phase II and Phase III testing, development of a second prototype, and decisions regarding commercialization of the tool and service.

5.1 Phase I—Feasibility

Phase I addressed five critical areas. Product feasibility depended on each of these having a satisfactory solution. These areas were:

1. Market, environmental, and economic analyses
2. System, acquisition, and power electronics
3. Sensors
4. Signal and power generation
5. High temperature and high pressure housings

5.1.1 Market, Environmental, and Economic Analyses

The initial activity for Phase I was to determine a proposed mission profile so that an economic analysis could be performed and environmental testing and qualification could commence. This proved to be a more difficult task than originally anticipated. One reason was that the market is very small and there was no established business on which to base projections. It is also sometimes difficult to separate real requirements from "nice-to-have" requirements. For this project, nine companies with past experience and future expectations for drilling high-temperature wells were polled. Some companies did not want their specific responses disclosed; those responses are not included in the summary.

For the purposes of this effort, discussion was generally limited to direction and inclination MWD tools except as noted below. The analysis included two classes of clients, those drilling occasional wells that require high-temperature and/or high-pressure capabilities and those planning at some point to drill very deep wells anticipating very high temperatures and/or pressures. From discussions with the polled companies, it was determined that at least some of them anticipate that during deep gas exploration in the 2005-2006 time frame, temperature extremes between 180°C (356°F) and 200°C (392°F) will be encountered, extending to 232°C (450°F) in the 2- to 4-year time frame. Anticipated maximum pressures were identified as 206 MPa (30,000 psi) to 241MPa (35,000 psi).

Given these requirements and the current state of high-temperature electronic development as described further in this report, the proposed mission profile for the prototype tool is shown in Table 1 below.

Table 1. HPHT MWD Mission Profile

Tool operating temperature	0°C to 200°C (392° F) 150 hours
Pressure measurement survival without damage	-40°C (-40°F) to 230°C (450°F)
Maximum pressure rating	206 MPa (30,000 psi)
Maximum measured depth (MD)	9144 m (30,000 ft)

Analysis of an HTHP MWD tool service indicated that a change in the design paradigm would enable the economic operation of such a tool. MWD tools are expensive to buy, operate, and maintain. The cost to operate MWD tools that function above 175°C (347°F) was not widely known because there was little industry experience and his has not been well publicized. However, two notable efforts to develop HPHT MWD tools using conventional technology provided background information. One was the effort by an oilfield service company to develop a 200°C (392°F) MWD tool that was reported in several meetings on high-temperature technologies. The other was the DOE/NETL program DE-AC26-97FT34345 for High Temperature Measurement While Drilling Development.

In the case of the first effort, reliability issues required that all the electronics including the wiring had to be replaced whenever the tool exceeded 175°C (347°F), regardless of duration (Rountree, 2002). While the cost of the electronics for this tool was not known, typical electronics including sensors for an MWD tool can approach 30% to 40% of the cost of the entire tool, making it prohibitive to run a tool above 175°C (347°F) by replacing the electronics after every job. This tool reportedly used silicon-on-insulator (SOI) components, which can cost anywhere from 5 to 50 times as much as conventional silicon electronics. In addition, only a very few SOI components were commercially available, and these had relatively low performance, even compared to conventional electronics available 10 to 15 years ago. From this experience, it became apparent that the use of high-temperature SOI components alone was not a complete solution to develop a reliable and therefore economically viable tool. SOI components are often rated to 225°C (437°F) or more, so the weak link is not the components themselves but rather the circuit board assemblies and their interconnections.

DE-AC26-97FT34345 showed that estimated high-temperature tool operating costs were three to five times as high as a lower-temperature equivalent, that 175ºC (350°F) was the practical limit for conventional electronics, and that binning to find components that survive extreme temperatures was not economically feasible (Cohen, 2002). The conventional electronics used for that tool were most likely plastic surface-mount components (SMC) as well as through-hole plastic and ceramic components. The relatively low cost of these components simply cannot be offset by the added cost of testing and screening. In addition, circuit board assemblies were susceptible to accelerated aging as temperatures increased, potentially reducing their useful life to a few tens of hours above 195°C (383°F). This was clear from experience gained with the tool mentioned in the previous paragraph.

As stated above, electronics are often 30% to 40% of the total tool cost with the mechanical components making up the balance. During Phase I of this project, major components were procured for environmental testing, many of which were higher-temperature versions of components currently in use in 175°C (350°F) downhole tools. A representative sample of those components and their associated higher temperature cost is shown in Table 2. Comparing the cost of these representative parts shows that a 200°C (392°F) HPHT MWD tool's estimated initial cost is about 75% greater than its lower-temperature- and pressure-rated counterpart.

Table 2. HPHT Incremental Cost

Component	**Cost for 175°C (350°F), USD**	**Cost for 200°C (392°F), USD**	**200°C (392°F) Premium, %**
Motor	6000	7500	25
Accelerometer (ea.)	2000	2320	16
Gamma ray sensor	11,000	15,569	46
Voltage reference	5	64	1,121
Magnetometer unit	4500	9000	100
Battery housing	2600	19,000	730

Designing and building an HPHT MWD tool that does not require binning of parts during manufacture or the replacement of the majority of its electronics and sensors each time it is used above 175°C (392°F) is an expensive endeavor. However, the advantages of such a tool are that it is substantially more reliable than a tool composed of surface-mount technology (SMT) electronics and conventional circuit boards and that it does not have the associated costs of part screening and refurbishment charges inherent in those technologies. In addition, if a tool does not need to be sent in to a repair center for refurbishment after each job, then it remains in the field, generating revenue. An analysis of such a tool from a total service standpoint indicated that it is an economically feasible approach, and that was the approach taken for the design of the tool in this project.

5.1.2 System, Acquisition, and Power Electronics

As part of the project in Phase I, candidate system electronics consisting of controllers, program memory, nonvolatile data memory, clock oscillators, and glue logic were identified and tested to 200°C (392°F) or more. As expected, some candidate parts did not function at 200°C (392°F), some exhibited significantly decreased performance, and some showed little or no degradation. As an example, a selection of three different manufacturers' voltage reference parts is shown in Figure 1 below.

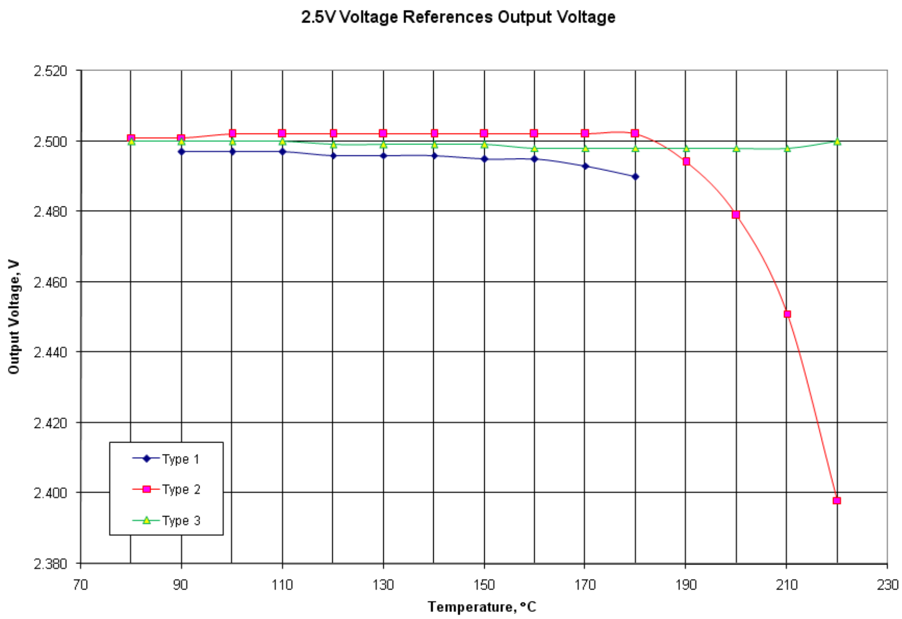

Figure 1. Type 3 voltage reference maintains performance vs. temperature.

Based on previous experience with other projects, a 16-bit, successive-approximation, analog-to-digital converter (ADC) suitable for general purpose data acquisition was tested to 200°C (392°F). A power spectral density plot of the ADC at various elevated temperatures in Figure 2 shows decreased but acceptable performance at the target temperature. Also, since the recipient was a member of the DOE/NETL-Honeywell Joint Industry Project (JIP) to produce very-high-temperature electronics, it was anticipated that the 18-bit sigma-delta ADC under development in that program would be incorporated in the HPHT MWD tool. That ADC was not available during the execution of this project and, as a result, was not used.

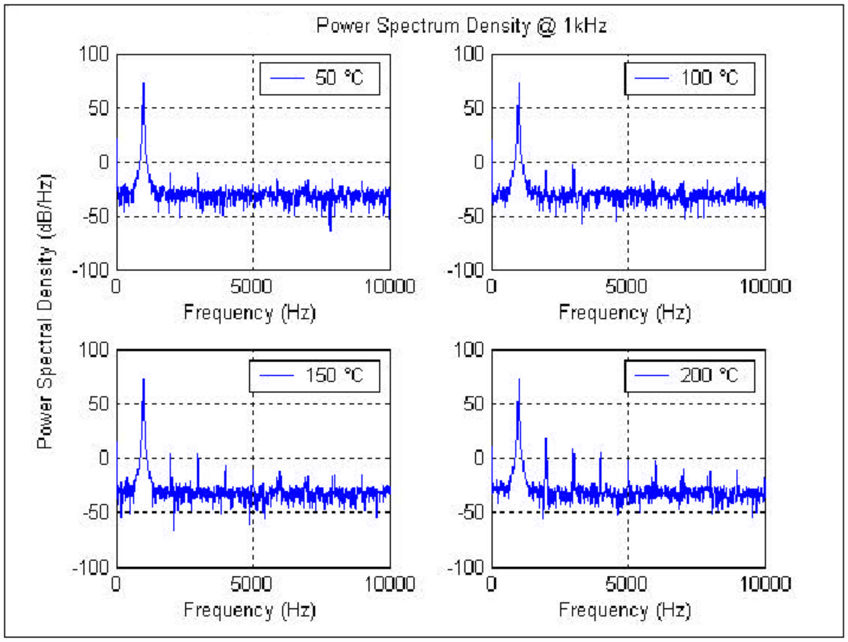

Figure 2. ADC power spectral density decreased performance vs. temperature.

One commercially available 200°C (392°F) power supply was tested to 200°C (392°F) but was an engineering sample not suitable for shock testing. A power supply from a second manufacturer was successfully tested to 200°C (392°F) but failed early in shock qualification testing.

5.1.3 Sensors

The 200°C (392°F)-rated accelerometers proposed for use in the direction and inclination subsystem passed initial temperature and shock screening, but one of three later failed environmental qualification during shock testing. Figure 3 shows the sensor bias in µA of the three units before (BGx, BGy, and BGz) and after (BGx2, BGy2, and BGz2) environmental testing, showing unacceptable drift of the bias models. Failure analysis by the vendor revealed an atypical failure not normally associated with high shock, so this failure was apparently a manufacturing defect. Additional parts were ordered for follow-up testing that took place in Phase II.

A gamma ray crystal detector, scintillation counter, and high-voltage power supply were all tested to 205°C (401°F). A discriminator and counting circuit was not developed in Phase I because it was anticipated that a high-temperature version of that circuit would be readily adapted from available components already known to perform to 205°C (401°F). A commercial vendor was developing a higher-temperature detector targeted for around 220°C (428°F) that was to be incorporated into the tool when it became available. These changes were partially successful and were integrated in the tool Phase II. Figure 4 shows a spectrum of response versus energy level of the gamma ray detector system.

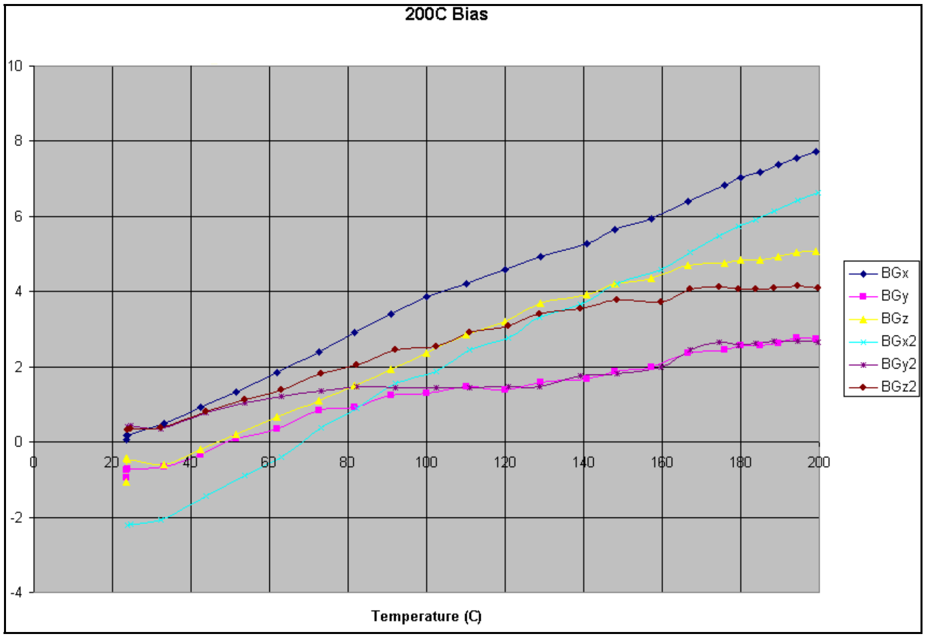

Figure 3. Accelerometer bias vs. temperature shows unacceptable drift.

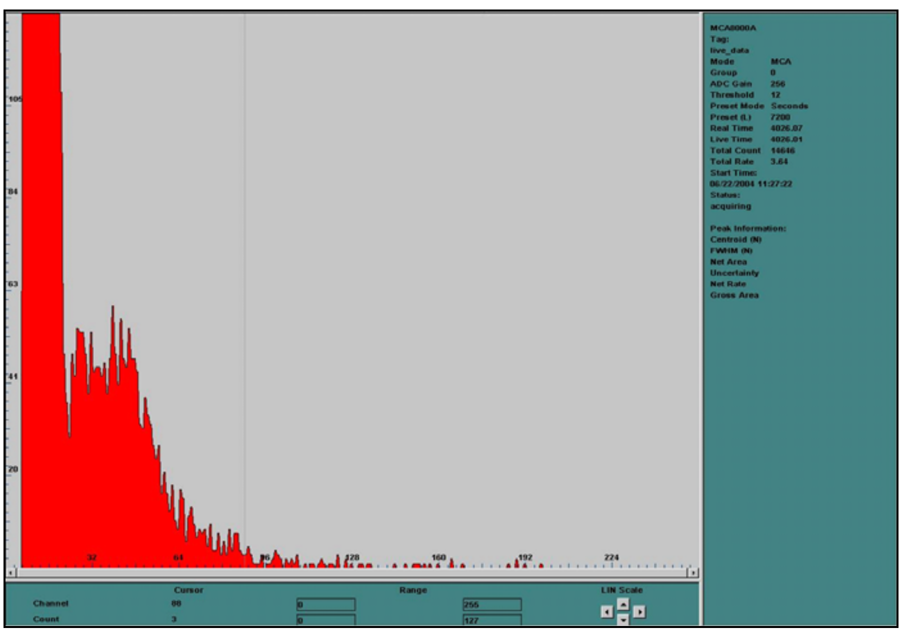

Figure 4. Gamma ray spectrum at 200°C.

Pressure sensors were also identified and tested to 200°C (392°F). A candidate mechanical architecture was conceived to allow retrievable and reseatable operation of the tool while maintaining collar integrity.

5.1.4 Signal and Power Generation

Materials for the modulator/generator were identified and tested for effectiveness at high temperature. A motor for driving the modulator/generator was tested to 200°C (392°F). Figure 5 shows a plot of the motor efficiency at 200°C under various torque loads, indicating acceptable performance at the loads anticipated in the design. Simulations indicated that the modulator could generate sufficient downhole signal strength to allow effective data transmission for the targeted mission profile.

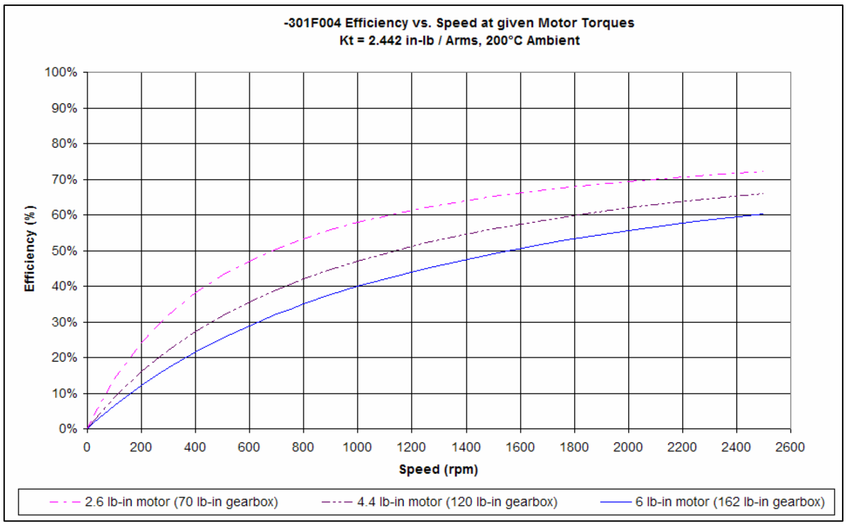

Figure 5. Motor efficiency at 200°C.

Battery chemistry was identified and tested to 200°C (392°F). Life testing and low-temperature performance verification tests were in progress in Phase I. Figure 6 shows a plot of voltage vs. time for a single cell tested at 200°C (392°F). Indications were that the operational temperature safety margin at 200°C (392°F) was unacceptably small and operation even slightly above 200°C (392°F) could cause the batteries to fail catastrophically. Additional development to improve the safety margin of these batteries was undertaken in Phase II.

5.1.5 Pressure Housings

Housing material to meet the requirements for the anticipated pressure housing size was identified, sourced, and successfully tested to 213 MPa (31,000 psi) and 210°C (410°F). Figure 7 shows the temperature and pressure traces from the combined test. Lead times and availability of this material prevented more extensive testing in Phase I. Housing material with a lower pressure rating was used for tool assembly in Phase II until the higher strength material was delivered.

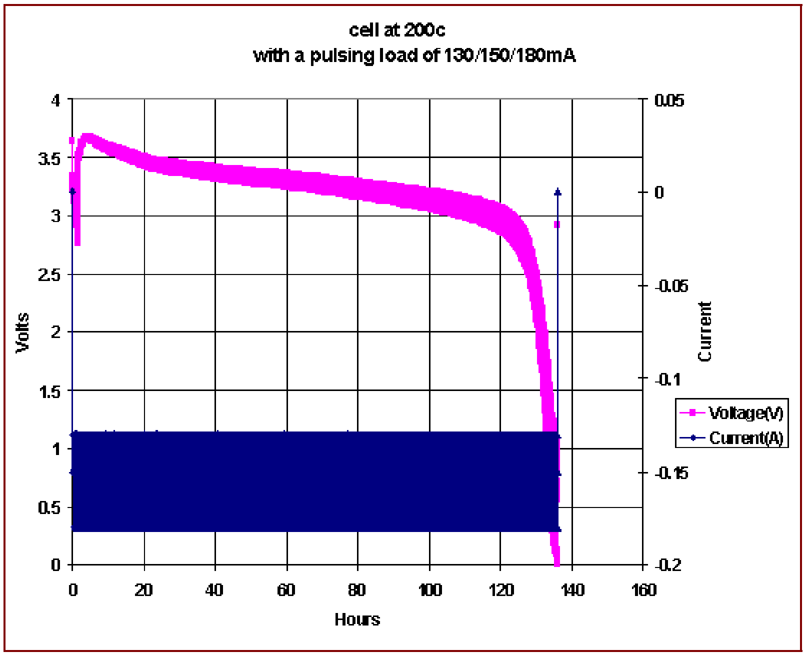

Figure 6. Battery testing at 200°C.

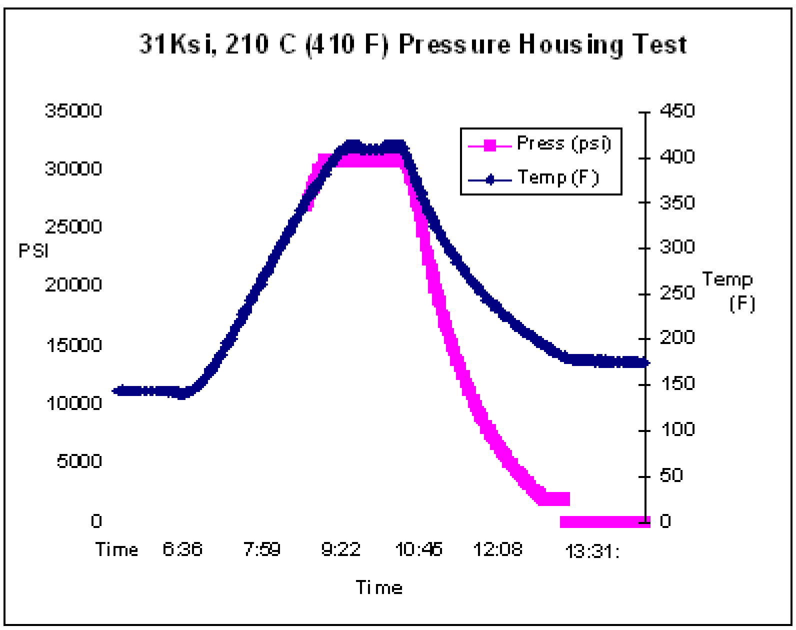

Figure 7. Housing combined pressure and temperature testing.

5.1.6 Phase I Summary

Research, development, and testing of candidate components and subassemblies were substantially complete at the conclusion of Phase I. However, additional testing was planned for phase II in a few areas, as detailed in Table 3. The original application included budgeting for this testing as well as refinement of the design based on the results of full scale testing. In addition, testing of the reseatability device required a full scale prototype, whose design and testing also took place in Phase II.

Table 3. Additional Testing

Technology	Results to Date	Additional Testing Required
Analog-to-Digital Converter for Pressure Measurement	Initial tests show the existing ADC functions but may not have sufficient resolution at the highest temperatures.	The ADC developed by the DOE/NETL-Honeywell JIP will be tested and adopted once it becomes available. Architecture for the tool will be such that that all SOI components developed as part of the JIP will be adopted once they become available.
Batteries	Batteries tested to 200°C (392°F).	Additional development is necessary for battery safety margin above 200°C (392°F).
Electronics	Conventional electronics functions to 200°C (392°F). High-temperature packaging sufficient to 200°C (392°F) or more.	SOI electronics developed by the DOE/NETL-Honeywell JIP will be tested and adopted once it becomes available. Architecture for the tool will be such that relevant SOI components developed as part of the JIP may be adopted once they become available.
Gamma Ray Detectors	Temperature testing to 200°C (392°F). Preliminary shock testing.	Final environmental qualification. Additional development to 200-230°C (392-446°F).
High Voltage Power Supply	Initial tests revealed existing commercially available HV power supplies do not withstand severe shock and vibration typically encountered during drilling.	Existing power supply designs currently working at high temperature will be tested, ruggedized, and qualified.
Motor testing	Motor torque has been tested to 200C (392°F).	Motors needed to be tested to failure to determine upper limit.
Pressure Housing	The pressure housing has been tested to 213 MPa (31 kpsi) at 210°C (410°F).	The pressure housing needs to be tested to failure to determine upper limit. In addition we will examine the possibility of increasing the temperature rating to 341 MPa (35 kpsi).

5.2 Phase II – Prototype Development

Based on the results of Phase I, an experimental prototype (EXP) tool was built following the tool architecture described below. To ease the development and testing effort, the tool architecture was based on one of the recipient’s commercial tools with a proven record in field operation and upgrades to that system already in progress. In addition to the proven reliability, this architecture was sufficiently modular to allow for upgrades to higher temperature by including parts such as the DOE-NETL-Honeywell JIP components when they become available without altering the basic tool layout. The chosen electrical circuit packaging was based on technology previously developed and qualified for use at high temperatures by the recipient. The prototype underwent in-house testing and qualification, including testing in the pressure vessels and the on-site test rig. Following in-house testing, the recipient's field coordination personnel located a suitable client well which was used for a field test.

In addition, a scope change amendment to the original cooperative agreement added efforts to increase the tool pressure rating from 206 MPa (30,000 psi) to 241 MPa (35,000 psi) improve the safety margin of the battery to allow safer operation at 200°C (392°F), and improve the temperature performance of the gamma ray detector. These efforts are further discussed below.

5.2.1 Top Level Tool Description

Figure 8 shows the physical architecture of the retrievable HPHT MWD EXP tool. The tool consists of three parts: the retrievable HPHT tool, the mounting collar (HTSA), and the pressure measurement assembly (HTRA).

The retrievable tool consists of the following subassemblies:

- HTMA (HPHT Modulator Assembly). The HTMA houses the mud siren-type modulator for downhole signal generation, motor and gear box to operate the modulator, pressure compensation system for the modulator, motor control and motor drive circuits, HTMA power supply, and intratool communication circuits.
- HTEC (HPHT Electronics Cartridge). The HTEC contains direction and inclination (D&I) sensors and measurement circuits, natural gamma ray detector and measurement circuits, the main controller used for signal processing and tool control/housekeeping functions, the HTEC power supply, and intratool communication circuits.
- HTBA (HPHT Battery Assembly). The HTBA consists of the battery pressure housing and the high-temperature battery itself. The battery provides power to turn the modulator and operate the electronics.
- HTHA (HPHT Host Assembly). The HTHA contains intratool communication circuits, the HTHA power supply, and circuits that provide communication between the host assembly in the retrievable tool and the remote assembly in the nonretrievable part of the tool housed in the pressure sub collar.
- Stinger Assembly. The stinger is the retrievable part of the coupling that facilitates pressure measurement between the nonretrievable part of the tool where the pressure sensors are physically packaged and the retrievable tool that transmits the pressure and other measurements to the surface via MWD telemetry.
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The nonretrievable tool components are:

- HTSA (HPHT Shock Assembly). The HTSA is a standard drill collar design used in other MWD tools. The collar provides the fluid path between its ID and the OD of the retrievable MWD tools for the mud circulation, landing, and orientation features for the retrievable tool, and centralizing components to reduce shock and vibration levels impacted on the tool.

- HTRA (HPHT Remote Assembly). The HTRA is a smaller collar (sub) that houses internal and annular pressure sensors, front-end signal amplification electronics, and the nonretrievable part of the coupling used for interfacing with the HTHA assembly.

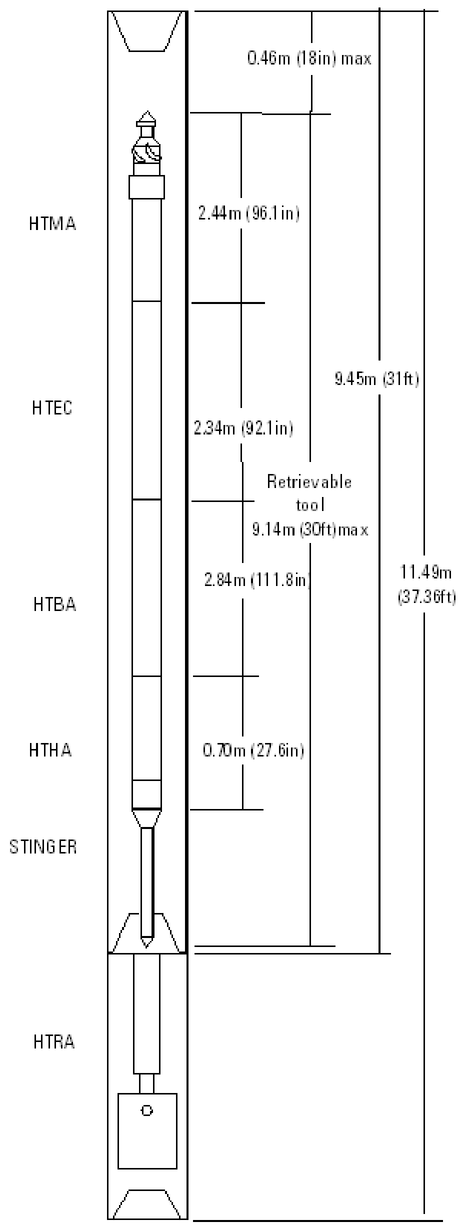

Figure 8. HPHT MWD in NC38-47 collar with pressure sub.

5.2.2 Component Descriptions

The summary below details the main tool components in the same order as described above. Development and testing results are included in the individual sections. The results from the system-level tool testing follow this section.

5.2.2.1 HTMA Mechanical

The HPHT modulator assembly was developed using the materials and components identified in Phase I of the project. The mechanical design of the modulator was based on an existing retrievable MWD tool with lower temperature and pressure rating developed by the recipient in the 1990s, as shown in Figure 9. As the HPHT tool was intended for deeper wells, the signal output from the modulator had to be significantly increased to the levels specified by the calculations performed in Phase I. This was achieved by increasing the effective relative flow area in the rotary valve restriction section. Special materials were used for the mechanical valve parts to ensure that the erosion of the components was kept to a manageable level. Along with flow loop and erosion tests performed in the on-site test facilities mentioned above, finite element analysis (FEA) simulations confirmed the required signal levels and erosion characteristics.

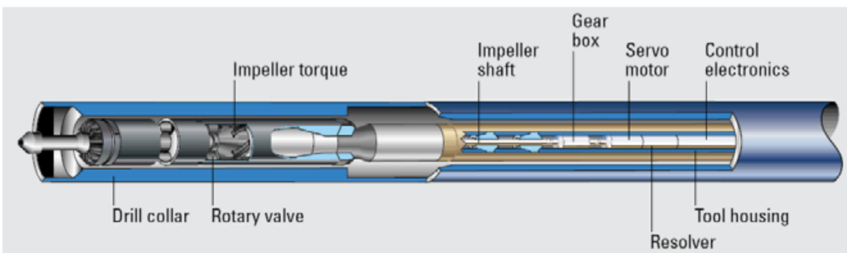

Figure 9. HPHT MWD modulator mechanical architecture.

The early testing of the assembly showed the need to improve the following components:

- Hydraulic Oil. The original hydraulic oil that operates the pressure compensation system and provides lubrication to various moving parts was insufficiently inert at high temperatures, resulting in the degradation of motor insulation. After an extensive program of oil and varnish compatibility testing the final replacement oil was selected and qualified. After 1,000 hours of testing at the target temperature, the integrity of the motor and oil remained adequate.
- Modulator Stator Assembly. The modulator stator assembly design was based on three parts joined together, and the material selection requirements for the parts did not allow the use of conventional joinery methods to provide the structural and pressure integrity needed in the design. As a result, the stator assembly went through eight design iterations before passing qualification testing. Besides tests with the HPHT MWD tool, the new design was also validated with the existing commercial, retrievable MWD tool at lower temperature/pressure conditions. While basic reliability of the design has been achieved, its manufacturing process involves several vendors and processes that result in somewhat inconsistent

quality and performance spread. Further work outside the scope of this project is ongoing to improve the design and performance consistency.

- Compensator Shaft Seal. The pressure compensator shaft seal used initially in the design would fail after several hours of exposure to downhole conditions. This seal failure allows drilling fluid to leak into the compensator section, which could eventually cause the modulator to fail. To improve the reliability of the tool, a different type of rotating shaft seal system was selected.

5.2.2.2 HTMA Electrical

The HTMA electronics section consists of a motor control circuit, motor drive circuit, power supply, and communications circuit. It connects to a motor and resolver for modulation control (Figure 10).

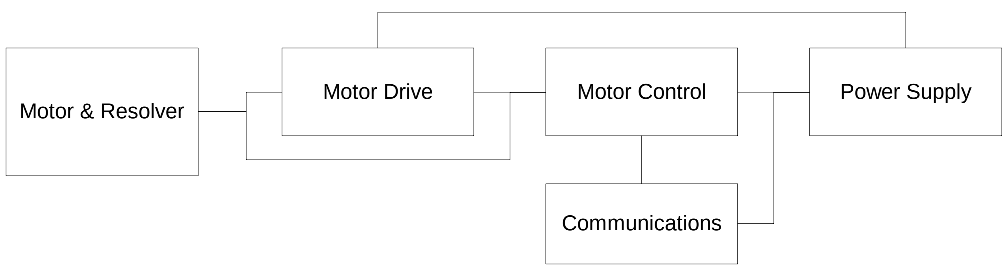

Figure 10. HTMA electrical architecture.

The motor drive circuit consists of switching transistors to drive the motor and associated drive electronics for the transistors. Aside from initial noise coupling issues that were uncovered during tool-integration testing, the circuit functioned exactly as expected. The mechanical mounting of the circuit was modified to alleviate the noise issues during early testing, and a second iteration of the board eliminated the issue completely.

5.2.2.2.1 Motor Control Circuit

The basic motor control circuit design (Figure 11) was taken from an existing design already in use by the recipient. Early testing of the existing circuit, however, identified a weakness in its memory IC at the target temperature. A temporary workaround was identified that allowed initial testing to continue and the circuit was redesigned to include a different memory chip already known to work at the target temperature. This redesign improved robustness of the system, which has demonstrated significant design margin at the target temperature of 200°C (392°F).

5.2.2.2.2 Communications Circuit

The communications circuit is common to all the larger modules, as discussed above. It consists of a modem using one of the recipient's existing protocols for intratool communication. Testing of the original implementation of the modem revealed marginal functionality and poor manufacturability for the target temperature, so a different design of the same modulation/demodulation scheme and protocol was implemented. Testing again showed significant temperature design margin at the target temperature of 200°C (392°F).

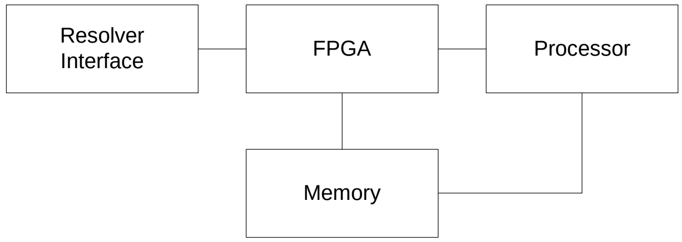

Figure 11. Motor control circuit.

5.2.2.2.3 Power Supply

The power supply circuit is also common to all the main modules. The function of the circuit is to convert the battery voltage to digital and analog supplies used by the control, acquisition, and communications circuits. After testing the recipient's existing designs and new candidate circuits, an existing power supply design already in use by the recipient was chosen as the starting point for the tool.

Modifications were immediately undertaken to upgrade the performance of the power supply to operate at the target temperature and load, both of which were different from the original application. Changes to the transformers, feedback circuits, and snubbing circuitry were necessary to allow operation at the target temperature. Ultimately a design stage was reached that allowed operation at the tool target temperature. The topology chosen and restrictions on available packaging space limited the net efficiency of the power supply to 40%. This, combined with battery issues discussed below, limited the length of time the tool would operate to a number lower than originally specified. The circuit also had an unintended limitation that prevented proper operation if power were applied at temperatures above approximately 185°C (365°F). This was an acceptable limitation because the tool operated on batteries and the batteries were always in circuit before the tool reached that temperature.

5.2.2.3 HTEC

The HTEC is the tool's main electronics cartridge. It contains the tool's directional and gamma ray sensors as well as electronics to acquire data from the sensors and send it to the modulator for transmission uphole. Figure 12 shows the electrical layout of the system.

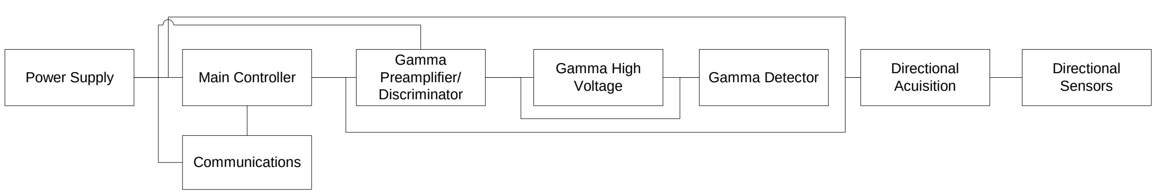

Figure 12. HTEC electrical architecture.

5.2.2.3.1 Main Controller

The main controller circuit (Figure 13) was also reused from the earlier project after component testing in Phase I and prior test data revealed that this circuit would be appropriate for this application. The system consists of a microprocessor; program, data, and recording memories; an FPGA that provides interfacing; and an analog acquisition circuit to acquire health monitoring status of the tool such as temperature, battery current, and shock measurements. It also contains a counter for the gamma ray detector and communication circuits to gather data from the directional module described below. The main controller suffered from the same memory weakness as the motor control circuit described above, and the same workaround was applied to it to allow operation in the prototype. A redesign of this circuit was started but not completed during the scope of the project.

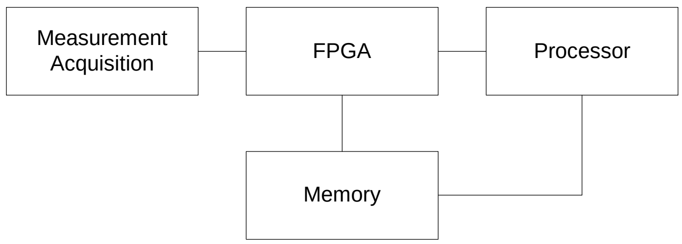

Figure 13. Main controller circuit.

This circuit serves as the central intelligence point of the entire tool, gathering data from subsystems, performing any necessary processing of that data, and formatting it properly for transmission to the surface. It also controls what modulation schemes will be used, what data will be sent depending on operation parameters such as inclination and rotation, when to acquire data such as pressure, and when to take survey measurements and transmit them to the surface.

5.2.2.3.2 Gamma ray

A high-temperature plateau-type scintillation gamma ray detector module was developed by the recipient’s detector research and production facility, and several prototypes were manufactured and tested. Initial testing in Phase I showed that the detectors had marginal performance at 200°C (392°F) and improvements were warranted.

The additional work to optimize and increase the reliability of the gamma ray sensors at maximum operating temperature rating was partially successful. The new gamma ray detectors were tested to alleviate concerns that thermionic noise and light leakage might cause unacceptable performance or significantly reduced life. Acceptable performance was achieved, but life at maximum temperature was still lower than hoped. However, the life (>100 hours) achieved at temperature was deemed acceptable for viable tool operation. Additional information gathered in this effort was used to determine the maximum number of high-temperature operating hours before replacement to ensure reliable and uninterrupted service. Sample high voltage plateaus showing decreasing plateau length with increasing temperature measured as part of complete tool system testing are shown in Figure 14.

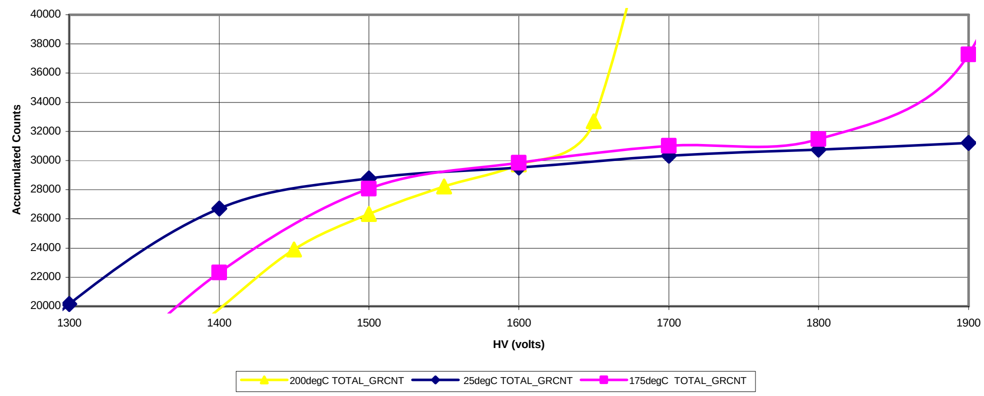

Figure 14. Gamma ray detector plateau.

A high-voltage ladder-type power supply circuit for the gamma ray was developed for use with the detector. This ladder was designed to generate at least 2,000 V for the detector. Testing demonstrated that the ladder can function for at least 600 hours at the target temperature and that it will operate in excess of 225°C (437°F).

A circuit developed for the gamma ray detector amplifies the electron pulses from the detector. These amplified pulses are then compared to a threshold specified by the detector vendor to discriminate incoming signals between "dark current" noise and actual-incident gamma rays. This circuit functions with at least 20°C (36°F) margin at the tool target temperature and has the ability to function correctly at that temperature for over 1,500 hours.

5.2.2.3.3 Direction and Inclination

The direction and inclination sensor package consists of three subparts: three orthogonal accelerometers, three orthogonal magnetometers, and a data acquisition and processing circuit (Figure 15).

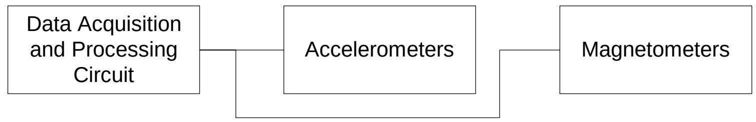

Figure 15. Direction and inclination system.

The accelerometers provide a measurement of the inclination (deviation from vertical) of the tool and also provide a measurement of toolface (the rotational orientation of the tool), which is useful for steering the bottomhole assembly (BHA). When combined with the accelerometers, the magnetometers provide a measurement of the direction (magnetic heading) of the BHA and also its orientation when the BHA is at or near vertical.

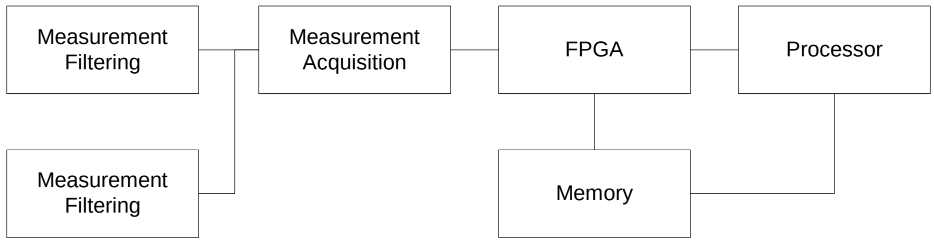

Figure 16. Data acquisition and processing circuit.

Initial investigation of accelerometer and magnetometer sensors started during Phase I of the project and continued in Phase II. The overall architecture and circuit design of the data acquisition and processing circuit (Figure 16) was based on existing circuits that had been developed for use in another of the recipient's projects.

Two vendors that were evaluated for accelerometers both initially failed the recipient's standard qualification testing regime. Subsequent design and testing ultimately resulted in both vendors' parts surviving qualification testing but with one vendor's parts demonstrating distinctly superior performance. This vendor was ultimately selected for the tool.

Several prototypes of high temperature magnetometers from a commercial supplier were obtained for use in the directional package. In addition to survival qualification using the normal methods, the recipient's direction and inclination calibration facility was used to thoroughly evaluate the sensor performance up to and including the tool's target temperature. Testing revealed a flaw in the electronics that manifested itself as a failure at the target temperature and also a sensor failure that appeared as a nonlinear, orientation-dependent, cross-axis coupling phenomenon. After presenting the data to the supplier, the circuit design was fixed, and further investigation revealed a systematic problem in the sensor manufacturing process that was ultimately corrected.

5.2.2.4 Batteries

As described above, battery technology was developed in Phase I to operate at 200°C (392°F) but with insufficient safety margin. During Phase II a modified chemistry was tested to increase the maximum temperature rating of the batteries and to determine the safety margin. The modified chemistry was successful for both purposes. Battery chemistry was optimized and engineering tests including shock vibration, temperature cycling, simultaneous heat and shock tests and a successful environmental qualification were performed. This testing determined that the battery could operate 10°C (13°F) above its original estimated rating and that a safety margin of more than 30°C (54°F) existed.

As the HPHT MWD tool prototype development progressed and data became available on its power consumption under various operating conditions, additional battery tests were carried out to characterize the tool's job-life performance (autonomy). These tests established the limits of the performance of the battery chemistry and its dependence on temperature and load. The load testing showed good correlation with other tool and battery test data (see below) that indicated that the tool would not meet its specification of 150 hours running life at 200°C (392°F). Also, the temperature dependence indicated an operational problem in that, although the batteries perform at a certain rate at 200°C (392°F), the performance drops off rapidly with decreasing temperature, making it difficult to manage the drilling temperature variations that arise from friction while rotating, cooling effects from surface mud, and heating effects from the formation when mud is not flowing from the surface. A circuit was added to the tool at the outset in anticipation of this issue to help minimize the problem, as described below.

5.2.2.5 HTHA

The HTHA is the bottom-most section of the HPHT MWD retrievable tool. It is an assembly that consists of a power supply and communications circuit, as with the HTMA and HTEC above, and a pressure while drilling (PWD) host circuit (Figure 17). In addition, a switch circuit (not shown in the block diagram) designed to help manage battery life interrupts the battery current and operates independently from the rest of the HTHA circuitry.

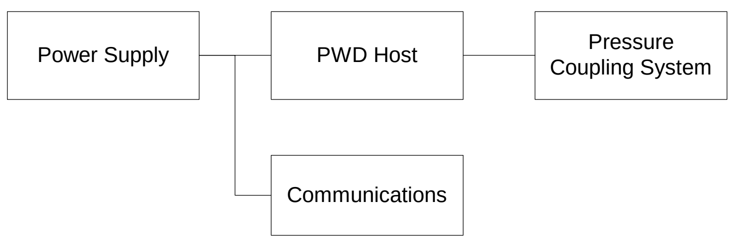

Figure 17. HTHA block diagram including pressure coupling.

5.2.2.5.1 PWD Host

The PWD host circuit (Figure 18) serves as the interface between the main electronics of the tool (HTEC) described above and the pressure system coupling described below. This circuit was designed using the best practices learned from design and testing of the motor control, main control, and direction and inclination acquisition circuits and did not have any temperature-related problems.

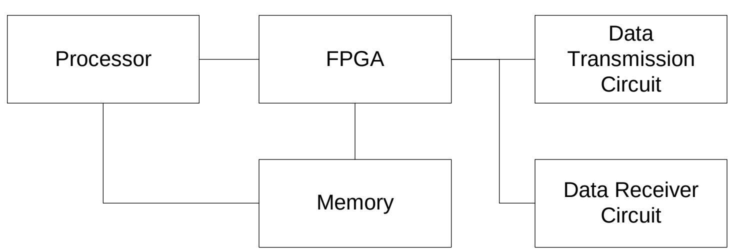

Figure 18. PWD host block diagram.

The function of this circuit is to transmit power and data, using the data transmission circuit, over the pressure interface to the HTRA described below. Following the data and power transmission, the host circuit waits a specified amount of time for the HTRA to transmit data back over the pressure interface. This data is received by the host processor and sent back to the main tool over the intratool communication link for transmission to the surface in real time.

5.2.2.5.2 Thermal Switch

The thermal switch circuit (Figure 19) is used to prevent premature battery discharge and damage from excessive power draw at temperatures too low for the battery to operate properly. The thermal switch circuit consists of a temperature sensing element, a setpoint element, a decision making circuit, and a switching element that turns the tool on. When the temperature sensing element indicates the temperature is above the setpoint appropriate to the battery that is being used, the tool is turned on and the battery is used as the power source for the tool.

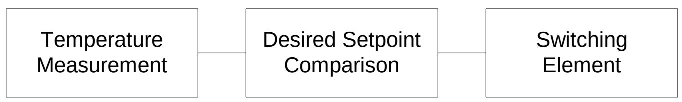

Figure 19. Thermal switch block diagram.

As mentioned above, the higher-temperature batteries do not operate well at temperatures below their target temperatures, and this causes a problem if the tool draws power from the batteries before the target well temperature has been reached. This could occur on the surface, during tripping operations when the drill string is being inserted into the well, or when the tool is being inserted into a BHA that is already in place. Because the switching circuit in this case presents a small load to the battery, it serves the additional purpose of depassivating the battery or preparing it for higher current loads while the tool is switched off.

5.2.2.6 Pressure System Coupling

The pressure system interface contains two parts that make up the halves of a separable transformer. The two halves are referred to as the male and female couplings. The male coupling is connected to the retrievable portion of the tool below the HTHA and extends to the bottom of the collar that houses the retrievable tool. The female coupling is connected to the remote pressure sub electronics described below. Both couplings extend into the threaded joint between the two collars and are fully mated when the two collars are torqued together and the retrievable portion of the tool is seated in the HTSA collar.

The design of the male/female coupling underwent several iterations. As the male part is retrieved with the rest of the HPHT MWD tool, both the male and female components are in contact with the wellbore fluids and high pressure. This poses certain challenges in terms of material selection to ensure the integrity of the structural construction and chemical compatibility with the wellbore fluids, which may be either water- or oil-based. Furthermore, the male coupling is a small diameter assembly that poses additional challenges in terms of packaging constraints and pressure/temperature rating. Early designs of the system exhibited wiring failures in both male and female assemblies during pressure/temperature cycling. Steps were taken to improve the design and manufacturing process, starting with the male as it is a more constrained design. As a result, the male assembly ultimately passed the 241 MPa (35,000 psi) and 200°C (392°F) test in December 2006. Figure 20 shows an X-ray image of the male coupling with arrows showing typical failure points encountered during testing. Further work outside the scope of this project will be required to validate the consistency of the manufacturing process and apply the design/process changes to the female design. At the conclusion of the project, the female coupling design had not successfully been qualified.

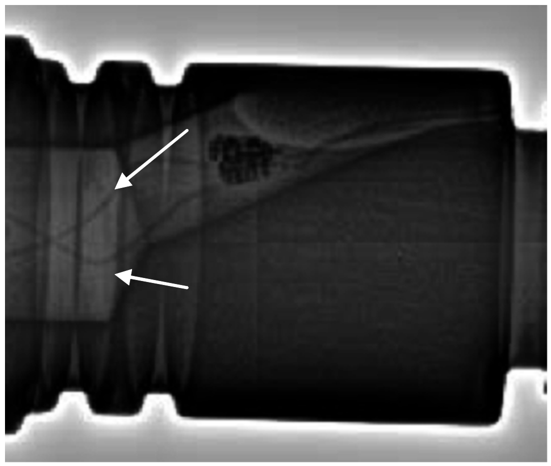

Figure 20. X-ray of the male coupling.

5.2.2.7 HTRA

The remote pressure assembly (HTRA) consists of the female portion of the pressure coupling system, a PWD remote circuit, and two pressure sensors (Figure 21). The mechanical architecture of the HTRA is such that there is no fluid connection between the inside of the collar where the pressure communication coupling is located and the collar annulus where the annular pressure measurement is taken. This allows the retrievable portion of the tool to be retrieved while maintaining the inside-to-outside pressure integrity of the collar. The HTRA has no battery as its power comes from the retrievable tool over the pressure coupling. This allows the HTRA to safely remain in place at the wellbore temperature, which might exceed the safe temperature rating of the retrievable tool or tool battery when the retrievable tool is being retrieved or replaced.

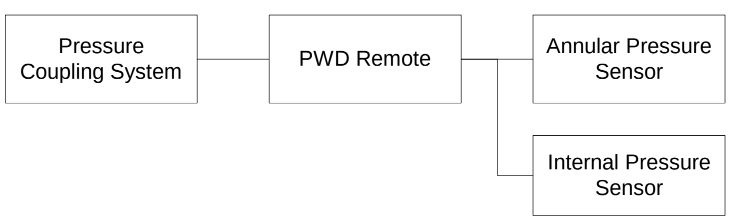

Figure 21. HTRA block diagram including pressure coupling.

5.2.2.7.1 PWD Remote

The PWD remote circuit (Figure 22) interfaces with the pressure coupling system and pressure sensors to deliver a pressure measurement and calibration coefficients to the

PWD host assembly as mentioned above. This system receives power from the retrievable tool over the coupling system, excites the pressure transducers, and makes readings of pressure and temperature through the data acquisition circuitry. It then transmits the readings and appropriate calibration data to the PWD host assembly through the pressure coupling system for further processing and transmission uphole.

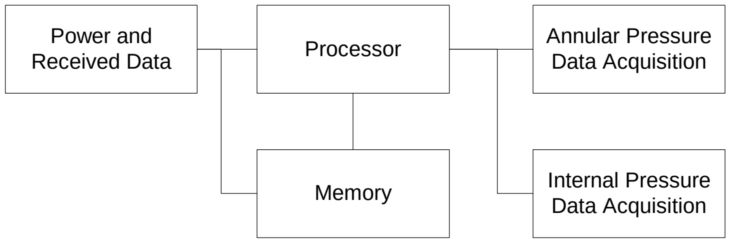

Figure 22. PWD remote block diagram.

5.2.2.8 System Software and Integration

Embedded firmware for the tool logic and software to interface with the recipient's standard surface system was developed in parallel with the electrical and mechanical hardware for the tool. The availability of full tool-level prototyping circuits assured the full functionality of the tool firmware even before the EXP tools were assembled. This greatly enhanced the ability to perform the critical integration tasks when the final hardware pieces were brought together on the tool chassis. As a result of the pre-integration testing, no serious issues were encountered during the actual integration process. All system components functioned as expected and their performance was not negatively impacted by the other components in the system.

Using the prototype hardware, hundreds of hours of testing were performed, validating the flow of data from the sensors, through the tool electronics and firmware, and ultimately through a simulated mud data link into the surface system and associated software, ensuring that the results were correct and robust, even after many hours of operation.

Significant effort was exerted to improve the data throughput of the system, ultimately ensuring, with the exception of the pressure measurement, data latency from acquisition to reception at surface of less than two seconds more than the actual transmission time. This helps ensure the timely delivery of data to the client and enhances the ability to make real-time decisions during the drilling process.

5.2.2.9 Pressure Housings

In Phase I the pressure rating requirement for the tool was 206 MPa (30,000 psi). Input from the marketing study showed that a rating of 241 MPa (35,000 psi) would be required to provide full pressure-dependent market coverage. The design analysis showed that this could be achieved without performance penalty. To achieve a 241 MPa (35,000 psi) pressure rating, the outer diameter of the tool housing was increased by 3.175 mm (0.125 in) and higher yield strength housing material was specified.

Pressure/temperature cycle tests at 241 MPa (35,000 psi) and 210°C (410°F) were successfully completed to qualify the housings.

5.2.3 System Level Testing

After all the major assemblies were developed and their functionality verified, system level tests began. The objectives of the system level tests were to confirm the performance of the entire tool in the typical operating environment of extreme conditions of temperature and pressure.

5.2.3.1 High Temperature Tests

An extended series of high-temperature oven tests was performed with the EXP1 tool during the period from June to November 2006. As is typically the case with large-scale integration, the tests revealed several hardware and software issues.

Hardware issues involved noise generated from the power supply and high voltage ladder circuits interfering with the proper operation of other modules, power sequencing, and communication reliability. These issues were easily dealt with by closer attention to detail regarding the hand-built tool wiring, modifying power supply circuits, and adding communications filters in appropriate locations.

Testing also uncovered temperature-dependent software and firmware issues that primarily were related to temperature reporting as well as measurements, filtering, and calculations that are otherwise dependent on temperature.

The longest temperature exposure reached during a single test was 2.5 hours between 204.6°C (400.3°F) and 205.2°C (401.36°F) external tool housing temperature.

The HTMA mechanical assembly was also separately successfully tested for 1,000 hours at the target temperature to validate the compatibility of oil and other materials in the modulator.

5.2.3.2 Pressure Vessel Tests

In addition to the various tests mentioned previously regarding housing pressure and temperature rating, and extensive pressure and temperature testing of the inductive coupling as previously described, testing was performed on the complete mechanical modulator assembly to validate proper operation of the pressure-bearing bulkhead and the pressure compensation system. Ultimately the tests were successful, but changes were made in the oil filling volume and procedure to compensate for thermal expansion and pressure contraction of the materials involved beyond what was originally expected.

5.2.3.3 Shock Testing

The extreme nature of the environment in which downhole tools operate makes shock testing essential to validate mechanical aspects of the tool assembly and packaging of the circuits. A variety of shock testing was performed on the HPHT tool and subcomponents for this purpose.

The direction and inclination package successfully completed the recipient's qualification testing for thermal cycling and shock testing. This testing was performed at the subassembly level to validate the typical electronics packaging of the tool and to reduce the performance risk of the tool's primary measurement. This testing revealed the electrical circuit failure noted above regarding the magnetometers. The conclusion of the test was that the planned design of the tool chassis and electronics packaging was sufficiently robust to be used in the targeted application.

The gamma ray module was qualified to appropriate shock stress levels based on subassembly level testing. The packaging of the detector was based on a mounting previously in use in the recipient's oilfield perforating equipment and was specially designed to help prevent mechanical damage and shock-induced scintillation. During tool cartridge-level shock screening mentioned below, the gamma ray detector registered no counts beyond what was normal for the local ambient environment.

Extensive shock testing was also performed on the electronics packaging at a component level after initial component-level testing indicated a weakness in adhesive choice and process control. The adhesive was changed to a different product already in use by the recipient from the same manufacturer, and the process was analyzed and brought under control to achieve the desired result. Ultimately, the electronics packaging proved very robust.

Shock qualification testing was performed on the modulator assembly specifically because the materials being used to control erosion in the area of signal generation were harder and slightly more brittle than the materials used in previous generation tools. After the development work on the stator described above, shock qualification testing was successful and found no further problems.

After the first EXP tool was assembled and heat tested, it was shock screened before testing in the test well. Complete shock qualification on the EXP assembly was not performed because qualification testing is expected to remove all the usable life from a product, and it was expected to use the tool in further field testing. Initial shock testing of the EXP1 tool uncovered a flaw in the electronics packaging related to the inside radius of a circuit mounting area. As a result, one power supply circuit was destroyed and the tool had to be disassembled and repaired. In addition, one of the modulator-drive electronics switching elements shifted during shock testing, resulting in short circuits that caused the tool to malfunction and modulation to stop. A modification to the mounting method solved this problem. After these fixes, the tool passed shock screening and showed no further shock-related problems.

5.2.3.4 Test Well Drilling Tests

Two tests were conducted in the recipient's on-site test well. The first test was designed to validate the approach for the inductive link for pressure communication, and the second test was a full-system test to validate the complete tool operation prior to field testing in a client's well.

The first test to demonstrate the inductive-link pressure communication and power coupling was conducted on June 27, 2005. The configuration used for this test was very similar to the normal HPHT MWD tool as described above, but the HTHA assembly was an early prototype and was connected to the downhole end of the recipient's existing similar tool, providing a convenient vehicle for testing the coupling mechanism. The tool operated successfully initially and while drilling. Internal and annular pressure measurements consistent with the well depth, mud weight, and pressure drop across the bit were successfully measured by the remote pressure system, sent across the inductive coupling, and transmitted to surface via the MWD tool. The MWD tool with the HTHA electronics and male inductive coupling was retrieved to the surface from the BHA while the BHA was still at the bottom of the well; it was then reseated in the BHA, testing the retrievability and reseatability of the inductive-link pressure coupling. Consistent pressure measurements made and transmitted to surface both before and after the retrieval and reseating operations validated the approach used for making the pressure measurement.

The second on-site well test took place on June 10, 2006. Because of integration problems regarding communication noise as described above, the PWD sub was not included in the test. After a successful shallow-hole test, the HPHT MWD EXP1 tool was tripped to the bottom of the well where drilling took place for almost an hour. The tool sent direction and inclination, gamma ray, and diagnostic data continuously to the surface with no problems. The tool was then retrieved from the BHA to surface via wireline and then sent back down again, where it was successfully reseated. Drilling resumed and data was sent up hole with no problem. Following that, the tool was again wirelined to the surface, still functioning. This was a critical test of the whole tool system with the exception of the pressure sub, confirming that under drilling and flow conditions the tool performed as expected.

5.3 Phase III—Field Test and Commercialization

In Phase III of the project, the tool pressure rating with the higher-strength housing material and a field test in a client's well was performed. Following this activity, an in-depth analysis of the future prospects of the tool was undertaken, making significant effort to analyzing the tool power budget, battery capacity and power delivery capability, signal strength limitations and power required, and internal marketing requirements. Ultimately the decision was made not to commercialize the tool in the form it was originally conceived but rather to pursue development of a turbine/alternator-powered tool with a similar temperature/pressure rating.

5.3.1 Full System Temperature/Pressure Test

Prior to the field test described below, a test was performed on July 19, 2006 in the recipient's on-site high-temperature pressure well. This test was performed on the EXP1 tool that had at this point completed the on-site drilling test and various high-temperature lab tests. This was a full system test with the exception of the modulator mechanics that had previously been pressure/temperature tested as described above, and was performed at 175°C (347°F) and 138 MPa (20,000 psi), the limit of the particular well and of the pressure housings that were installed on the tool at that time. This test was performed to validate the whole system performance and assess the turn-on and turn-off temperatures of the tool with the thermal switch and the behavior of the high-temperature battery technology. The tool turned on during this test at 120°C (248°F) as expected and operated properly to 175°C (374°F). The temperature was decreased to determine the point at which the tool would turn off. The tool turned off at 140°C (284°F), higher than the expected temperature. The tool did not turn on when it was heated again to 155°C (311°F), at which point the test was terminated. The ultimate cause of the unexpected temperature behavior was traced to the battery technology behavior during temperature cycling and loads. Testing to confirm this was performed in August 2007 outside the scope of this project.

A subsequent pressure well test to further explore the life of the tool at elevated temperatures with the high-temperature batteries was initiated two days later but was terminated because the male inductive coupling was damaged when loading the parts into the well and the tool did not operate correctly after the coupling was removed. The incorrect tool operation was ultimately traced to a hardware problem with the HTHA electronics and its interaction with the HTEC firmware. Because of the limited quantity of high-temperature batteries on hand at the time and their single-use nature, it was decided not to further pursue this system testing until after field testing.

5.3.2 Field Test in a Client's Well

A field test in a client's well was performed between September 22 and September 28, 2006 in Zapata County, Texas. This test was also conducted using the HPHT MWD EXP1 tool. At the time, the EXP2 tool had not yet completed assembly because a sufficient quantity of working electrical parts was not on hand, so no backup tool was available for the job. The EXP1 tool had at this point completed the on-site drilling test, high-temperature lab tests, and full-system testing in the pressure well as described above. The test described below ultimately served as valuable training, and also revealed significant shortcomings with the high-temperature battery when operated at lower temperature.

5.3.2.1 Field Test Objectives

The main objectives for this field test were to:

1. Test the entire system in an actual well, subjecting the tool to more realistic combined conditions than those achievable in the recipient's test well. A maximum temperature of 150°C (302°F) and maximum pressure of 83 MPa (12,000 psi) while drilling were anticipated.
2. Test the functionality of all subsystems and sensors, along with the tool's retrievability and reseatability capabilities.
3. Train the engineering team, field test coordinator, and field personnel; and become familiar with any special handling or rig-up procedures.

5.3.2.2 Well Details

The well details were as follows:

Location	Zapata County, Texas
Proposed Depth	3993 m (13,100 ft) MD, permitted to 4145 m (13,600 ft)
Expected TD Temp	150°C (302°F) static
Mud Weight	1.438-1.558 s.g. (12-13 ppg)
Hole Size	171 mm (6.75 in.), 121 mm (4.75 in.) collars and drill-pipe
Flow Range	379-757l pm (100-200 gpm)

5.3.2.3 Job Setup and Tool Details

The complete NC38-47 HPHT MWD tool (Figure 8) was mobilized and assembled for this test. A modified standard job box was used to transport the HPHT MWD tool parts, rig up and testing equipment, batteries, and spare parts to the job. Both 150°C (302°F) and 200°C (392°F)-rated batteries were included in the job mobilization kit. Because of material availability at the time and requirements for the job, the tool housings were of the 138 MPa (20,000 psi), low-pressure variety.

Based on signal strength vs. depth modeling, the low flow "H3"-type modulator was selected and a 3-mm (0.120-in) restrictor-stator gap was set for signal generation with a contingency to lower the gap to 2 mm (0.080 in) for higher signal strength if necessary. Modeling indicated the signal strength at the surface would be approximately 96.5 kPa (14 psi) ± 50%, which would be sufficient for demodulation, and the "zero gap" configuration of 0.38 mm (0.015 in) designed for ultradeep wells would not be necessary at the anticipated well depth.

The thermal switch circuit in the HTHA was bypassed with a shunt to allow the HPHT MWD tool to operate at lower temperatures with a 150°C (302°F) battery for the initial portion of the job. As the test progressed and the well temperature approached the 150°C (302°F) limit of the batteries, the plan was to retrieve the tool via wireline, remove the shunt, and replace the tool in the well with the 200°C (392°F)-rated batteries.

Surface pressure and demodulation data were recorded on the surface system using a pre-release version of the recipient's surface acquisition and processing software. The downhole HPHT MWD tool was configured to record surveys and temperature vs. time. The real-time data transmitted were surveys, temperature, battery voltage, internal and annular pressure, modulator battery current, mechanical shock information, and natural gamma ray counts.

5.3.2.4 Operational details

Following is the sequence of events between September 22 and 28, 2006.

5.3.2.4.1 Friday, September 22, 2006

The first day of field testing consisted primarily of arrival of the personnel and equipment at the wellsite and orientation.

1600 h The recipient's engineers arrived on site. This group consisted of a field engineer, field test coordinator, lead electrical engineer, lead mechanical engineer, and project manager.

1800 h The HPHT MWD experimental tool and all associated equipment arrived on site.

1900 h The rig crew started setting casing in the well.

2200 h Cementing operations commenced.

5.3.2.4.2 Saturday, September 23, 2006

Rig repairs were conducted most of the day, with the HPHT tool being rigged up for the first time in the evening.

0730 h The engineers initialized and tested the HPHT MWD tool with a 150°C (302°F)-rated battery. This "basket test" (Figure 23) was successful and the tool was powered down.

Figure 23. Surface testing the HPHT MWD tool.

0830 h The retrievable portion of the tool was inserted in the NC38-47 HTSA collar assembly to ensure all equipment was correct before running in the well. It was immediately realized that the spear-point top of the HPHT MWD tool was positioned far above the collar's flow sleeve, indicating that the incorrect collar had been shipped to the wellsite. This occurred because the HTSA assembly is indistinguishable from the outside from the equivalent collar used in the recipient's commercial tool but has slightly longer internal parts. The engineers contacted personnel at the engineering center and arranged for transport of the correct collar to the wellsite.

1800 h The correct collar was received at the wellsite and the retrievable tool was installed to confirm correct position in the collar's flow sleeve (Figure 24).

Figure 24. HPHT MWD spearpoint positioning in the flow sleeve.

2100 h The HPHT MWD tool was powered up by installing the 150°C (302°F)-rated battery. The retrievable tool string was carried to the catwalk in preparation for running in the well (Figure 25).

Figure 25. Carrying the tool to the catwalk.

2350h The retrievable tool assembly was installed in the collar and the whole assembly descended below the rotary table (Figure 26).

Figure 26. Installing the HPHT MWD tool in the NC38-47 collar.

5.3.2.4.3 Sunday, September 24, 2006

This was the first day that the HPHT MWD tool ran in a client's well sent data to the surface.

- 0015 h A successful shallow-hole test (SHT) was performed with a 50 psi modulator signal. This verified that the retrievable tool was correctly seated in the collar and positioned in the flow sleeve and was transmitting all required data.
- 0200 h The HPHT tool and the BHA started their descent into the well. This is also known as being "run in hole" (RIH).
- 1600 h At 2738 m (8,982 ft), the operator started displacing water-based mud (WBM) in the well with oil-based mud (OBM).
- 1815 h The mud pumps started with pump pressure approximately 12.41 MPa (1,800 psi) with a downhole tool signal strength of approximately 25.5 kPa (3.7 psi). The calculated signal prediction indicated approximately 62 kPa (9 psi) under these conditions, but demodulation was still possible with the lower-than-expected signal, and the tool provided surveys consistent with the existing well trajectory.
- 1930 h At 2768 m (9,082 ft) the bit reached the bottom of the well and started drilling out the plug and cement.
- 2100 h At 2776 m (9,109 ft) the surface acquisition software started having signal demodulation problems, apparently caused by downhole drilling noise.
- 2300 h At 2781 m (9,125 ft) the client was reaming the hole to clean cuttings and pressure test the formation.

5.3.2.4.4 Monday, September 25, 2006

The majority of the day was spent pumping lost-circulation material (LCM) to control mud losses to the formation. The HPHT MWD tool was successfully fished for the first time, and the modulator gap was lowered to 2 mm (0.080 in) in an effort to improve signal strength and surface signal demodulation.

- 0037 h The operator was cleaning the hole at 4.516 MPa (655 psi) pump pressure (PP) and 87 strokes per minute (SPM). The HPHT modulator signal increased to approximately 55 kPa (8 psi), still lower than the predicted 103 kPa (15 psi), but within the estimate's margin of accuracy.
- 0100 h Mud loss into the formation was detected at the rig. The operator began pumping LCM consisting of 50 bbl of medium nut-plug at 20.4 kg/bbl (45 lb/bbl).
- 1145 h While the operator was trying to establish control of the well, it was decided to replace the battery in use with a fresh one as the tool had been running for approximately 40 hours. The engineers assembled the fishing tool (Figure 27) and began a slickline operation to retrieve the tool from the BHA (Figure 28). The operation went smoothly except for some delays related to tangling of the wire on the slickline unit while running in.
- 1230 h The engineers latched the fishing tool onto the tool in the BHA successfully.
- 1330 h The tool was retrieved to the rotary table still operating. While the operator continued cleaning the hole, the HPHT MWD tool was inspected. The position of the primary compensating piston indicated that modulator primary compensator was not flooded, and all was functioning as designed. The modulator gap was reduced to 2 mm (0.080 in) in an effort to increase the signal strength and reduce surface demodulation problems.
- 1930 h A fresh set of 150°C (302°F)-rated batteries was installed in the tool and the tool was successfully basket tested in preparation for reinstallation in the BHA.
- 2000 h The rig operator continued cleaning the hole.

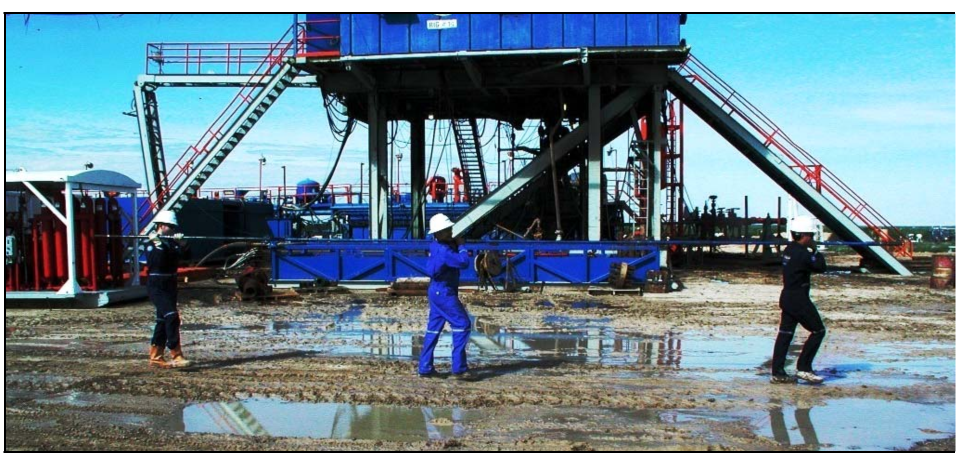

Figure 27. Moving the fishing tool to the slickline unit.

Figure 28. Retrieving the HPHT MWD tool via slickline.

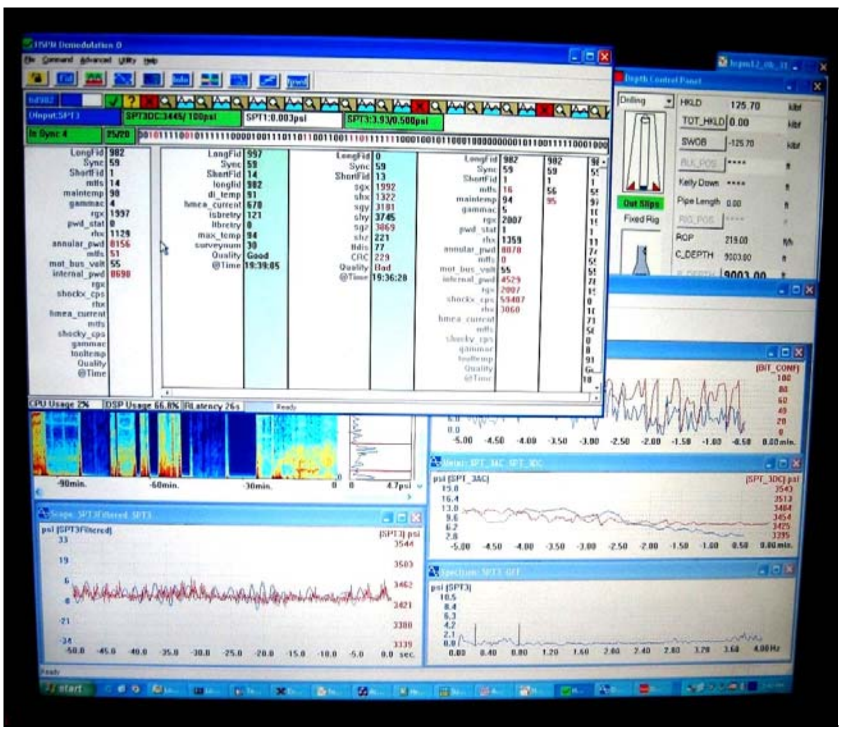

Figure 29. Snapshot of real-time demodulation.

5.3.2.4.5 Tuesday, September 26, 2006

The tool was successfully reseated into the collar in the BHA and MWD operations continued all day. The lead engineers and project manager returned to the engineering center and were replaced on site by an electronics technician from the engineering center.

- 0145 h The fishing tool was configured for reseating operations and was run in the hole on the slickline equipment.
- 0230 h The HPHT MWD tool was successfully landed in the rigid-mount collar in the BHA and released from the slickline fishing tool.

0250 h The fishing tool was back at the rotary table.

0330 h Problems continued with demodulation. The pump pressure was 17.2 MPa (2,500 psi) and the tool signal was 57 kPa (8.5 psi).

0400 h The driller adjusted the pump speed in strokes per minute both higher and lower in an effort to move pump noise away from the modulation frequency and reduce interference, but bit confidence was still low. Demodulation was good when the bit was off the bottom of the hole but poor when drilling took place.

0830 h During a connection, it was decided to change the surface pressure transducer in an attempt to improve signal demodulation. The new pressure transducer did not seem to improve the demodulation, and the bit confidence remained at approximately 35% while drilling for most of the day. Static surveys were successfully transmitted by ensuring that the BHA was off bottom when the surveys were taken and sent.

2100 h The bit was at 3156 m (10,355 ft), rotating, pump pressure of 193 MPa (2,800 psi), tool signal of 37.9 kPa (5.5 psi), bit confidence increased to 75%, and ROP increased to 30.5 m/h (100 ft/h).

5.3.2.4.6 Wednesday, September 27, 2006

Drilling continued successfully for the entire day with the bit confidence at approximately 75%. The modulator signal slowly decreased on average from 34 kPa (5 psi) to 21 kPa (3 psi) with the ROP decreasing during that same interval from 46 m/h (150ft/h) to 15 m/h (50 ft/h).

0410 h The pressure sub responsible for making annular pressure while drilling (APWD) and internal pressure while drilling (IPWD) measurements started sending checksum errors. This was an indication that the communication link between the HTHA and HTRA was not working as well as expected, though communication was still occurring.

1616 h At 3522 m (11,557 ft) the HTHA began reporting that no communication was taking place with the HTRA pressure sub.

2200 h At a circulating temperature of 140°C (284°F), it was decided that it was necessary to replace the 150°C (302°F)-rated batteries with 200°C (392°F)-rated batteries to avoid the risk of failure of the lower-temperature batteries. The rig operator started circulating bottoms up in preparation to retrieve and reseat the HPHT tool via slickline.

2330 h The slickline fishing tool was deployed below the rotary table to retrieve the tool.

5.3.2.4.7 Thursday, September 28, 2006

The 200°C-rated batteries were installed and operated for approximately 4 hours visibly at surface, at an average formation temperature of 140°C. No HTRA communication was received on this day.

0000 h The fishing tool was attached to HPHT tool.

0045 h The HPHT MWD tool was retrieved to the rotary table, still operating.

0115 h The HPHT MWD tool’s 150°C-rated batteries were replaced with 200°C-rated batteries. The bypass around the thermal switch circuit was removed, allowing normal operation of this circuit. The tool was sent back down on the slickline using the same procedures as before.

0200 h The tool successfully landed in its collar in the BHA and the fishing tool was at the rotary table 30 minutes later.

0245 h The mud pumps were up and the modulator signal was 26.6 kPa (4 psi) with 90% bit confidence on demodulation.

0400 h Drilling on bottom at 3647 m (11,964 ft), the modulator signal was 25.5 kPa (3.7 psi) with 75% bit confidence.

0600 h The last survey was received from the tool at 3677 m (12,064 ft). The tool turned off soon after this, apparently because of a depleted battery.

5.3.2.5 Field Test Summary

In terms of the stated objectives, the field test was a success. The functionality of the entire tool in the NC38-47 collar configuration was validated, including the inductively coupled pressure sub. The functionality of all subsystems and sensors was tested, along with the tool's retrieving and reseating capability. Direction, inclination, gamma ray, temperature, battery voltage, and current measurements were all acquired and sent to the surface. Annular and internal pressure measurements were successfully acquired and transmitted over the inductive link, and these measurements also detected lost circulation. In addition, the engineering team, field test coordinator, and field personnel were trained in the operation of the tool and its special operational and handling requirements.

On this job the HPHT MWD tool operated over 114 pumping hours and drilled 909 m (2,982 ft). It recorded a maximum downhole temperature of 149°C (300°F). As can be seen in Figure 30, the temperature when the mud was not flowing was approximately 10°C (18°F) lower than during drilling operation. With the anticipation of further increases in temperature, the decision to replace the 150°C (302°F) batteries with 200°C (392°F) batteries was validated, though a battery with better performance near 150°C (302°) would have been more desirable than the 200°C (392°F) battery used. The end of the temperature log indicates that the tool stopped recording abruptly when the battery became depleted, an issue discussed below.

The retrievability and reseatability of the tool were also tested. The tool was successfully retrieved three times and reseated twice. The first operation allowed the rig operator to pump LCM and also replacement of the 150°C (302°F)-rated batteries to reduce the risk that they would deplete during the run. The second operation executed replace the 150°C (302°F) batteries with 200°C (392°F) batteries because the operational temperature limit of the 150°C (302°F) batteries was approaching. The third operation retrieved the tool after the 200°C (392°F) battery depleted.

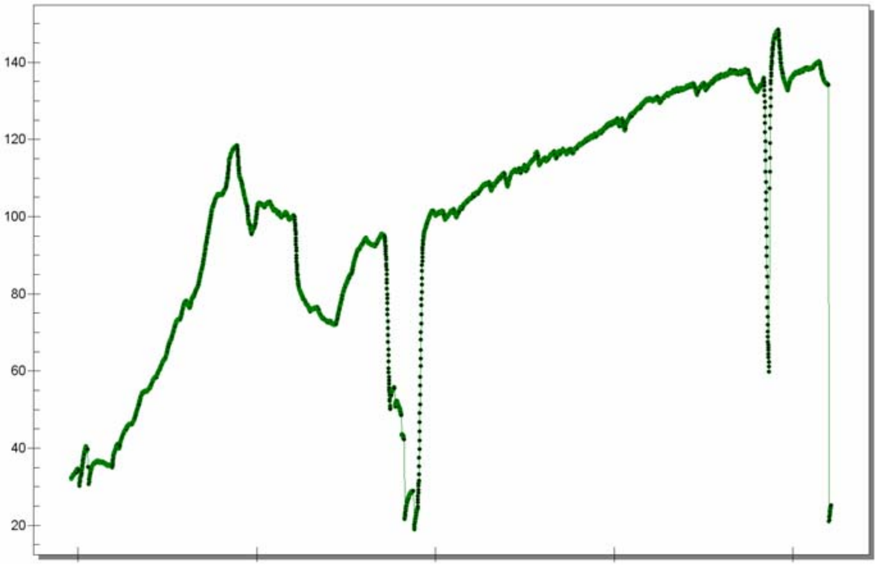

Figure 30. HPHT MWD temperature (°C) vs. time (days) during the field test.

The pressure measurement and communication methodology in the tool was validated. Analysis of the pressure measurements indicated that not only were the measurements consistent with mud weight and depth (Figure 31). In addition, lost circulation was detected at 2783 m (9,132 ft) with analysis of equivalent circulating density (ECD) (Figure 32) as shown by the decreasing ECD calculations with repeated measurements at the same depth.

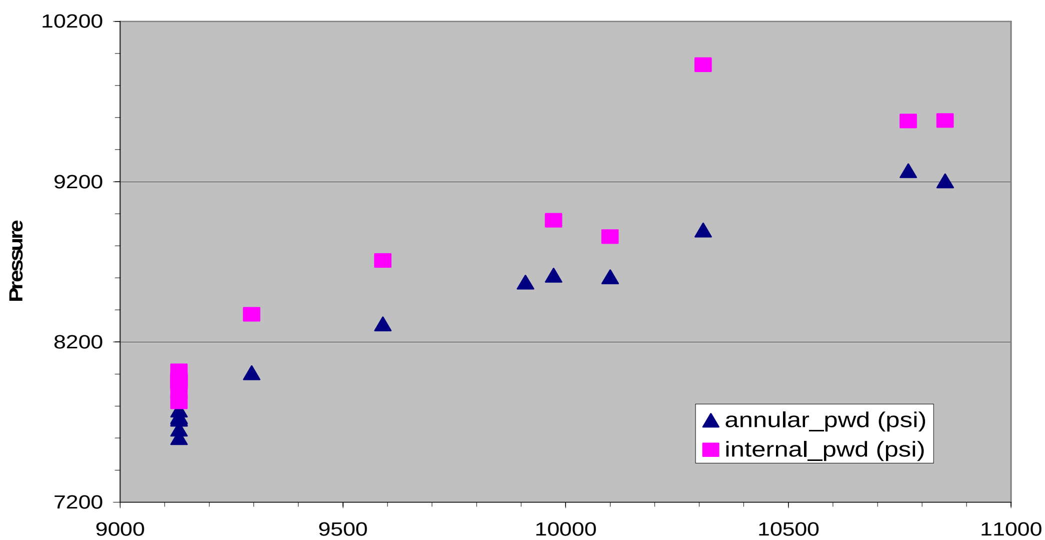

Figure 31. Pressure (psi) vs. depth (ft) consistent with mud weight

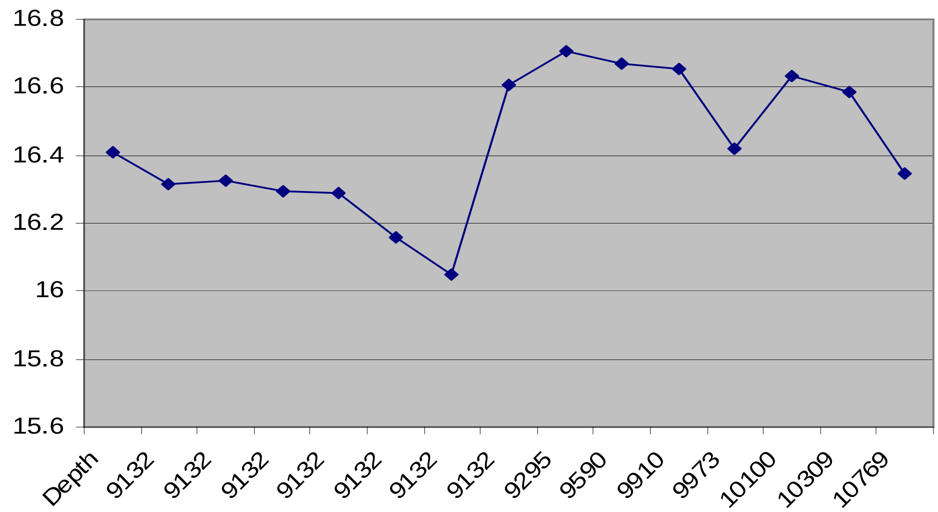

Figure 32. ECD (ppg) vs. Depth (ft) shows lost circulation

5.3.2.6 Issues and Opportunities for Improvement

Some issues encountered during the field test demonstrated opportunities to modify the tool design and to improve operational usage. These concerned battery chemistry, the pressure sub communication link, modulator signal strength, and the gamma ray measurement.

The 200°C (392°F)-rated battery lasted only 4.5 hours observed on surface, though the tool recorded log later indicated the tool ran downhole approximately 8 hours of operation. It was known ahead of time that the 200°C (392°F) batteries would have reduced performance at lower temperatures, but the extent of that performance degradation was not realized until this test. This pointed out the need for more options in battery availability for the HPHT MWD tool to manage the gap in performance between temperature ratings. Batteries with ratings above 150°C (302°F) but potentially below 200°C (302°F) need to be made available. Batteries rated to 170°C (338°F) and 198°C (388°F) were eventually procured but not used in field testing.

The pressure sub HTRA stopped communicating after 90 hours during the second low-temperature battery operation. Initially the tool logged checksum errors indicating poor communication, and eventually it stopped communicating altogether. The post-job tool analysis, described below, indicated that the inductive coupling may need to be further refined to enable more robust reseating operations for communication.

The modulator signal strength was less than expected, but was still ultimately sufficient for demodulation when the bit was off bottom. Figure 33 shows the measured signal strength at the surface vs. the well depth, showing the expected trend to lower signal with increasing depth. The signal strength may have been measured as artificially low, and much of the demodulation issues that were encountered may have been caused by pump interference and drilling noise. Both of these are low-frequency phenomena that interfere with the tool's modulation frequency of 0.5Hz and could have been mitigated by adding higher-frequency telemetry options to the tool operation. These options were not available at the time of the field test but were added later.

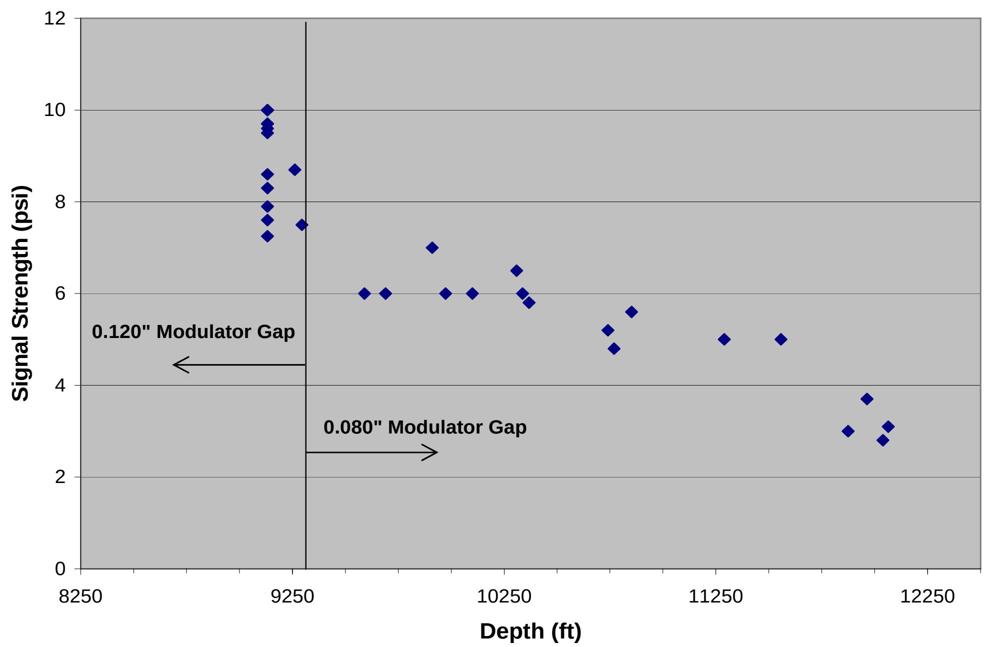

Figure 33. Modulator signal strength vs. depth.

The natural gamma ray measurements were lower than expected. Gamma ray counts that had previously seemed low at the engineering center had been attributed to environment, a less sensitive detector developed for 200°C (392°F) operation, and thicker pressure housings that block more incident radiation. Ultimately, the root cause for the low count rate was traced to a threshold discrimination circuit with a threshold set higher than appropriate to reject noise coupled from a different part of the tool, causing lower-energy gamma ray counts to be discarded. When the noise coupling was remedied and the threshold was set to the correct value, the HPHT MWD tool indicated the expected sensitivity to natural gamma radiation that was consistent with the recipient's existing tool fleet.

5.3.2.7 Post-Job Tool Inspection

The HPHT MWD tool was returned to the engineering center on Saturday, September 30, 2006. As the tool was inspected, repaired, and analyzed, several observations were made.

The modulator showed signs of separation between the tungsten carbide stator and the stator adaptor, as shown on the left side of Figure 34. This was an anticipated risk in the construction of the stator, and a solution to this issue was undergoing engineering tests at the time of the field test. The damage was not noticed during the first two retrieval operations and it likely occurred during the last run, after the high-temperature batteries were installed. The final engineering solution to this problem has yet to be determined, though a new design has been built and is being tested outside the scope of this project with expected delivery in 2009.

Figure 34. Separation Between Modulator Stator and Stator Adapter

On further inspection of the modulator assembly, it was realized that the primary oil compensator volume was flooded with mud (Figure 35), even though this had not been noted at the well site. On disassembly, it was obvious that the primary rotating seals, excluder seal, and oil compensation bladder were invaded with drilling mud. As expected, the secondary oil compensator volume was not flooded with drilling mud (Figure 36), as the primary compensator is largely sacrificial and is designed to protect the secondary compensator.

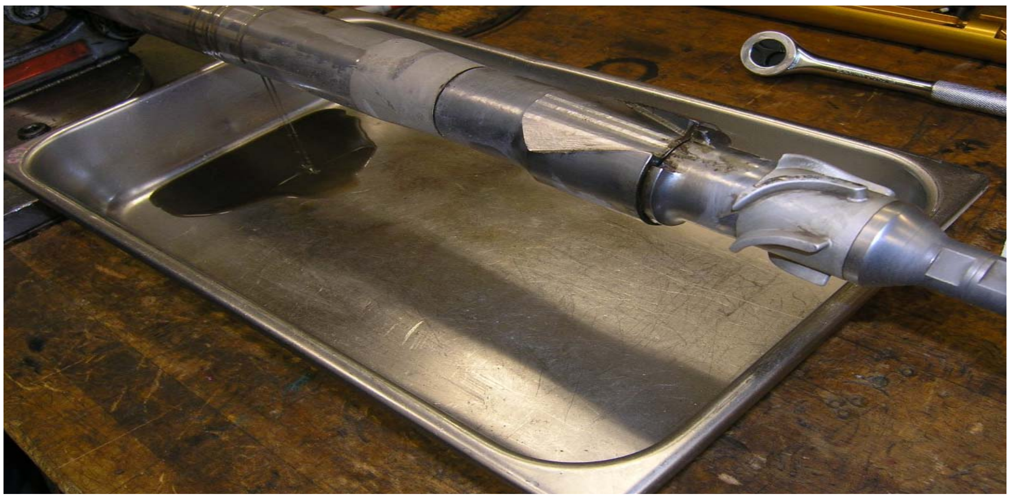

Figure 35. Primary compensator oil volume, mud invaded.

Inspection of the inductive stinger and coil showed no critical damage. A small tear or possible erosion was noted in the rubber of the inductive stinger tip (Figure 37). Engagement between the male and female portions of the inductive stinger assembly was initially impossible by hand, primarily because of the buildup of mud in the female coil (Figure 38), and to a lesser extent to swelling of the rubber on the stinger tip. Once the mud was cleaned, the stinger and coil interface was possible, though engagement was tighter than before the field test.

Figure 36. Secondary oil compensator volume, not mud invaded.

Figure 37. Inductive stinger tip damage.

Figure 38. Inductive coil with internal mud buildup.

All the tool electronics functioned normally after the test, including the host and remote pressure sub electronics. The reason for the failure of communication of the pressure sub during the later part of the field test was not conclusively shown, though indications are that the inductive coupling may have not been fully engaged when the tool was reseated.

5.3.3 Continued Tool Testing and Improvements

Analysis of the data and experiments to date following the field test showed that while the poor performance of the 200°C (392°F) battery at temperatures close to 150°C (302°F) was not entirely unexpected, the interaction between the tool power draw and the battery was not well understood. Significant effort was dedicated to understanding the tool power profile and battery performance vs. temperature, operational modes, and drilling conditions to be able to assess the technical issues surrounding the tool that would lead to a commercialization decision in the future.

As mentioned above, many of the design elements of the tool were reused directly from the recipient's existing designs because they were either already known to work at the target temperature or were shown to work through testing. It was anticipated from the initial stages of the HPHT MWD design that many of these elements would eventually need to be redesigned for reasons related to function and/or power efficiency. This future expectation had two effects: the power consumption of the tool was not carefully monitored during the design stage, and the 200°C (392°F) batteries were initially tested in Phase I at the load that was expected of the final design, not the actual experimental design.

5.3.3.1 Battery Tests in the Pressure Vessel

In addition to the tool housing pressure/temperature testing and qualification mentioned above, a series of full-system tests with high temperature batteries in the recipient's on-site pressure wells took place to validate system performance. Operational difficulties led to only two of these tests completely meeting their objectives.

The first test evaluated the usable life of the tool using the recipient's standard 150°C (302°F) battery chemistry in the same size pack as the 200°C (392°F) battery. Using the 150°C (302°F) chemistry, the tool ran for 79 hours continuously at 145°C (293°F). Given the power consumption of the tool at the time and the fact that the modulator did not have any assist from mud flow, this number was within expectations.

The second test evaluated the usable life of the 200°C (392°F) battery pack at 175°C (347°F) with the same tool configuration as above. This test lasted 13 hours, less than expected by approximately a factor of two given prior testing results of the battery chemistry.

An additional test undertaken to explore whether the batteries could be reused after being exposed to temperature validated previous information that the batteries are single-use.

5.3.3.2 Electrical Power Consumption Analysis

After it was shown that the tool did not operate as long as initially expected using the 200°C (392°F) batteries, an in-depth analysis of the tool power consumption was performed.

The first part of the analysis consisted of a complete characterization of the tool power consumption under static conditions. The supply current to each circuit on each supply voltage was measured under all operational conditions, including varying the frequency of the modulator to understand the effects of modulation on power consumption. This allowed an in-depth analysis of the operational efficiency of the power supplies and the tool as a whole.

The tool power consumption was also measured against temperature up to 205°C (401°F), again including the modulator frequency variation. This also allowed separation of the power required to run the electronic system and the power required to run the mechanical system. As expected, the tool acted as a constant power load with respect to battery voltage, and the electrical power required increased somewhat with temperature, while the mechanical power (driven mainly by frictional and viscous losses) decreased slightly with temperature as oil viscosity decreased.

5.3.3.3 Battery Characterization

With a better idea of the actual tool load requirements, a set of characterization tests were initiated on an alternative battery chemistry now rated to 198°C (388°F). This chemistry was originally identified in Phase I but was not used because it lacked a safety margin at 200°C (392°F). This testing showed that the 198°C (388°F) chemistry performed similarly to the 200°C (392°F) chemistry at the target temperature of 200°C (392°F) but significantly better at temperatures below 200°C (392°F) down to 162.5°C (325°F). The tests, performed at two different loads (200 mA and 400 mA), also showed that at the lower temperatures the available energy from the battery was much more dependent on the load than previously expected. During this investigation, it was realized that more information was needed regarding the performance of the batteries under varying temperature and load. A much larger characterization test, started after the completion of this project, was designed to explore these issues under a more realistic tool power profile over time for 200°C (392°F), 198°C (388°F), and 170°C (338°F) battery chemistries. This testing was started after the completion of this project.

5.3.3.4 Modulation and Power Generation Characterization

In addition to the static tool power analysis described above, a complete characterization of the power generation and draw of the modulator assembly during signal modulation was undertaken in the lab and in the recipient's on-site flow loop. This characterization encompassed varying the telemetry rate, position of the rotary valve modulator, and flow rate.

The first outcome of this characterization (Figure 39) was a family of curves showing the amount of power in Watts required to control the modulator assembly with varying amounts of applied torque at different telemetry rates. This data was an important input into the analysis of the ability of the tool to operate on battery for a period of time at different operational conditions.

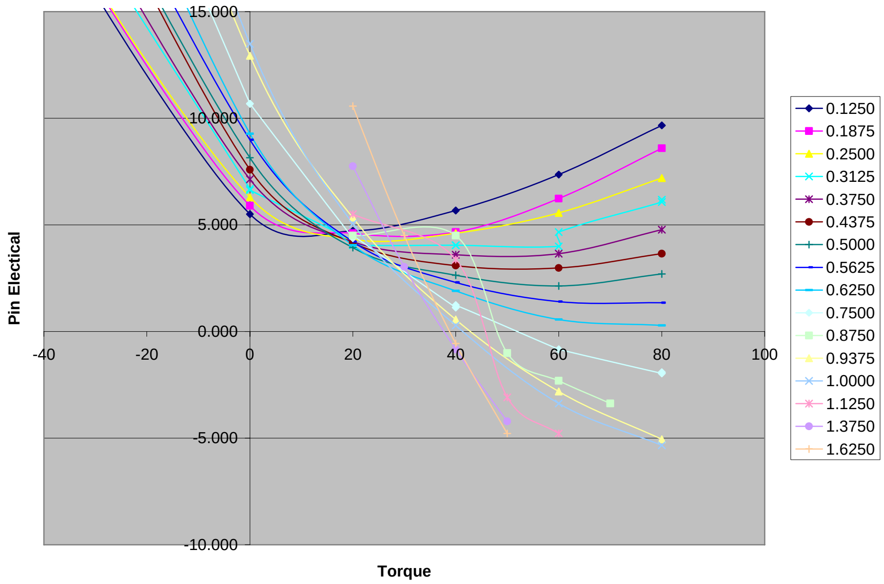

Figure 39. Modulator electrical power vs. torque for various telemetry rates.

A second outcome was a characterization of required unloaded torque against temperature of the modulator at various telemetry rates (Figure 40). This quantitatively verified assumptions regarding power consumption of the modulator and also served as an important input into calculations of tool operational life.

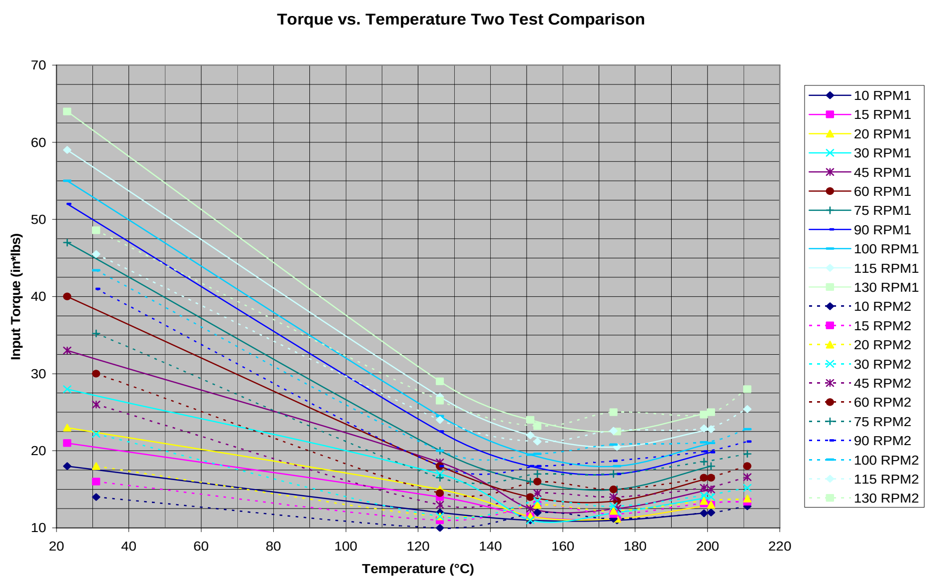

Figure 40. Modulator torque vs. temperature for various telemetry rates.

The last outcome was the discovery that with a 0.38 mm (0.015 in) gap, the modulator required a significantly larger amount of current to rotate under flowing mud conditions than previously anticipated. Figure 41 shows a plot of supply current against time for the same modulator with no flow (yellow), with flow at a 3 mm (0.120 in) gap (blue), and with flow at a 0.38 mm (0.015 in) gap (magenta). The regenerative power of the modulator can be seen by the lower average power in the 3 mm (0.120 in) gap as compared to the no-flow condition. The increased average power can be seen in the 0.38 mm (0.015 in) gap as well as the high peak current draw. The significance of this high peak current draw was that it was suspected, and later confirmed, that the battery could not provide sufficient current to turn the modulator in those conditions. This meant that the smaller gap was not feasible for use with the battery-powered tool, because the larger gap cannot generate sufficient signal strength to operate at extreme depths, the operational measured depth of the tool would be restricted to 6,096 m (20,000 ft) rather than the planned 9144 m (30,000 ft).

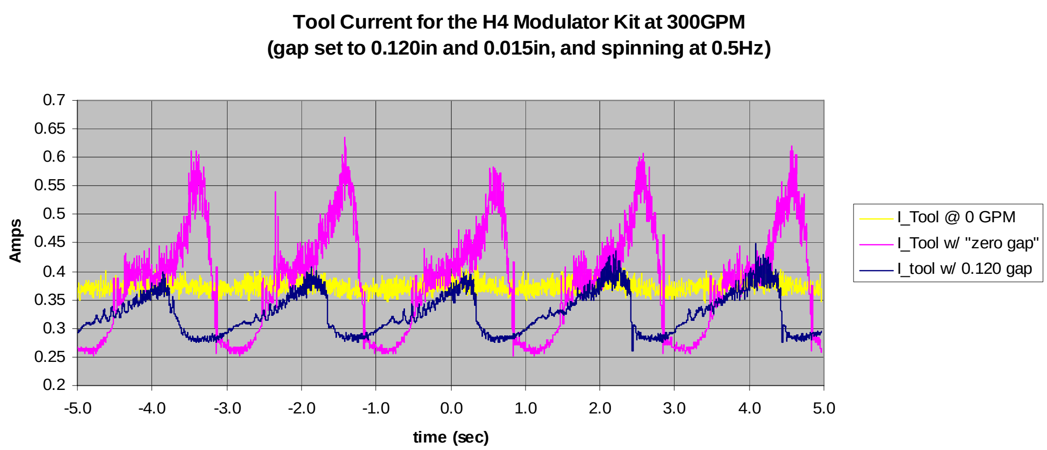

Figure 41. Modulator current draw vs. time for various gap conditions.

5.3.3.5 Tool Design Changes and Power Consumption Improvements

After the tool power characterization was completed, it was realized that the tool in its configuration at that point would not be able to operate at the originally required depth and that in shallower depths its use would be limited by the battery chemistry and associated tool operating life. As a result, in an attempt to make the tool viable as a commercial service, several actions were undertaken to reduce the power consumption of the tool to a level the battery could support. At the same time an investigation was undertaken to determine whether an alternate tool architecture with a power generating turbine and alternator was feasible.

The first step was the elimination of the pressure measurement. This measurement was seen as relatively expendable as it was not part of a basic MWD service. Since problems still existed in qualifying the inductive coupler parts to pressure and temperature, pressure was not viewed as significant in reduction of tool performance. This reduced the nonmodulating total tool power consumption from 17.8 W to 14.1 W.

The next step was to ensure that all of the three processors were appropriately using their idle modes. The processor in the direction and inclination module was already using its idle mode correctly, but the two others were not. The modulator code was modified, saving 5% of its net power. The main controller processor code was also modified, saving 40% of its net power usage.

At this point, the power supplies were operating at approximately 36% efficiency because of legacy design decisions in the power supply architecture and also because the supply was designed for approximately four times the load that was being used. Improvements were made in transformer design and post-transformer regulation, dramatically improving the power supply efficiency and the tool power consumption.

These changes combined to reduce the tool power consumption from 17.8 W to approximately 10 W, not including modulation power. In addition, improvements in the modulator impeller design, aided by flow loop testing and computational fluid dynamic (CFD) modeling were made to increase power regeneration from the mud flow during modulation. To maximize the usability of the tool, the flow range was ultimately subdivided further than originally intended. With all of these changes, it was estimated that with the 200°C (392°F) battery, the tool would last approximately 20 hours downhole, with the depth limitation described previously.

Adding a second or third battery to the tool in a second drill collar was also considered, which would at least double the running life of the tool. This concept was ultimately discarded, however, because of concerns that the pressure housings might buckle during the loading procedure.

Additional design consideration was given to greatly modifying the tool architecture, replacing the battery with a turbine/alternator. This would eliminate the tool battery lifetime problem by providing power on demand rather than a limited battery capacity. It also would have more available power to enable the modulator to operate in the 0.38 mm (0.015 in) gap configuration. Configurations with retrievable turbines and nonretrievable, collar mounted turbines were also considered. This entailed an analysis of retrievable vs. nonretrievable MWD tools and their development risk and benefits, which was used as input to the commercialization decision.

5.3.4 Commercialization

Analysis of the power consumption data after various power optimizations were undertaken and the ability of the battery to provide power at high temperature conclusively demonstrated that it was not reasonable to expect the HPHT MWD tool to provide continuous survey and data transmission service for more than 20 hours above 175°C (347°F) and, depending on drilling conditions, potentially much less. This would not be an economically viable service, and the decision was made not to commercialize the tool covered by the DE-FC26-03NT41835 program. During this decision-making process, a number of alternative tool modifications were proposed that would be able to provide a viable service:

Option 1. Modifying the existing tool to send only static surveys on a timed basis or on demand when a pipe connection occurs. The tool would go into a low power mode in between surveys to reduce power consumption and extend battery life. This would allow operation up to 100 hours rather than 20 hours.

Option 2. Modifying the existing tool with a retrievable turbine/alternator assembly in place of the battery. This would provide sufficient power to generate a modulation signal even at deeper depths and would not depend on a finite battery resource to determine the amount of time the tool could operate downhole.

Option 3. Modifying the tool into a nonretrievable configuration similar to the recipient's existing nonretrievable tool fleet that operates to 175°C (374°F). This would allow a larger opening for the modulator, making it easier to generate the large required downhole signal. It would also provide for reuse of existing turbine technology with temperature upgrades similar to those already applied to the HTMA modulator.

After extensive internal review concerning the technical, economic, and market merits of the three options, it was decided that Option 3 fit best with the recipient's future tool fleet vision and that a project would be launched to design such a tool based on the electrical and packaging design of the HPHT MWD tool covered under this agreement. As the architecture and many components of the nonretrievable HPHT MWD tool will be completely different from the retrievable tool covered by the DE-FC26-03NT41835 program, its development would be undertaken as an entirely new project.

It was also decided to continue to pursue field testing of the HPHT MWD EXP tool with the limited battery capability in place. In addition, extended reliability growth studies using the electrical designs of the HPHT MWD tool would be launched to validate the design choices under controlled lab conditions.

6 Conclusion

The objective of this project was to design and commercialize a retrievable and reseatable HPHT MWD tool with real-time continuous inclination, vibration, annular pressure, and gamma ray detection. In Phase I of the project a feasibility study determined that developing such a tool was feasible with existing technology and some additional development and that a market existed for such a tool. In Phase II an experimental prototype of this tool was designed and built based on pre-existing technology, new development, and best practices already in the recipient's portfolio and identified in Phase I. This EXP tool was field tested with mixed results. Investigation in Phase III revealed that the limiting factor in the tool performance was battery technology, and a number of actions were taken to mitigate that issue. Unfortunately, none of the actions taken were sufficient to make the tool into a marketable product and the decision was taken not to commercialize the tool developed under the DE-FC26-03NT41835 program and instead to pursue development of a tool based on its electronics but in a nonretrievable, turbine-powered configuration.

7 References

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Rountree, S., *High Temperature MWD*, HiTec 2002.

8 List of Acronyms and Abbreviations

ADC – analog to digital converter
APWD – Annular Pressure While Drilling
BHA - bottomhole assembly
BRT – below rotary table
CFD – computational fluid dynamics
D&I – direction and inclination
DUT – device under test
ECD – equivalent circulating density
EXP – experimental prototype
FEA – finite element analysis
HPHT – high pressure/high temperature
HTBA – HPHT battery assembly
HTEC – HPHT electronics cartridge
HTHA – HPHT host assembly
HTMA – HPHT modulator assembly
HTRA – HPHT remote assembly
HTSA – HPHT shock assembly
IPWD – internal pressure while drilling
JIP – joint industry project
LCM – lost-circulation material
MD – measured depth
MWD – measurement while drilling
OBM – oil-based mud
PP – pump pressure
PWD – pressure while drilling
RIH – run in hole
ROP – rate of penetration
SOI – silicon on insulator
SHT – shallow hole test
SMT – surface mount technology
SPM – strokes per minute
WBM – water-based mud

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