DOE/MC/29252-T1

**Development of a Near-Bit
MWD System**

Phase II - Final Report

TR96-14

Submitted to:

**Mr. Al Yost
U. S. DEPARTMENT OF ENERGY
Morgantown Energy Technology Center
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26505-0880**

DOE Contract No. DE-AC21-93MC29252

By

**W. J. McDonald, Maurer Engineering Inc.
G. T. Pittard, Guided Boring Systems, Inc.**

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

February 1996

pg 1

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

	Page
EXECUTIVE SUMMARY	iii
OBJECTIVE AND BACKGROUND	iii
RESULTS	iv
1. INTRODUCTION	1
1.1 NEED FOR NEAR-BIT MWD SYSTEMS	1
1.2 PROGRAM STRUCTURE	1
PHASE I	2
PHASE II	3
2. TECHNICAL DESCRIPTION OF NEAR-BIT MWD SYSTEM	5
3. FIELD TEST RESULTS	8
4. CONCLUSIONS AND RECOMMENDATIONS	11

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

EXECUTIVE SUMMARY

OBJECTIVE AND BACKGROUND:

The program objective was to develop a Near-Bit Measurement-While-Drilling (MWD) system which collects borehole directional data and formation parameters directly at the drill bit-rock interface and transmits this information electromagnetically to a distant receiver located some 50 - 100 feet above the bit. The system is to be designed to work with positive-displacement motors and stabilized bottomhole assemblies from all manufacturers and to pass its data message to third party steering tools and conventional MWD telemetry systems for subsequent transmission to the surface. The work was performed by a joint team from Maurer Engineering Inc. (MEI) and Guided Boring Systems (GBS), both of Houston, Texas, under contract from the Morgantown Energy Technology Center, U. S. Department of Energy (METC).

The basic design of the Near-Bit MWD system is based upon GBS' commercially successful AccuNav® EM MWD guidance system. This system is widely employed in under-river utility crossings and environmental remediation activities. The system has been demonstrated to be accurate and extremely reliable in these applications.

The project has been completed through the end of Phase II. The Phase I effort was used to define the technical specifications of the Near-Bit MWD device, followed by design, fabrication and laboratory testing of a first generation prototype. This allowed demonstrating that the required functionality, form and fit had been achieved before embarking on the Phase II field testing program. The Phase I prototype was originally configured with tri-axis accelerometers, temperature and pressure sensors. The accelerometers provide a direct measure of the borehole inclination angle, which in conjunction with natural gamma ray and formation resistivity logs are the most sought after data elements with respect to optimized well placement with the targeted production zone(s).

The Phase II objective was to incorporate a formation-measuring sensor and to assess the system performance and reliability in a series of field experiments. Based on the results of these tests, final design modifications were to be implemented in support of commercialization.

The genesis for a Near-Bit MWD system which can be operated with commercial MWD or wireline steering tools and bottomhole directional assemblies responds to the need for enhanced information to support directional drilling operations in general, and horizontal drilling in particular. Horizontal drilling has been demonstrated to increase oil and gas production rates in tight formations and to mitigate production-associated problems such as sand production and water and gas coning.

Correspondingly, as horizontal and directional drilling and completion technology has improved through evolution, the length of the horizontal sections have grown longer and the need for more accurate well placement has become more critical. The reliance on examining formation properties and directional data gathered some 50 - 100 feet above the drill bit becomes increasingly less acceptable as turning radii decrease and target sands become thinner. This is because the impact of standoff distance, namely, examining what has occurred above the bit rather than what is now transpiring, can result in missing thin targets, falling out of the productive zone(s), or dipping into the water or gas cap. Corrections may result in significant additional costs, especially if plugging back and redrilling the lower portion of the well is required. Combined inclination angle and formation data allows the driller to employ "geosteering" (as coined by Schlumberger) — optimizing well placement in terms of productivity, minimized installation costs and lower lifetime maintenance requirements.

This research effort, by adopting a design philosophy of "bolt-on" performance in a small package size, can provide the market a short- and medium-radius near-bit MWD tool that can be operated in conjunction with equipment offered by many vendors. This reduces overall costs required to implement this technology and will speed commercialization due to the breadth of customers served.

RESULTS:

The Phase I Near-Bit MWD prototype was redesigned in Phase II to include a natural gamma ray sensor system. The size, power requirements and packaging constraints necessary to incorporate this additional sensor required a complete redesign of the near-bit mechanical components, modification of the power supply circuitry as well as considerable software modifications. The near-bit receiver system was also modified to have a data recording capability (> 2 mega-bytes of storage memory) to more easily support field experiments. The latter allowed the Near-Bit transmitter-sensor sub to transmit its data to the receiver where it is stored in a time-tagged format. This allows assessment of system performance and reliability without the time and costs associated with integrating the data transfer from the near-bit receiver to a third party MWD or steering tool.

The completed system has been designed for use with 6½ and 6¾ inch multi-lobe mud motors. The device components are pictured in Figures 1 - 4 with their technical specifications listed in Table 1. The transmitter-sensor sub dimensions are 6.500 inches diameter with a shoulder-to-shoulder length of 42.5 inches. The unit has 4½ inch A.P.I. regular tool joints run pin by box (down). This allows the transmitter sub to be connected to the mud motor bit box with the drill bit connected to the transmitter's 4½ inch A.P.I. regular box connection. The receiver electronics are mounted on a 52 inch mandrel which is run inside a 1-3/4 inch diameter beryllium copper pressure housing. The pressure housing, in turn, is placed inside a standard non-magnetic drill collar in direct proximity to the host wireline or MWD tool.

Referring to Figures 1 - 4, the device operates as follows:

1. The software control program residing in EEPROM in the downhole microprocessor collects the tri-axis accelerometer, temperature and gamma ray data via its multiplexed A/D converter. All aspects of the data collection routine are fully programmable.
2. The collected sensor data and system status information (e.g. battery life and self-diagnostics) are assembled by the microprocessor into a digitally-formatted message string.
3. The message string is electromagnetically impressed onto the drill pipe via the high power transmitter circuit. As with the message format, the start of transmission trigger, repetition rate, transmission duration, and transmission frequencies used are fully programmable by adjusting the operating variables prior to running in the hole.
4. The transmitted message is received by the receiver-demodulator located some convenient distance above the transmitter in close proximity to the third party wireline or steering tool. The received message is decoded, stored into buffered memory and available for transfer to the MWD or wireline host for integration and transmission to the surface. To maximize communication flexibility, the Near-Bit receiver design allows data transfer to the host as either fully buffered digital (serial and parallel interface protocols) or as an analog message using its D/A circuitry.
5. Operating power for both the Near-Bit MWD transmitter and receiver is provided by on-board battery packs. Rechargeable nickel-cadmium and high temperature lithium batteries are supported with the selection made on the basis of the wellbore temperature.

Figure 1. Near-Bit MWD System Block Diagram

The unit was fully assembled, calibrated and then subjected to field testing of its performance and reliability. The first two test sequences were conducted in cemented, cased wellbores at MEI and the Chevron Training Center. The MEI test well is 200 feet deep and completed with 7-7/8 inch cemented steel casing from surface to total depth. The Chevron well has a measured depth of 5047 feet and is completed with 7-inch, 26 lb/ft, K-55 casing as illustrated in Figure 5.

The near-bit system unit was operated in MEI test well with a transmitter-receiver separation distance of 100 feet. The well was liquid-filled with a measured AC impedance of 25 ohms. The unit performed successfully with no problems of any kind. signal-to-noise ratio was quite favorable with a typical range of 13:1.

The Chevron tests allowed increasing the receiver-to-transmitter separation distance and to examine the performance at lower impedance values (4 - 6 ohms). The maximum separation distance at which continuous, successful data transfer was accomplished (100% success rate) was 300 feet using a 24 volt, 5 KHz center frequency and 350 feet when operated at 2 KHz and 24 volts. Both distances are substantially greater than that required for Near-Bit MWD operations.

TABLE 1. Technical Specifications

6½ Inch Near-BIT EM MWD System

1. MECHANICAL

Sub Diameter:	6.500 Inches
Sub length:	42.5 Inches (Shoulder to Shoulder)
Flow Area:	1.375 Inch ID (1.48 square inches)
Over Pull Capacity:	220,000 Lbs. (2:1 SF)
Pressure Rating:	13,400 PSI (2:1 SF)
Materials of Construction:	4140 Commercial heat Treat
Tool Joints:	4½ API Reg. Pin x 4½ API Box (Down)

2. SENSORY

Triaxial Acceleration Range:	+/- 1g
Inclination:	0.1 Degrees
Temperature:	125 Degrees C
Geiger-Mueller Gamma Ray:	Counts/Time
Temperature:	150 degrees C

3. COMMUNICATIONS

Telemetry:	EM Frequency Shift Keying
Transmit Frequencies:	Selectable
Baud Rate:	Selectable Up to 1200 BPS
Transmission Trigger:	Stop Pumps (Stop Rotation)
Data Transfer to Host:	RS-232, Parallel and Analog

4. OTHER

Power Source:	Rechargeable Ni-Cads or High Temp. Lithium
Operating Life:	100 - 150 Hours depending upon Configuration and Duty Cycle
Lost Circulation Material:	Pass

Figure 2. Near-Bit MWD Transmitter-Sensor Components

Figure 3. Side View of Near-Bit Electronics and Sensor Mandrel

Based on the results of the Phase II effort, we offer the following conclusions and recommendations:

1. A Near-Bit MWD system suitable for use in short, medium and long-radius directional drilling applications has been successfully developed. The device contains a natural gamma ray sensor, tri-axial accelerometer set and temperature sensor.
2. The Near-Bit MWD system is capable of operating in both cased- and open-hole sections of the wellbore.
3. The operation of the transmitter-sensor sub and the receiver-recorder electronics has been fully verified in laboratory and field environments.
4. The inclusion of additional sensor types, such as formation resistivity will further increase the commercial viability of the device.
5. Further field testing is required before proceeding to commercialization to assure the required levels of reliability have been obtained.
6. Additional field tests should be conducted in cooperation with service companies interested in commercializing the Near-Bit EM MWD technology. In this way, the process of technology transfer, economics and marketing issues can be addressed as the final stage of development testing is completed.

Figure 4. Near-Bit Receiver-Recorder

DTC WELL No. 1

COMPLETED JULY 2, 1984

Figure 5. Chevron Test Well (Houston, Texas)

1. INTRODUCTION

1.1 NEED FOR NEAR-BIT MWD SYSTEMS

The oil and gas industry is constantly improving the technologies employed in the exploration and production of fossil fuels in response to keenly competitive market conditions and the increasingly more hostile environments from which reserves are being produced. This is especially true for offshore drilling activities.

The development of a Measurement-While-Drilling (MWD) system that can reliably provide real-time reports of drilling conditions at the bit and can be used in conjunction with third party steering tools and MWD systems is especially attractive. Commercialization of such a device will allow optimized well placement while the length of the Near-Bit MWD package can support both medium and short radius horizontal drilling activities. The latter capability is currently unique with respect to Near-Bit MWD systems and directly responds to the desire to use short radius drilling to further reduce drilling costs. Finally, the cost of the near-bit system, when combined with its compatibility with third party vendor hardware, should significantly speed its commercial introduction as the additional costs to operate the device should be quite low relative to the expanded capabilities it affords.

A fully configured near-bit system will provide numerous benefits to the industry. These include:

1. More accurate wellbore placement resulting from real-time knowledge of the wellbore inclination angle and formation properties.
2. Improved well control (requires wellbore pressure sensors) by identifying kicks as they first occur — thereby maximizing the response time available to the rig crew.
3. Increased penetration rates and extension of downhole tool life (based on vibration monitoring) by minimizing detrimental operating conditions.
4. Reduced drilling costs based on improved well placement, higher penetration rates and extending equipment life achieved from items 1 - 3.

1.2 PROGRAM STRUCTURE

The development program has been conducted in two phases. The statement of work for each phase is described below to fully verse the reader with the planned effort and the deliverables provided to METC.

PHASE I

Task 1 — Define System Requirements

This task was used to prepare a set of technical specifications for the Near-Bit MWD system. The process consisted of first performing a series of trade-off analyses regarding mechanical strength requirements, type of sensors to be incorporated and the performance and reliability specifications for these sensors. Several discussions were held within the project team and among outside organizations to ascertain the informational content and features desired in a Near-Bit MWD system. The results of the trade-off analyses and industry input were applied to generate the detailed specifications and prioritize development activities. The preferred sensor suite consisted of measuring the wellbore inclination angle and providing some means of tracking changes in lithology. The most popular sensor candidates for formation evaluation were the use of a natural gamma ray and formation resistivity logs. Both types of formation sensors would ideally be included in a Near-Bit MWD system.

Interface protocols employed by various MWD and steering tool manufacturers were identified and used to develop a data transfer method from the Near-Bit MWD receiver unit to the host MWD/steering tool. As discussed in this report, these communication requirements were supplied in as broad a range as possible to obviate the need to reconfigure the communications to support each different manufacturer.

Task 2 — System Electronics and Mechanical Designs

The EM transmission properties of the bottom hole assembly and drilling environment were bounded and applied to our signal propagation models to define the most effective means to transmit data from the near-bit transmitter/sensor sub to the near-bit receiver. In addition, GBS' AccuNav® electronic designs were reviewed in terms of their shock and vibration resistance characteristics and strengthened where deemed necessary. The design layouts were also modified as required to accommodate the physical packaging scheme identified in Task 1.

The near-bit mechanical housings were designed to afford maximum protection to the electronics and batteries. Substantial use of multi-chip module and surface-mount technologies were employed. This reduces the overall mass of each package. The lower the mass of each mounted component and the shorter its height, the lower the probability of component-circuit board trace separations. In addition, special stress bars and high quality soldering techniques were employed with the surface mount elements to further minimize the potential for failure.

The Near-Bit transmitter sensor housing lengths was kept as short as possible (excepting some additional length for thread re-cuts) to minimize the increase in bending moment on the Moineau motor bearing packs and its impact on steering rates.

Task 3 — Fabrication of Near-Bit MWD Prototype

This task was used to fabricate the first generation, fully functioning prototype which provided a test and debugging module for conducting laboratory performance and reliability tests.

Task 4 — Conduct Laboratory Performance Tests

This task was used to measure the performance and reliability of the Near-Bit MWD system under laboratory conditions which simulated the actual drilling conditions expected in the field as closely as possible. Tests were conducted at the Drilling Research Center in Houston, Texas. Two types of data were collected: 1) signal transmission and reception performance and 2) reliability data. The latter included a series of long-term shock and vibration tests.

Task 5 — Prepare Phase I Final Report

The results of the Phase I program were documented in a written report to METC. The report included a full summary of the results of the work along with conclusions and recommendations for the Phase II program.

PHASE II

Task 6 — Develop Commercial Sensor Suite

This task was used to develop an expanded Near-Bit MWD sensor suite in order to provide the measurement capabilities desired by the industry. For example, a gamma ray detector has added to provide a means of identifying boundaries between different types of lithology. While still further types of sensors are desirable to the industry, the level of funding did not allow development of an even broader sensor array.

Task 7 — Extended Shock and Vibration Testing

Running concurrent with Task 6, each of the downhole elements were subjected to extended periods of shock and vibration testing in order to identify weak areas to be strengthened to support long-term reliability in "real world" operations. The deliverable of this task was a packaging scheme for field testing which was expected to provide acceptable MTBF values for commercialization.

Task 8 — Fabrication and Testing of Field Prototypes

Two second generation prototypes were built and subjected to field testing. Due to the limited funds, a total of three test sequences were conducted. The first two sequences assessed basic performance while third test examined design reliability under actual drilling conditions.

Task 9 — Implement Engineering Design Changes

The purpose of this task was to apply the knowledge gained from the field test results to further improve the performance and reliability of the Near-Bit MWD device. The objective was to institute the useful/required improvements and verify the benefits of each through additional field trials.

Task 10 — Final Report

This report documents the results of the completed Phase II program and provides conclusions and recommendations regarding further development and commercialization.

2. TECHNICAL DESCRIPTION OF NEAR-BIT MWD SYSTEM

The Near-Bit EM MWD system is composed of two main subassemblies. These are: 1) the EM transmitter-sensor assembly which is placed directly between the drill bit and the steerable mud motor, and 2) the receiver-demodulator which is located in one of the non-magnetic drilling collars above the motor immediately adjacent to a conventional MWD or wireline steering tool probe assembly. The typical placement locations are illustrated in Figure 6.

Figure 6. Location of Near-Bit MWD Components in the Bottomhole Assembly

The design and operation of the Near-Bit EM MWD system will now be described. The sensors and electronics are mounted on a machined aluminum mandrel as previously shown in Figures 2 and 3. The outer periphery of the mandrel features two milled slots. One slot is used to mount the tri-axial accelerometers, temperature sensor and the corresponding signal conditioning and thermal compensation printed circuit board. The second slot houses both the switching power supply and combination transmitter-central processor printed circuit boards. All of these boards are multi-layer, polyamide construction with separate ground and power planes to minimize noise and maximize reliability.

The mandrel has six (6) circular through holes. Four of these holes are 1.28 inches in diameter and are used to package the nickel-cadmium or lithium battery pack (depending on wellbore temperature) in a gatling gun or cartridge-like arrangement. The fifth hole measures 1.50 inches in diameter and houses the Geiger-Mueller tube gamma ray probe. The placement of the gamma ray minimizes the degree of shielding from the outer mechanical housing. The last hole is on centerline and measures 1.875 inches in diameter. It receives the flow tube whose function is to provide a conduit for the drilling mud exiting the motor to the drill bit. The completed mandrel measures approximately 23 inches in length and is 5 inches in diameter.

The gamma ray sensor employs a Schmitt trigger or flip-flop circuit where each gamma ray received by the probe results in a change of logic state from its original high or low voltage to the opposite state. These changes are counted versus elapsed time and stored into memory. Based on the calibration related to the thickness of the outer collar and the window averaging parameters selected, a conversion to API counts can be made. The use of a Geiger-Mueller (GM) tube design over the often-employed scintillation crystal configuration was made based on the higher durability we believe is offered by the GM design.

The mandrel features a variety of shock mountings to protect the electronic printed circuit boards and the sensors from damage that can be caused from axial and transverse loads developed during the drilling process. The shock mounting is redundant (applied in multiple levels) such that the sensors are protected relative to the mandrel, and the mandrel is shock mounted relative to the torque and axial loads transmitted through the housings and load bearing members.

The mandrel is mounted into the transmitter-sensor assembly by lowering it over the center drilled mud flow tube which is threaded to the bottom sub. Appropriate fluid seals and a keying arrangement assure a fixed sensor orientation and fluid-tight installation. The transmitter-sensor sub assembly is completed by threading the outer pressure/mechanical housing to the bottom sub. The complete assembly is illustrated in Figure 7.

Figure 7. Near-Bit MWD Transmitter-Sensor Assembly

The Near-Bit EM MWD transmitter-sensor assembly is activated at the surface prior to entering the well by installing a removable run plug. The plug consists of a series of jumpers which initiate system start up procedures and field operations. The same plug port allows for recharging of the battery pack when Ni-Cad packs are used and can also be used to reprogram the system setup variables.

All of the Near-Bit MWD receiver functions have been fully integrated onto a single printed circuit board. The front end of the receiver is composed of a high Q, phase lock loop filter-demodulator circuit. Other features include a wide dynamic range automatic gain control and full error detection and correction (EDC) processing scheme. The demodulated signal is stored in fully-addressed memory which can be forwarded to the third party host telemetry/sensor system without interrupting the operation of the receiver. The receiver supports both digital and analog data transfer. Digital transfer can be accomplished via parallel or serial interfaces. The analog message is produced by running through a D/A convertor which can be programmed via the receiver microprocessor to emulate the requirements of the host machine. The receiver electronics and battery pack measure 52 inches in length.

The receiver is placed into a 1.75 inch OD pressure barrel. The pressure barrel is fitted with a hanger sub whose dimensions are selected to match the specific drill collars to be run on the bottomhole assembly. The design can also be run in an orientated muleshoe assembly depending upon customer preferences. All tests were conducted with the top hanger sub design.

3. FIELD TEST RESULTS

A total of three field tests were performed during the Phase II project. The first two test series examined only performance-related issues while the third included assessing the Near-Bit MWD reliability under actual drilling conditions. The results of each of these tests are described below.

The tests conducted in the MEI test well were staged to follow the hardware-software development cycle. Therefore, the first series of tests only examined operation of the Near-Bit transmitter-sensor sub and employed a standard GBS AccuNav® surface receiver. These tests were then followed by assessing the performance of the transmitter-sensor sub in conjunction with the Near-Bit receiver-recorder. Tests were performed with the cased well being liquid-filled ($Z_{\text{drilling mud}} = 26 \text{ ohms}$).

All tests were performed with a maximum transmitter-receiver spacing of 100 feet. For each test, successful operation distance was defined as the ability to receive 100% of the transmitted messages. This requirement was easily tracked by programming the transmitter to send its complete sensor data message string once every three seconds. Thus, by recording the number of messages received per unit time, a concise success rate was known. Corrupted messages would also be easily found since they would fail the error-detection-correction (EDC) logic.

The tests were successful. Figures 8 and 9 show typical signal-to-noise comparisons. These readings were taken with the receiver automatic gain control (AGC) circuit bypassed and a manual gain of one (no attenuation or amplification) selected in its place. The tests highlighted the following requirements for Near-Bit operation in cased wellbores:

CASED WELLBORES:

1. The transmitter antenna must be prevented from contacting the casing wall. Otherwise, a high loss current path will be formed – greatly reducing the operating range between the transmitter and receiver. In practical applications, this condition is easily satisfied since the transmitter sub will be located directly behind the drill bit which is of significantly larger diameter.
2. Likewise, the receiver antenna should be maintained off the casing wall to maximize the telemetry range. This can be accomplished by either recessing the antenna relative to the collar OD or by employing a set of drill pipe protectors immediately above and below the receiver antenna. The first technique has been employed for the field tests.

OPENHOLE WELLBORES:

The performance of the Near-Bit MWD system in openhole sections was taken directly from the operation experiences gathered from everyday use of GBS' AccuNav® Guidance System. For example, in openhole applications, there is no requirement to recess either the transmitter or receiver antennae. Furthermore, the operating range in openhole applications is significantly greater than that possible in cased portions of the well owing to the absence of the "signal parasitic" behavior of the casing. While the exact range realized will be dictated by the local conditions, GBS has successfully transmitted in openhole conditions to distances in excess of 1000 feet with the AccuNav®

The tests conducted in the Chevron well allowed us to further extend the separation distance between the transmitter and receiver as well as to assess the effect of decreased impedance. The test procedure consisted of lowering the EM transmitter-sensor sub into the well and recording the maximum depth at which 100% of the transmitted messages were received. The well was mud-filled and had an AC impedance of 4 ohms as measured across the transmitter outputs.

Successful data reception inside the cased hole was consistently obtained (100% success rate) for separation distances up to 340 feet when operating at a nominal 2 KHz center frequency and 24 volt output and 298 feet when operated at 5 KHz and 24 volts. These distances are well in excess of the 100 ft. objective for Near-Bit operation. Successful data captured was observed for S/N ratios as low as 1.5:1.

Figure 8. Received Signal (Gain = 1)

23-Feb-96
11:03:11

LeCroy

Figure 9. Background Noise (Gain = 1)

The final field test had the specific objective of examining the reliability of the Near-Bit transmitter-sensor sub and the receiver-recorder when operated in actual drilling environments. The plan was to operate the complete system in an actual drilling operation for a total of 75 hours after which the hardware would be pulled out of the hole and examined for any reliability problems. Obviously, the exact in-hole period would be dictated by other drill rig operations such as bit trips, casing points etc. These tests were not conducted due to funding limitations.

4. CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the Phase II effort, we offer the following conclusions and recommendations:

1. A Near-Bit MWD system suitable for use in short, medium and long-radius directional drilling applications has been successfully developed. The device contains a natural gamma ray sensor, tri-axial accelerometer set and temperature sensor.
2. The Near-Bit MWD system is capable of operating in both cased- and open-hole sections of the wellbore.
3. The operation of the transmitter-sensor sub and the receiver-recorder electronics have been fully verified in laboratory and field environments.
4. The inclusion of additional sensor types, such as formation resistivity will further increase the commercial viability of the device.
5. Further field testing is required before proceeding to commercialization to assure the required levels of reliability have been obtained.
6. Field tests should be conducted in cooperation with service companies interested in commercializing the Near-Bit EM MWD technology. In this way, the process of technology transfer, economics and marketing issues can be addressed as the final stage of development testing is completed.