Drilling Optimization Utilizing Surface Instrumentation for Downhole Event Recognition

Final Report

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by

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Abstract

This DOE project was undertaken to develop and test an instrumented data-acquisition sub that is mounted in a drill string below the top drive and used to detect downhole events. Data recorded at the surface during drilling operations would then be processed and presented to the driller to discern undesirable drilling conditions and help optimize drilling rates and maximize the life of components in the BHA.

This instrumented sub was originally conceived and developed solely as a single-point collection center for rig data that would be used in a number of Noble’s products. The sub was designed to collect hook load, rotary torque, rotary speed, rotary position, drill pipe pressure, mud temperature, triaxial vibration, and triaxial magnetometer data. The original design and fabrication was by Sandia National Labs under Noble’s direction, which was then tested with Sandia’s diagnostics-while-drilling downhole package.

After initial results were analyzed, the team surmised that important information describing performance and condition of the bottom-hole assembly (BHA) was embedded in the data recorded by the instrumented sub, and began investigating the potential of using surface measurements from the sub to highlight problems occurring downhole before they could be discerned by the driller. Later, a proposal was submitted to DOE for funding to more broadly investigate use of the system for detecting downhole problems while drilling. Soon after DOE awarded this contract, the Noble team responsible for the previous developments was disbanded and their work terminated (due to factors unrelated to the sub development). This change halted the complementary work that Noble had planned to conduct during the DOE project, and necessitated that all the development work be completed by the DOE project.

More effort was expended on the project to develop a field-ready prototype than was originally foreseen. The sub’s design had to be significantly modified during the project based on results of field tests. The original slip ring for communication was replaced with a radio link, which makes the sub easier to move to different rigs and simplifies the set-up process. In addition, the sub’s previous design would prevent it being used on oil and gas rigs due to potential explosion hazard. The sub was redesigned so that during operation all electrical components on the sub are under a blanket of nitrogen. A pressure switch is used so that, should a leak develop, the sub will shut itself down until any problems are repaired.

A total of four series of field tests were conducted. The first (mentioned above) was part of the original Noble-sponsored program and in conjunction with Sandia’s diagnostics-while-drilling system. Although these tests highlighted important problems, they showed significant promise for the concept, and the sub was returned to Sandia for early repairs and modifications. After the DOE project took possession of the sub, it was tested three more times in the field.

The first two DOE tests had the same objective, which was to establish that the sub could function correctly on the rig and deliver usable data, and to develop procedures for setting up and operating the sub and support computer on a rig. During the first test most of the time was spent troubleshooting the sub. Several significant problems were revealed, demonstrating that the current design was not robust enough to survive typical oil field operations.

The sub was then redesigned to increase its robustness and allow it to run safely in areas where explosive gases might be present. Once these changes were implemented, the sub was
sent to a second shake-down field test. The new design was found to be greatly improved. The sub operated throughout the test, and quality of the data was significantly higher.

Near the end of this project, a final field test was conducted with the objective of creating (or simulating) specific problem conditions and recording data to determine if signatures could be recorded and identified that, after analysis, might signify particular types of drilling activities or conditions. Tests included normal rig operations as well as dropping the string, bit stick/slip, bit bounce, and rough drilling. The sub worked very well throughout these tests, and signatures were obtained for each of the conditions. Some events, most notably stick/slip and rough drilling, exhibited unique signatures that were recorded by the instrumented sub.

The final field tests were conducted in a relatively shallow well, and further testing is needed to determine the range of depths from which usable signals can be detected. However, these tests clearly demonstrated that useful data can be gathered in this manner and that much of this data, typically collected by several sensors in various locations, can be collected at a single point and that the data are of higher quality than is often the case. The field tests also showed that the sub has potential for basic data collection not directly related to the goals of this project.

Since the end of the DOE-sponsored phase of the effort, several parties have expressed interest in the sub. These leads will continue to be pursued regarding further development and commercialization of the technology.
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1. Introduction

1.1 Background

Objectives of this DOE project were to develop and test a multi-parameter instrumented data-acquisition sub that is mounted below the top drive at the surface and used to detect downhole events (Figure 1). Data recorded at the surface during drilling operations would then be processed and presented to the driller to help optimize the rate of penetration (ROP) and to maximize the life of components in the BHA.

Vibration of the drill string can often be measured at the surface, and can serve as an indicator of undesired downhole events. Drill-string vibration can lead to premature failure of downhole components and the bit, and represents a waste of drilling energy. Various sources can excite the drill string. The amplitude of vibration will depend on the level of excitation, system damping, and whether excitation frequencies are close to any natural frequencies of the drill string. Vibration levels are generally highest at resonance (axial, torsional or lateral), but high vibration levels may exist in the drill string independent of resonance whenever high excitation is present.

High vibration accelerates drill-string fatigue, a primary cause of failure. Significant effort has been expended by researchers to understand and control drill-string vibration to reduce component failures. As importantly, high amplitude drill-string vibration represents a loss of drilling energy and drilling efficiency. Therefore, high vibration not only results in component failures, but also in reduced ROP.

There are two approaches taken by researchers historically to reduce vibration levels:

1. Model BHA performance and conduct a harmonic analysis to predict optimal operating conditions (WOB, RPM) to avoid conditions that lead to resonance
2. Directly monitor vibration levels during drilling to determine optimum operating conditions in real time (or near real time)

The first approach—harmonic modeling—is limited by the number of unknowns in real-time drilling operations. In addition, most models focus on drill-string resonance frequencies, and predict rotary speeds that will avoid exciting those frequencies ("critical speed" analysis). Therefore, they do not consider high levels of excitation independent of resonance analysis.
The second approach—monitoring vibration levels to detect suboptimal drilling performance—is more easily implemented into field operations. This is the approach pursued by this project.

The highest levels of vibration are often caused by stick/slip behavior at the bit/rock and drill string/borehole wall interfaces. Stick/slip of the bit and BHA can be regarded as large, self-sustained oscillations of the lowest mode of torsion—the so-called pendulum mode. Stick/slip is characterized by short time intervals when the bit is stationary and the drill pipe is elastically twisted by the rotary table (or top drive). When drill-string torque then reaches a sufficiently high level (dictated by static friction resistance of the BHA), the bit breaks free and accelerates to more than twice the nominal rotary speed before it slows and stops again. In some cases the bit actually reverses direction momentarily before it sticks again. This dynamic process is accompanied by large cyclic stresses in the drill string.

Problems caused by stick/slip include accelerated fatigue of the drill pipe, axial and lateral vibration in the BHA (damaging components and connections), excessive bit wear, and reduction in ROP.

1.2 Noble’s Stick/Slip Simulator

As part of Noble’s previous R&D that contributed to development of the instrumented sub, Noble investigated the feasibility of measuring parameters at the surface that reflect downhole operating conditions. While much positive evidence was gathered and analyzed from similar projects by Noble and others, an area of particular interest included results from a special drilling simulator, and field data from equipment developed using this simulator.

An initiative launched by Noble Corporation (and now being pursued by a private company) was to develop surface equipment that would, through computer-assisted control, improve directional drilling operations that incorporate mud motors and bent housings. An automated system (Slider™) is now commercially available and reduces friction of the drill pipe when slide drilling as well as helping control and maintain the proper orientation of the BHA during directional operations. Early in Slider’s development, a special drilling simulator was constructed that represented a rig, drill string, and typical directional BHA. This simulator (Figure 2) was used to measure the response of drilling systems to variation of various parameters under drilling conditions. These data were later used to develop equipment required to make Slider function correctly. This simulator was used to investigate whether data measured at the surface could reflect conditions downhole.
On the simulator, the rig is represented by two variable-speed electric motors (Figure 3). The top-drive motor is used to turn the drill pipe and bit, and is instrumented to measure rotational angle, speed, string weight and torque. The second motor translates the top drive to simulate raising and lowering the drawworks, and a sensor attached to the top drive measures position as it would on a rig.

The simulated BHA (Figure 4) consists of a bit represented by two disks whose surfaces are pressed together to act as a clutch. Bit drag can be changed by adjusting the contact pressure on the clutch or changing the material on the face of the clutch. The bit is also instrumented so that torque, bit weight, and angular position are known. Another motor is used to simulate the mud motor. It has variable speed control and is attached to one of the bit clutch plates. These components are mounted on a carriage that is attached to a hydraulic cylinder that controls drill-off of the bit. Formation hardness is changed by adjusting a needle valve that controls how fast fluid can drain from the cylinder back to the reservoir. Closing the valve simulates a harder formation; opening it a softer one. WOB is applied by the drawworks motor.
An innovative feature of this simulator is in its representation of the drill string and borehole. The borehole component consists of two aluminum bars with a milled semi-circular groove in each (Figure 5). Friction acting between the wellbore and drilling string can be modified by changing pressure on pneumatic cylinders that hold the two halves of the “borehole” together. Drill pipe is represented by a length of plastic tubing. The particular tubing used was selected after a careful analysis of typical drill pipe properties, particularly torsional stiffness. Pipe properties were reduced to dimensionless parameters and results compared to those obtained with various materials in the simulator. The plastic drill-pipe material was then selected based on response analogous to drill pipe in a typical well.

The simulator is controlled and monitored by a computer located in the console (see Figure 2). Data recorded from many series of simulated drilling operations were used to develop the
Slider™ directional drilling system and to program the control parameters. Experience showed that the simulator was an accurate analog of the complete well and drilling system. This simulator was also used to demonstrate that measurements made at the surface would indeed indicate changing downhole conditions.

Figure 6 shows a Slider output screen from the torque measurement taken at the top drive when the system was running with no stick/slip at the bit. Variations in torque (see the graph on the display screen) are relatively random and small in amplitude.

![Figure 6. Simulator Output with no Stick/Slip](image)

In another test, drilling parameters were adjusted to produce stick/slip of the bit (see Section 1.1). Stick/slip is a common occurrence in directional wells because the drill string has added friction or drag on the borehole wall. Figure 7 shows the output of the simulator under stick/slip conditions. Each peak on the curve represents a cycle of stick/slip, and has the same period of time as the rotational speed of the top drive.
Data from field tests with the Slider automated drilling control system were examined. Slider records torque on the top drive as part of its normal function. On a well drilled in British Columbia, the data clearly showed bit stick/slip similar to that observed in this project’s tests. Figure 8 shows the characteristic spring and decay pattern as the bit became stuck and then released. In this well the bit was reaming a section of hole. These data prove that in many wells bit stick/slip could be detected at the surface. If the driller were alerted, he could alter the drilling parameters to maximize ROP without sacrificing bit life.
1.3 Using Data Recorded at the Surface to Detect Downhole Conditions

In conventional operations, drilling engineers track various operational parameters such as ROP, torque, and pressure logs. These can provide only a simple picture of the behavior of the drillstring, bit and well. Typically, a driller will use this type of operational information, a few rules of thumb, and experience as he attempts to manage drilling operations in the most efficient manner. In addition to these traditional tools, dynamic data can be useful for providing a clearer picture of the process. These are used to complement conventional data (ordinary parameter measurements, measurement-while-drilling (MWD), mud logging, etc.).

Measurement of drill-string dynamic behavior can address several goals:

- Optimization of rock destruction processes
- Reducing trips to examine/replace the bit
- Reducing drillstring fatigue
- Tracking rock formations encountered in real time
- Optimizing mud circulation (cleaning and lubrication)
- Assessing the overall operation during drilling

Real-time drilling dynamics data may help achieve these goals through indicating beneficial adjustments to drilling parameters in real time, optimization of BHAs, and continuous monitoring of the bit. Other damaging conditions may also be observed and corrected in real time.
Using surface measurements to detect abnormal drill-string vibration is not a new concept. In 1971, Lutz et al. used an advanced surface data acquisition and treatment system to produce a log (termed a SNAP log). This log was constructed from surface measurements of tension and vertical acceleration. The same measurements were also used to detect poor performance of tricone bits.

The idea to use surface measurements to detect downhole vibration was again pursued in the latter half of the 1980s. An important early step was to design an advanced surface data-acquisition system. Most noteworthy is the ADAMS system by EXLOG (Besaisow et al., 1990) developed in conjunction with Elf’s Dynafor project (Dufeyte et al., 1991). Subs were built to record surface data related to mechanical behavior of the drill string including tension, torque, and vertical and rotational acceleration. The subs were connected under the kelly or power swivel, and measured drill-string vibration directly. These units were commercially available for a limited time.

The complete ADAMS system (Figure 9) was designed to measure and analyze various drill-string data, and consisted of a sub mounted above the kelly that contained strain gauges and accelerometers. Microwave telemetry was used to transmit data to an on-site receiving unit where the data were processed and analyzed. Energy peaks in the spectrum were related to resonant vibration in the drill string. The on-site engineer would then make recommendations to the driller based on the data analysis in real time.

Elf Aquitaine Production developed the surface sub (Figure 10) originally and licensed the technology to EXLOG. Elf called the system Dynafor. From analysis of several thousand hours of drilling dynamics measurements in several fields, Elf found that the stick/slip phenomenon occurred during about half of all rotary drilling. Furthermore, torque measured at the surface did not change much, and conventional torque gauges usually did not detect the small changes in
surface torque. Similar to speed fluctuations at the bit, torque at the bit can also vary widely during stick/slip.

Stick/slip was observed to result in short-term downhole rotational speeds of 3 to 10 times the specified surface speed. These speed fluctuations lasted from 1 sec to 40 sec, depending on the length of the drill string and the source of the friction. During stick/slip, the drillstring was subjected to high torque, occasionally exceeding the maximum elastic limit of the pipe. As the drillstring is torque-loaded during these oscillations, fatigue loading can occur.

Based on their analysis of field data, Elf found that early measurement of stick/slip was a critical factor in preventing stick-slip problems. The rig should have accurate tools to measure torque and rotational speed. One of the most reliable measurements of torque is through strain gauges at the top of the drill string. Another method is the measurement of the current in the driving motor. Dynameter torque measurements were reported to provide a good indication of torque amplitude and period for the driller. Among the rules of thumb Elf developed are:

- When warning signs of stick/slip appear, the driller should increase rotary speed (if rig equipment, drilling conditions, and drilling program permit).
- If RPM is too high when stick/slip warnings appear, the driller should reduce WOB momentarily to break the torsional waves.
- Frictional conditions in the well may be changed by picking up on the bit until friction is reduced. The bit can be rotated rapidly to break the torsion cycle. Drilling can then resume.
- Reaming the hole or a short trip will also reduce friction conditions in the well.
- If stick/slip persists and drilling performance remains low, the driller should use more aggressive methods, such as modifying the lubricating properties of the mud.

In addition to stick/slip, the Dynafor system was reportedly used to reveal bit bouncing, bit wear, blocked cones, balling of the BHA, hang-up of stabilizers, and backward whirl. ADAMS was reported to provide good results in several field trials. In one case, washouts were occurring in a particular field setting. After ADAMS was deployed, these washouts were eliminated while bit life was markedly increased. In another application, analysis of drilling data at the rig led to recommendations to the driller on WOB and RPM very different from those suggested by the bit.
manufacturer. The new operational parameters resulted in some of the best runs ever recorded in that field, with time to TD reduced from an average of 21 days to 14 and 12 days.

Halsey et al. (1988) described another system they hoped would control stick/slip phenomena. They built a model representative of a drill string in torsion. To keep the model simple, they included the first mode of drill string vibration in torsion, but ignored friction between the drill string and borehole wall or between the bit and formation are not included. They proposed that torque feedback be used to control stick/slip. In this approach, speed of the rotary table would not remain constant, but would be dynamically adjusted in response to torque oscillations. Then the rotary table, rather than acting as a simple reflector for torsional waves, would damp these waves. Field tests showed that, in many cases, their model was found to be sufficient to note stick/slip.

At about the same time, IFP began a program to analyze sources of abnormal vibration in drill strings. They developed a data-acquisition system named TRAFOR (Figure 11) that included both surface and downhole measurement subs (Guesnon and Pignard, 1992). A wireline link was deployed for synchronization between the two subs so the system can be used during rotary drilling. The data sampling rate was 360 Hz.

Problems were encountered when attempting to interpret data recorded with these systems. A variety of theoretical models were constructed to simulate principal drill-string vibration. Few accounted for the relationship between the drill string and borehole wall or the bit and formation. Clayer and al. (1990) showed that the effect of the rig on the top section of drill string must be considered along with the interaction of the bit and formation. Both were found to have significant effects on drill-string dynamics.

Models have rarely been used in real time for interpreting data recorded via surface subs. MacPherson et al. (1993) and Mason and Sprawls (1996) used conventional approaches such as root mean square or spectrograms to detect abnormal vibration. This approach was shown as valuable since the onset of resonance can be observed and subsequently halted by changing drilling parameters.

### 1.4 Justification

Previously developed surface data-acquisition systems described in Section 1.3 were all successful at various levels, but none were able to be offered commercially for an extended period. This was primarily due to high costs required to be charged for these services. These
also required experienced technical personnel to be present at the rig to aid in assembling equipment and to analyze the data in real time. In many cases, interpretation of results was accurate, but techniques then used to derive concrete instructions for the driller were unique to an individual operator or engineer. Drilling budgets, except in a few cases, could not support the cost of the extra personnel and equipment.

This project was envisioned to reduce this economic barrier in two ways. First, use of off-the-shelf components and computer chips would reduce equipment costs. All equipment was to be designed to fit below the top drive and not include any downhole equipment, thereby minimizing the impact on rig operations. Second, computers would be programmed to automatically process the data in real time and, through custom algorithms, identify and alert the operator to the presence of damaging vibration. This approach would eliminate the need for additional expert technical personnel on the rig. An added benefit is that the sub would be used to collect a number of different parameters that are currently being gathered by separate and often less accurate and/or difficult-to-install sensors. Costs for the sub could then be spread over two different applications.

Use of custom computer algorithms to detect events on the rig using various sensor inputs was proven by Noble’s Event Recognition project, where well kicks were detected well in advance of any personnel being able to detect it, even when the kick was expected and personnel were carefully monitoring for signs. Improved response and low cost of computers can help reduce costs and eliminate down time or increase equipment life, thereby further offsetting incremental costs of the equipment. It is possible that in the future a computer can be connected to the top drive and automatic driller, and adjust speed and/or bit weight within defined limits according to a series of predetermined formulas for each set of conditions.
2. Experimental

2.1 Objectives

The original objective of Phase I was to develop special algorithms to process critical drilling parameters measured by an instrumented surface sub to detect downhole events to optimize the ROP and to maximize BHA component life. As the tasks were pursued, the existing sub was tested and, unfortunately, proved to be of inadequate design and in need of significant re-engineering. As a result, much of the Phase I effort was redirected to design and implement essential changes and develop a working sub.

Phase II (not yet initiated) was also mapped in the original project design. Phase II objectives included upgrading the sub and detection algorithms based on overall Phase I results as appropriate, conducting staged field trials, integrating the system into an overall field data-acquisition package, developing a commercialization plan and transferring technology to industry.

2.2 Scope of Work

In the original plan for Phase I, the project team was to conduct a series of side-by-side laboratory calibration tests of the instrumented surface and one or more third-party downhole data-acquisition subs. The tests were to be structured to exercise each measured parameter over the expected ranges to be encountered in field tests. Concurrent with the test activities, the team would review prior work on downhole event recognition and drilling optimization efforts.

The project team was to conduct at least two drilling tests to collect time- and depth-based data from both the instrumented surface sub and a third-party downhole sub. The tests were to be organized and staged to measure the impact of drilling depth and hole geometry (vertical, inclined and horizontal wells) on signals recorded at surface versus those measured downhole. Data from both systems were to be analyzed and compared. Numerical analysis and digital filtering would then be applied to the surface recorded data for all observed events to determine what can be detected at the surface (i.e., signature of the event) and how it differs (level of attenuation, signal modification) from data recorded on bottom. The data would then be analyzed to gauge feasibility of using surface measurements for drilling optimization and event recognition based on the fidelity of the surface measurements and the uniqueness/ease of detecting the event signature.

In Phase II, the project team would then develop event recognition software and drilling optimization routines. A series of increasingly more difficult drilling tests would be planned to first define which of these elements have commercial viability and then optimize their performance.

Phase I tasks, as originally envisioned, are summarized in Table 1.
### Table 1. Phase I Tasks

<table>
<thead>
<tr>
<th>Task</th>
<th>Description</th>
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<tbody>
<tr>
<td>1</td>
<td>Review Previous Test Results and Develop Preliminary Recognition Algorithms</td>
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<tr>
<td>2</td>
<td>Laboratory Characterization and Calibration of Field Instrumentation</td>
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<tr>
<td>3</td>
<td>Conduct Staged Field Tests with Instrumented Surface and Downhole Subs (Anadarko wells)</td>
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<tr>
<td>4</td>
<td>Analyze/Compare Data Sets and Improve Preliminary Recognition Algorithms</td>
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<tr>
<td>5</td>
<td>Determine Quality of Event Recognition and Well Depths Achievable</td>
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<tr>
<td>6</td>
<td>Phase I Final Report</td>
</tr>
</tbody>
</table>

This project originally focused on Noble’s ongoing in-house development of an instrumented surface sub. The thrust of the original effort was to use the sub as a single point of collection for critical data to be used by automatic drillers and an improved directional drilling control system. However, at the start of this DOE project, complementary in-house efforts were discontinued by management (based on a high-level restructuring decision by Noble management) and the entire development transferred to this project.

The sub had been tested on one field test and needed several changes, design improvements, and repairs. Since the sub was no longer being developed by Noble for its original mission, the improvements implemented were much more specific to the needs of this DOE project. However, after another field test to determine operational requirements of the sub, it became apparent that the design of the sub electronics was not satisfactory and data could not be obtained reliably by the sub in its then-current configuration. Various changes were designed and implemented, and two additional field tests conducted, one as a cost-shared test with Noble’s rotary steerable tool and one as an independent test to measure parameters under specific drilling conditions.

Due to these unforeseen developments and design requirements, and the time and costs required to address various shortcomings; time and funding were not available in Phase I to thoroughly pursue the goals of Tasks 4 and 5.

### 2.3 System Design

Prior to this project, Noble had funded several developments for which the instrument sub was to serve as a data-acquisition point for several critical measurements. Mechanical design of the body of the instrumented sub was performed primarily by Sandia National Laboratories. Their efforts included an extensive mechanical analysis, including finite element analysis, to minimize the length of the sub body while still providing linear behavior as a transducer to measure critical parameters such as string weight and drilling torque. Their objectives were met by the resultant design, as was demonstrated during mechanical calibration of the sub after it was built.
2.3.1 Safety Factors

Results of Sandia’s analysis did not indicate any mechanical or thermal concerns for the design of the sub body. The overall minimum safety factor (SF) using the PH13-8 Mo stainless steel with all loads applied simultaneously was due to shear and was:

\[
SF_{\text{min}, \tau} = \frac{0.5 \cdot \sigma_y}{\tau_{\text{max}}} = \frac{0.5 \cdot (210,000 \text{ psi})}{71,570 \text{ psi}} = 1.467
\]

Eq. 1

The SF for tensile stress was:

\[
SF_{\text{min}, \sigma} = \frac{\sigma_y}{\sigma_{\text{max}}} = \frac{210,000 \text{ psi}}{125,300 \text{ psi}} = 1.676
\]

Eq. 2

However, in terms of axial load, internal pressure would only act to reduce the maximum tensile stress in the center section of the part. Therefore, the analysis was repeated without internal pressure applied. Results of this showed that maximum tensile and shear stresses both decreased slightly when internal pressure was removed (Figure 12 and Figure 13).

Figure 12. Sectioned Stress Plot – Combined Simultaneous Loads
Stresses and strains in the necked-down region of the part (where the strain gauges are mounted) are both approximately 3% higher with no applied internal pressure. As can be seen from both figures, the areas of highest stress are at the lower API thread interface and at the necked-down center section of the body. These also corresponded to the areas of highest strain, as shown in Figure 14. Strain gauges will be mounted in the necked-down area due to the uniform strain field at that position. This will allow separation of the internal pressure-induced strain from the tensile load strain.
Sandia also conducted a study of the sub's design and the use of strain gauges to measure internal pressure in the sub. These data were successfully recorded during calibration runs showing that internal pressure can be measured with the gauges. However, in field usage, string weight causes an offset of the pressure data. Since the sub was also equipped with a pressure transducer, this area was not pursued during this project.

### 2.3.2 Voltage/Strain Sensitivities

Load sensing by the instrumented sub is based on conventional strain-gauge technology. If a strip of conductive metal is stretched, it becomes thinner and longer, both changes resulting in an increase of electrical resistance. If these stresses are kept within the elastic limit of the metal strip, the strip can be used as a measuring element for physical force, the amount of applied force inferred from measuring its resistance. Strain gauges are frequently used in mechanical engineering research and development to measure stresses and strains. Strain-gauge strips are affixed to structural members, linkages, and other critical components. Strain gauges are normally wired in Wheatstone bridge circuits (Figure 15).
When unstrained, the bridge is balanced and output voltage is constant. When strain is added to the part, voltage changes (Figure 16) proportional to the movement of the structure.

Output, $V_{out}$, of a strain-gauge bridge for torsional loading, $M_z$, is:

$$V_{out}(\theta, \beta) = \frac{FV}{4} \sum_{i=0}^{3} (-1)^i \varepsilon(\theta_i, \beta_i)$$  \hfill Eq. 3

where

- $\theta$ = angle of deflection
- $\beta$ = torsional moment
- $F$ = gauge factor
- $V$ = input voltage
- $\varepsilon$ = strain (in./in.)

A four-arm bridge for $M_z$ is:

$$\theta_{Mz} = \left\langle 0; \frac{\pi}{2}; \pi; 3 \frac{\pi}{2} \right\rangle$$  \hfill Eq. 4

$$\beta_{Mz} = \left\langle \beta_z; -\beta_z; \beta_z; \beta_z \right\rangle$$  \hfill Eq. 5
The $M_z$ bridge is independent of all other loads.

Sensitivity for axial loading, $P_z$, is:

$$\theta_{P_z} = \left\langle 0; \frac{\pi}{2}; \pi; \frac{3\pi}{2} \right\rangle$$  \hspace{1cm} Eq. 7

$$\beta_{P_z} = \left\langle 0; \frac{\pi}{2}; 0; \frac{\pi}{2} \right\rangle$$  \hspace{1cm} Eq. 8

$$\frac{V_{out}(\theta_{P_z}, \beta_{P_z})}{P_z} = 0.0234 \mu V/lbf$$  \hspace{1cm} Eq. 9

The axial bridge does exhibit a pressure sensitivity. The closed form of bridge output is:

$$\frac{2(1+\nu)}{E} \left( \frac{P_z}{A} - \frac{d^2 P_i}{D^2 - d^2} \right) = 6000.8983 \mu \varepsilon$$  \hspace{1cm} Eq. 10

where:

$\nu$ = Poisson’s ratio

$E$ = Young’s modulus

$A$ = cross-sectional area

$P_i$ = internal pressure

$D$ = outer diameter

$d$ = inner diameter

If we consider a two-arm additive bridge (opposite arms) of Poisson ($\beta = \frac{\pi}{2}$) gauges, output is:

$$\frac{2}{E} \left( \frac{P_i d^2}{D^2 - d^2} (2 - \nu) - \frac{P_z \nu}{A} \right) = -820.388 \mu \varepsilon$$  \hspace{1cm} Eq. 11

These two outputs can be combined to separate $P_z$ (torsion) and $P_i$ (axial) as follows:

$$\frac{1}{1+\nu} \left[ \frac{2(1+\nu)}{E} \left( \frac{P_z}{A} - \frac{d^2 P_i}{D^2 - d^2} \right) \right] + \frac{1}{\nu} \left[ \frac{2}{E} \left( \frac{P_i d^2}{D^2 - d^2} (2 - \nu) - \frac{P_z \nu}{A} \right) \right] = \frac{4P_i d^2}{E(D^2 - d^2)} \cdot \frac{1-\nu}{\nu} = 1758.24 \mu \varepsilon$$  \hspace{1cm} Eq. 12
\[
\frac{1}{1+\nu} \left[ \frac{2(1+\nu)}{E} \left( \frac{P_z}{A} - \frac{d^2 P_i}{D^2 - d^2} \right) \right] + \frac{1}{2-\nu} \left[ \frac{2}{E} \left( \frac{P_z d^2}{D^2 - d^2} (2-\nu) - \frac{P_i}{A} \right) \right]
\]

\[
= \frac{4P_z}{AE} \cdot \frac{1-\nu}{2-\nu} = 4211.23 \mu e
\]

Eq. 13

Then, sensitivities are:

**Axial Sensitivity**

\[
\frac{VF d^2}{E(D^2 - d^2)} \cdot \frac{1-\nu}{\nu} = 1.1154 \frac{\mu V}{\text{psi}}
\]

Eq. 14

**Torsional Sensitivity**

\[
\frac{VF}{AE} \cdot \frac{1-\nu}{2-\nu} = 0.0164 \frac{\mu V}{\text{lbf}}
\]

Eq. 15

A four-arm pressure bridge cannot be constructed because the angle-dependent pressure term cancels out and the angle-dependent term is tied to an axial load term. If we consider a two-arm additive bridge, \(\beta\) must be zero or \(\pi/2\) to cancel \(P_x, P_y,\) and \(M_z, \theta\) must be \(\pi\) space to cancel \(M_x\) and \(M_y\). If both gauges have the same \(\beta\), then the axial term will result. This then requires a \(\pi\)-spaced additive pair at zero and \(\pi/2\) \(\beta\) as follows:

\[
\frac{M_r}{EJ} (1+\nu) \sin (2\beta) + \frac{P_i d^2}{E(D^2 - d^2)} (1-\nu) + \frac{M_r}{EJ} (1+\nu) \sin (2\beta) + \frac{P_i d^2}{E(D^2 - d^2)} (1-\nu)
\]

Eq. 16

where

- \(r\) = radius
- \(J\) = polar moment of inertia

If a two-arm bridge (opposite, not adjacent) is used at positive and negative \(\beta\), effective axial strain is reduced to:

\[
\varepsilon_{pi} = 2 \frac{P_i d^2}{E(D^2 - d^2)} (1-\nu) = 246.15 \mu e
\]

Eq. 17

### 2.4 Field Test Site

Three series of field tests were conducted at GTI's Catoosa test site. Formerly an Amoco test facility, GTI Catoosa is located 18 miles northeast of Tulsa, Oklahoma, on an 80-acre site. Prior to sale of the facility to GTI, Amoco and its customers drilled about 2,000 wells at the site. These dry holes became the foundation for continuing field testing. GTI Catoosa is now available for developing tools and techniques in a low-cost and confidential environment.
Site Geology

The Catoosa site has a wide variety of sedimentary rock—limestone, dolomite, sandstone, shale—compacted into a 3,100-ft-deep section overlying crystalline basement rock (Figure 17). Rock types represented in this section have compressive strengths ranging from 1,000 to 60,000 psi, providing an ideal environment for testing bits and downhole tools. Fluid content of the porous rocks includes connate water and (in certain sections) hydrocarbons thus giving geophysical logging devices being tested a degree of variability in fluid character.

Equipment

The rig at Catoosa (Figure 18) is a top-drive rig featuring a pivot system to minimize time to move and set up the rig. The pivoting rail system allows the rig to skid from location to location (less than one hour) along a semi-circular path. Other features include:

- Several drill strings (4½" aluminum and steel drill pipe; 2½" steel drill pipe)
- A 107-ft double-mast derrick
- Rig kelly bushing at a height of 22 ft
- Venturetech VK-150 power hydraulic power swivel (12,000 ft-lb at 250 rpm) top drive system
- National T-20 hydraulic draw works hoisting system (up to 200,000 lb)
- 330-bbl active mud system capable of pumping 130–650 gpm
- Solids-control system features two low-profile, ultrafine screen shakers, a set of 14 hydrocyclones, and a Sharples PM 20,000 centrifuge
- Triplex pumps with flow capacity of 5 to 650 gpm
- Maximum stand-pipe pressure: 3,500 psi
The test site at Catoosa is an ideal area for conducting research and performing tests on new equipment. Removing the commercial need to “make hole” allows researchers to conduct specific experiments that are time-consuming and may or may not advance the borehole. For this project the team was able to purposefully establish certain conditions that would create vibration and stick/slip so that the sub could record data when this occurred. In this way the team knows with relative certainty where to look in the data for important signals as opposed to looking at field data that may or may not have the desired events and signatures.
3. Results and Discussion

3.1 Summary of Project Activities

Accomplishments for this project can be categorized into three distinct areas:

1. **Design and manufacture** of prototype equipment based on system and sensor concepts developed prior to Phase I of the project
2. **Laboratory testing** of the prototype system
3. **Field testing** the equipment and analyzing recorded data

Field testing of this equipment demonstrated that tools for oil and gas drilling often require staged prototype development under field conditions. It was found that laboratory/shop testing was not as effective as field testing in shaking out system performance. Various weaknesses in tool design were not (and probably could not be) observed in conventional laboratory tests.

3.2 Previous Development

Prior to the work reported here, the instrumented sub was developed by Noble Engineering and Development Ltd. (NED), a sister subsidiary of MTI, to be a point source for data collection that could be utilized in a number of hardware and software developments that NED was pursuing. These developments included:

1. **DrillGraph™** – a data collection and display software for drilling rigs
2. **Event Recognition** – an add-on to DrillGraph that uses computer algorithms to determine when certain events were occurring on the rig
3. **OptiDrill™** – an automatic driller that operates the rig brake to maximize ROP under a specific set of conditions. It uses high-speed data collection to improve the control process and is able to optimize ROP based on multiple parameters as specified by the operator.
4. **Slider™** – a computer-controlled directional drilling system that oriented the drill pipe automatically and allowed continuous transition from rotary to slide drilling, thus increasing ROP by reducing nonproductive time.

To meet all of its needs, NED designed the sub to track a number of parameters including:

- String weight
- Torque applied to drill pipe
- Rotational speed of drill pipe
- Direction of drill pipe as it related to BHA
- Stand-pipe pressure
- Mud temperature
- Triaxial vibration of the drill string
- Triaxial magnetometer
- Sub electronics temperature

Sandia National Laboratory was contracted to design and build the first sub. It was designed to fit into the quill of a typical Noble Corporation top drive and be able to support 1,000,000 lb in tension and 50,000 ft-lb in torque. Communication and power were to be transferred over wires that connected to the sub through an inductive style slip-ring assembly.

Sub specifications are summarized in Table 2.

<table>
<thead>
<tr>
<th>Table 2. Sub Specifications – Original Design</th>
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<tbody>
<tr>
<td>Length</td>
</tr>
<tr>
<td>Diameter</td>
</tr>
<tr>
<td>Top Connection</td>
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<tr>
<td>Bottom Connection</td>
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<td>Power Source</td>
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<td>Maximum Vibration</td>
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<td>Rotary Speed</td>
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</table>

Sandia manufactured the initial prototype sub and supporting electronics. This sub was used for a single test with Sandia Laboratories at Catoosa. Sandia tested a diagnostics-while-drilling sub in conjunction with the instrumented sub. While results of this first test were promising, a number of sensors either did not work or functioned only intermittently during the test. The development team planned to refurbish and test the sub again. At this point in the sub’s development, the DOE contract for this project was awarded. Then, in an unforeseen turn of events, Noble dropped development on all the NED projects discussed above. By default, this DOE project took complete charge of the sub.

The sub’s original design (Figure 19) consisted of a center body portion that used an hour-glass shape to maximize responses from tension and torsional strain gauges. The electronics were mounted on the two halves of the clam-shell housing (Figure 20) that bolted onto the center body. After a second test at Catoosa it became obvious to the team that further changes would be essential to develop a tool suitable for drill rings and capable of producing high-quality data.
Figure 19. Original Sub Design

Figure 20. Electronics Mounted on Sub Housing
3.3 Upgrading Sub Design

Early in the current effort, the project team surveyed the industry to define the state of the art in instrumented subs. It was found that an instrumented sub that encompassed the capabilities as proposed was not commercially available. In the mid-1990s, Baker Hughes had offered a system commercially (the ADAMS system through its subsidiary EXLOG; see Section 1.3). Their success was limited primarily because a trained engineer was required for operating the sub and interpreting the data (that is, these systems were neither simple nor user-friendly). Baker and other service companies now offer downhole measurement subs that are operated in conjunction with their MWD systems.

After the first tests of the early sub design were performed, several repairs were required and it was discovered that the sub was much less field-ready than originally assumed. Several months of in-house development work were followed by various laboratory tests and calibration efforts. At the beginning of the current DOE-sponsored phase of development, the first task was complete refurbishment of the sub to correct design shortcomings that were clearly demonstrated by the first test. The sub had previously been sent to Sandia for evaluation. Based on consultations with Sandia and Noble personnel who had been directing earlier development, the project team determined to incorporate several changes to the sub:

1. The inductive slip ring had proven to be very difficult to assemble and align in the field. Since the sub was designed to be used on many different rig configurations, the slip ring was replaced by battery power and a radio link for data. To back up the telemetered data, an on-board memory system was added.

2. The sub had included a gyroscope to measure and track angular position. The gyroscope broke on the first run and, since it consumed a lot of electrical power, the team decided to remove it. The new objectives for the sub did not require the ability to rotate a specific number of degrees, but only required tracking rotary speed.

Sandia began working with the project team to refurbish and upgrade the sub in March 2004. Unfortunately, Sandia’s schedule was very active at that time, and they were not able to complete their work and return the sub to MTI until September 2004. This delay placed the project even further behind schedule.

Early calibration and testing of the refurbished sub in the laboratory showed that the initial mechanical design was also not adequate. The sub was demonstrated to be relatively delicate and subject to damage when handled. This issue alone would prevent the sub as then designed from being used in an oilfield environment. Figure 21 shows the early design of the sub with one half of the clam-shell outer housing in place. This design did not provide sealing and protection from water and mud for the interior electronics. It also made it possible that, in an explosive atmosphere, the electronics would be exposed and present a potential ignition source.
Despite these design flaws, the then-current sub was taken to Catoosa for a shake-down test and to evaluate running procedures. This test series was also to determine the usefulness of the data as collected. Based on what was learned from this field test (see Section 3.7.1), it was determined that additional changes were needed before the instrumented sub would be usable in the field.

In the earliest modifications described above, Sandia added a box to the exterior of one of the clam-shell halves of the housing (Figure 22) to house the batteries, radio antenna, and memory card. In addition, the on/off switch was placed on the outside of this box. These changes created more leak paths for fluid and exposed components to the danger of being struck or broken during operation.
During field tests, the on/off switch was broken (Figure 23) despite extra care taken by the experienced rig crew at Catoosa. Catoosa personnel are very familiar with experimental tools. Much rougher care is expected from normal rig personnel in the field.

The first test demonstrated clearly that a considerable change in the design of the sub would be necessary for safe operations on a rig. The bolt wings on the clam-shell cover presented a hazard as the sub rotates, so these needed to be removed. All switches or other components needed to be fully protected and placed under cover.

Another important shortcoming was that the sub’s original design did not account for requirements of operation in a Class I, Division 1 zone. This recommended practice (ANSI/API RP 500-1998 – Recommended Practice for Classification of Locations for Electrical Installations at Petroleum Facilities Classified as Class I, Division 1 and Division 2) provides guidelines for selection and installation of electrical equipment within petroleum facilities. RP 500 is intended to be applied where there may be a risk of ignition due to the presence of flammable gas or vapor, mixed with air under normal atmospheric conditions.

If Class I, Division 1 rating specifications were not met by the sub, it would be very difficult to obtain permission from a rig contractor or operator to run the sub in the field. Since the original clam-shell outer housing could not be sealed, the team redesigned the outer housing so that all components are inside and cannot be damaged as the sub is transported. The new one-piece housing design was effectively sealed so that its interior can be flooded with an inert gas (Figure 24). A pressure-activated switch was added. The sub is turned on by charging its interior space with nitrogen to at least 10 psi above atmospheric pressure. If the nitrogen blanket leaks off during operations, the sub will turn itself off. This will prevent a possible explosion if the sub should ever be exposed to explosive or flammable gas during operation.
Figure 25 shows the final sub design (unassembled). It incorporates a carrier for all the electronics and a one-piece outer housing that fully encloses the electronics and provides a gas-tight chamber.

MTI met with Sandia Laboratories in August 2004 to review ongoing work to upgrade the instrumented sub and associated decoding software. Several important problems were discovered. The original design of the electronics did not include any type of control chip, either a microprocessor or a PIC (peripheral interface controller), that can store data in a buffer and then send it out when requested. Consequently, the computer that captures data from the sub must read data constantly on the radio input port. This made performing any other tasks on the computer (such as data display) very difficult, if not impossible.

In addition, analysis of the data from the first field test during the project showed it to be of only limited value. Firstly, data quality was poor. The sub radio transmitted a stream of serial data when activated which allowed the computer to only record the data and display what was received. There was no capability to check data quality. Secondly, the data were not time-tagged, making it very difficult to match data to an event that occurred on the rig. To correct these problems, the radio (relatively obsolete in capability) was exchanged for a new system based on the current 802.11 B protocol. The data stream was changed so that all channels were reported sequentially on each pass. This made decoding much easier. Programming was added that time-tagged each line of data so that it could later be related to specific rig activity. The new radio and data protocol record data at 100 samples per second on 26 channels for a total of 2,600 readings per second.

Sub electronics were also modified. A new power supply was developed. The new design allowed space for more batteries to increase working hours between battery changes. The original Sandia electronics used a programmable gate array to control operations. This method programs the chip once and does not allow modifications. The original controller board was
changed and a PIC was used to control sub operations. A PIC program can be modified, allowing more flexibility. Changes were also made to several of the A/D circuits connected to the various transducers. This reduced noise, increased reliability and performance of the circuits, thus improving the quality of the data.

Sandia personnel also reported that they could not locate and deliver sub calibration data recorded prior to the DOE project. As a result, work at Mohr Engineering test facilities to complete sub calibration was more extensive than originally planned.

### 3.4 Software Development

Success of the instrumented sub hinges on the quality of the data recorded. Consequently, considerable effort was expended to develop programs and interfaces to save and display data. Omnia Technology was contracted to write a customized computer program based on LabVIEW to perform three functions:

1. Acquire data over the sub’s radio link and store it on the computer’s hard drive
2. Display data from the sub on the screen for review, both in real time and post processing
3. Read data from the memory card on the sub

The program developed simultaneously displayed three (selectable) channels of data and an FFT of one channel. Since data received from the sub were raw (not calibrated or scaled for engineering units), the program used a table that contained offset, scale-factor and units data to scale the measurements. Adjusting the values in this table allows raw data, counts, or engineering units to be displayed on the screen while retaining the integrity of the raw data on the hard drive. If scales or offset selections were incorrect, they can be changed either while recording data or after data collection for post-processing.

Figure 26 shows the LabVIEW display screen in its final version. The program has several other important features including the ability to write processed data into a file for use by other programs. It also can apply a tare value to any channel. Since the sub records string weight this feature is useful for converting it to bit weight by subtracting the reading from the original string weight when off bottom. A time-averaging function is also available, if needed. A slide bar below the graphs allows data that have passed off the screen to be brought back into view.
Customizing the program for the project proved to be a very difficult task due to the large volume of data to be recorded and displayed. The program was upgraded through several iterations before it could effectively accomplish all functions as desired. Even though the LabVIEW platform is now effective and field-tested, more work remains. Eventually, algorithms will need to be written so that the program will recognize signatures in the data that herald conditions where damaging vibration occurs, and alert the driller accordingly. Without the capability to automatically warn the driller, the sub (as was true in similar developments in the past) will not be economically viable.

### 3.5 Sub Calibration

After the first version of the LabVIEW software to receive and display data from the sub was complete, calibration of the output from sub sensors was begun. Torque was calibrated first since this could be accomplished with equipment available in Noble’s shop. The sub was loaded into Noble’s rotary torque machine (a breakout unit) that is typically used to make up and break rotary connections on downhole tools. The machine (Figure 27) consists of two sets of jaws—one that remains stationary and one that rotates. Short crossover subs were fitted onto the instrumented sub for this procedure to serve as surfaces the jaws could grip.
To calibrate torque output, the sub was activated and then torque applied, maintained for about one minute, and then incrementally increased. The data card was then removed, and the data processed to yield an offset and scale factor.

The initial calibration curve for torque (Figure 28) yielded some unexpected results. The most obvious characteristic the team noted is that torque response flattened above about 15,000 ft-lb. Sandia reviewed these data and reported that a single resistor on one of the sub’s electronics boards controls gain on the torque channel. Even though the sub is capable of transmitting loads up to 100,000 ft-lb of torque, this resistor had been selected for the maximum torque that could be applied at the Catoosa test facility. While this design decision (made prior to this project) may have been sensible strictly with respect to data collection (use maximum available number of counts for the maximum expected reading to give the highest data resolution), it does not make sense for field application of the system. This gain resistor was also very difficult to change, and doing so could damage its circuit board. The sub is expected to be deployed to rigs with much higher torque capability than at Catoosa. To account for these requirements, this design was changed in later prototypes so that the value of this resistor could be changed without damaging the circuit board.
Another problem observed during calibration was crosstalk between data channels. Figure 29 shows the response of the weight-on-bit (WOB) channel during torque calibration. Response of the WOB sensor changed as torque was applied to the sub. (It should be noted that the sub does not actually measure WOB, but rather measures total string weight. WOB can be inferred by subtracting the string weight while on bottom from string weight while off bottom.)

This crosstalk is easily understood. Strain gauges consist of flat wire coils affixed to a substrate (see Section 2.3.2). A constant voltage is applied across the coil and the current required to maintain this voltage is monitored. If the wire in the gauge is stretched, the cross-section is reduced and more current is required to maintain the voltage drop. Consequently, current required to maintain a constant voltage drop across the gauge is proportional to the cross-sectional area of the wire. Each gauge has several coils of wire to multiply the effect of lengthening or shortening.
In a load cell, the strain gauge substrate is mounted to a structural member which will undergo strain when load is applied. Gauges are usually oriented with their long axis in the same direction as maximum strain. For cylindrical objects such as the instrumented sub, tension/compression gauges are placed parallel to the axis of the cylinder and torque gauges will be placed at 45° to align with the direction of maximum shear strain that occurs when torque is applied to the tube. However, strain in any direction can affect each gauge. Tension loads will also lengthen gauges placed to measure torsion, albeit to a lesser degree. In a similar way, tension gauges will be lengthened somewhat when torque is applied to the tube. Commercial load cells restrict the type of load that is applied—tension cells cannot have torsion and torsion cells cannot be loaded axially. Engineers are warned that incorrect loading can lead to erroneous readings and can in some cases damage the cell. A cell designed to measure both types of loading would be overly complicated, so some cross-talk must be accepted.

Crosstalk in a load cell is normally not of great concern. For this project, however, we are looking for subtle changes in sensor response that may signify downhole behavior. Further analysis of field data is required to reveal whether crosstalk may be a significant problem and whether it masks subtle changes in sensor response.

After torque was calibrated at Noble’s shop, the sub was transported to Mohr Engineering in Houston. There it was placed into a 300,000-lb load frame and calibrated for tension loads. Even though the sub is designed to hold up to 1,000,000 lb in tension, this would not be experienced during drilling operations. String weights were estimated for typical applications and, based on the results, the sub was calibrated for 100,000 lb tension. Should weights above this limit be applied, no damage will occur; but the readout will only indicate 100,000 lb.

The sub was then returned to Noble’s shop where pressure and rotary speed were calibrated (Figure 30). These were calibrated by applying known internal pressure or rotational speed, and then calculating the offset and scale factors. These results were then entered into the calibration file and the test repeated to ensure that the program was now reading correctly.
3.6 Data Analysis

Dr. Stuart Hunter, professor emeritus at Princeton University's School of Engineering and Applied Science, served early in the project as a data-mining consultant. His expertise includes industrial applications of statistics. The project team supplied him with a set of data recorded during the early Noble/Sandia tests conducted at the Catoosa test facility. These data were from comparative tests of the instrumented surface sub and Sandia's diagnostics-while-drilling sub. Sandia’s sub is designed to be placed in the BHA very near the bit where it measures and records data directly generated from the bit/rock interaction. This is the best type of data for determining downhole drilling conditions and measuring damaging vibration. The major disadvantage is cost and difficulty collecting these data and transmitting them to the surface in a timely manner.

Three interesting samples of data were selected for further consideration and supplied to Dr. Hunter. He analyzed these data to look for correlations between uphole signals and downhole events. After his analysis was completed, he reported to the team that he was not able to discern correlations in the data. While this was discouraging, the team then surmised that the data may have been of poor quality due to the problems reported above. Subsequent investigation showed that some of the data channels had very limited operating ranges due to circuit design or component selection. Under some circumstances, the power supply output could be pulled down due to loads changing the circuit output. Changes to circuit design and a new power supply alleviated these problems so testing was continued.

After the fourth field test sequence, data from several events were analyzed for signatures that could be used as warnings for specific undesirable drilling conditions or events. These results are presented in Section 3.8.

3.7 GTI Catoosa Field Tests

3.7.1 Field Test Series 1 (December 2004)

The first series of field tests was conducted at Gas Technology Institute’s (GTI) Catoosa test facility (see Section 2.4). The project team was on site for several days in December 2004. This test was cost-shared with Noble Downhole Technology (NDT). The instrumented sub was run while NDT’s rotary steerable tool was tested downhole. This test was planned as a shake-down for the instrumented sub and to gauge the exact logistics of what was needed to use the sub in the field. This test was very valuable and highlighted many weaknesses that had to be addressed before further testing.

The first problem was unreliability. During operation, the instrumented ran only intermittently. On two occasions the sub had to be removed from the rig, all crossovers broken off and the sub disassembled for bench diagnostic work. In one case a low-resistance electrical short was discovered in the battery holder. This caused several lithium cells to be rapidly drained of power or the internal fuse on the battery set to melt. After trouble-shooting highlighted the problem, the short was repaired in the field and the sub returned to the rig.

Figure 31 shows example data recorded during this field test. Vibration is observed on both the weight on bit (WOB) and torque on bit (TOB) channels. (The sub was not yet calibrated so
output is displayed in counts rather than engineering units.) In Figure 32 the scale is changed to spread out the data along the x axis (zoomed into x axis). Now it is seen that WOB and TOB are counter-cyclical. As WOB increases, TOB decreases. To understand this behavior, we must consider the function of the sub.

Figure 31. Field Test 1 Data – Vibration in WOB and TOB

Figure 32. Field Test 1 Data – Vibration in WOB and TOB (zoomed)
It is important to note that the instrumented sub does not actually measure WOB. This must be inferred by measuring string weight off bottom and then subtracting weight on bottom. Correspondingly, the middle (red) trace in Figure 32 is not true WOB, but string weight. This is why TOB is counter-cyclical to WOB. As the bit drills off, true WOB decreases, the bit takes less of a bite into the formation, and thus the TOB decreases. When the driller lowers the drill string incrementally, string weight decreases (that is, the bit supports more of the total string weight), true WOB increases, the bit takes a bigger bite into the rock, and TOB increases. Data in the figure thus show that the sub is recording drilling data as expected.

Reviewing these test data revealed another very important problem with the instrumented sub as it was initially configured. The electronics measured and stored data but no computer was used. The data were not time-stamped, making it very difficult to correlate to field operations after the fact. In the second prototype design, the electronics were changed to allow for time-stamping the data.

A final problem that was highlighted concerned the physical layout of the sub. Several components including batteries, memory card, and the on/off switch were housed in a box external to the main sub body (see Figure 22). This design, while it allowed easy access to batteries in the field, increases the difficulty of handling the sub and is not rugged enough for the rig environment. In clear demonstration of this deficiency, the on/off switch was broken during this test even though the crews at GTI Catoosa are much more careful handling this type of equipment than is typical. In addition, the area above the rotary is a Class 1 Division 1 area, which dictates that no open electronics are allowable. The housing of the sub was required to be redesigned to enclose these components and seal them from possible explosive gases.

Based on these initial field tests, designs were developed to modify the sub housing so that all electronics are kept under a blanket of inert gas, making the sub safe for use in explosive areas such as above the rotary table. The new housing also provides more structural protection for the electronics and other components.

A new controller board was also designed. This allowed each line of data to be time-stamped for later coordination of the data with rig activities. A new radio was also installed that uses 802.11 B protocol, meaning that it has built-in software that performs several functions, including error checking. This gives clear indication that the data collected are good as well as when data have been skipped.

### 3.7.2 Field Test Series 2 (September 2005)

In September 2005, the sub was again tested in conjunction with Noble’s rotary steerable tool on a cost-shared test sequence at the Catoosa test site (see Section 2.4). The team’s experiences during the first tests (see Section 3.7.1), during which most of the time was spent tracking down problems and troubleshooting, strongly highlighted the need for a second shake-down test. Objectives of the test were simple: rig up the sub and confirm that it functions reliably, and be able to coordinate recorded data with events on the rig.

The redesigned sub worked very well. Tests were run on four consecutive days with data recorded each day. Improved software added a time stamp to the data so it could be readily coordinated with events occurring on the rig. Most of the field time was spent monitoring drilling during runs of Noble’s Well Director rotary-steerable tool. It was not possible to purposefully
simulate signatures of downhole events. However, some tests were conducted specifically for
the instrumented sub to check performance, including radio signal and distance checks.

This second test sequence at Catoosa was much more successful than the first. Highlights of
these tests include:

- The sub’s radio transmitter link functioned well
- A significant volume of data was gathered
- A majority of the sensors worked correctly
- Sensors that did not function correctly were identified
- The new sub design demonstrated more than adequate ruggedness for operation in
  the oilfield environment

Figure 33 displays recorded signals as the drill string was whipping in the derrick and then after
drilling conditions were modified to stop the whipping action. The graphs show plots for the x, y,
and z RMS signals from the accelerometers. (The y accelerometer measures axial motion, x
tangential, and z radial.)

Figure 33. Field Test 2 Data – Drill String Whipping

Figure 34 shows the drill string transitioning from no rotation to rotation. The middle graph
displays torque, which exhibits a sudden increase when rotation is begun.
After field testing was completed, the sub was returned to the shop in Houston for evaluation. While this test sequence was much more successful than the first shake-down tests, there were some problems that needed to be corrected. The pressure sensor and rate-sensor circuits experienced problems during the test, which were later found to be due to low voltage on the batteries. In two of the battery packs, the center battery had become loose, reducing the amperage available from those packs. To prevent this problem, special brackets were constructed to secure the batteries in the packs. The on-board memory storage unit uses a small watch-style battery to keep the program alive when the sub is shut down. This battery also was shaken loose during the test. Potting material was applied to prevent this problem on later runs.

Further improvements were added to the monitoring software to increase the ease of reading data and to provide a more user-friendly interface. These changes included adding an FFT graph for any selected channel. After these modifications were completed, the system was deemed ready for the next field tests.

3.7.3 Field Test Series 3 (November 2005)

A third series of field tests was conducted late in the project on 16–17 November 2005. This test sequence was the most comprehensive trial during the project and benefited from the fact that the instrumented sub had sole usage of the rig. Although this was more costly than sharing the rig with another tool, the project team enjoyed complete control of the operation and could request specific rig operations and drilling processes that would best demonstrate the ability of the surface measurements to discern downhole conditions.

The rig driller (Figure 35) was given specific instructions prior to each step of the test sequence. After each test sequence, the project team was able to review the results and determine
whether the data were good, whether a test needed to be repeated, and whether an interesting event had been recorded.

Figure 35. Driller’s Station at Catoosa

Members of the project team closely observed all testing operations from the “dog house” next to the rig floor (Figure 36). Data were displayed for review immediately after being transmitted. The radio link worked well throughout the entire testing sequence.

Figure 36. Doghouse next to Rig Floor at Catoosa
On the first day of testing, an 8½-in. PDC bit (an experimental bit supplied by MTI) was run in the well. This bit (Figure 37) had been used for various other tests in MTI’s shop prior to these tests, but was in good condition.

![Figure 37. PDC Bit after Testing](image1)

![Figure 38. Roller Bit for Day 2](image2)

On the second day of testing, several tests from day 1 were repeated with a roller-cone bit (Figure 38) run in the hole. This bit (also supplied by MTI) was moderately used but in good condition. Used bits were selected so that trouble conditions could be purposefully created that might lead to bit damage without risking damage to expensive bits and other equipment. For example, new bits in this size range cost from $25,000 to $50,000.

**Field Test Plan**

The team prepared a field test plan prior to going to the field. As described above, the first series of tests was conducted with a PDC bit; the second with a roller-cone bit. Types of activities conducted are summarized below. (Tests are described in greater detail in Appendix A.)

1. Run the string in and out of the wellbore 30 to 60 ft (one stand of pipe) while recording data. Repeat for various running speeds. (This procedure to establish base-line performance.)
2. Rotate the bit off bottom at various rotary speeds. Measure both pulling out and running into the well.
3. Measure sub response with various mud flow rates.
4. Measure sub response while drilling new formation at various flow rates, bit weights, and rotary speeds.
5. Simulate stick/slip behavior by setting bit on bottom with a low bit weight, then starting rotation and drilling for 1 minute. Then repeat with successively higher initial bit weights and rotary speeds.
7. Repeat tests (1)–(6) using a roller cone bit.

These field tests were very successful. A log of the test activities and comments is presented in Appendix B. All equipment worked well throughout the tests. Several interesting events (signatures) were observed and marked for more detailed review and analysis after the team returned to the office.

3.8 Analysis of Field Data

Tests reported here were conducted at the Catoosa test site in a shallow well of about 1300 ft. The field test site is described in Section 2.4, and tests conducted are summarized in Section 3.7. The well was near vertical, which, along with a relatively shallow depth, improved the chance of detecting vibration related to downhole conditions at the surface. No downhole instrumentation was deployed during these tests. A series of specific tests was run with conditions that would produce certain types of downhole vibration. It should be noted that there was no means of calibrating the accelerometer sensor prior to the test, so data shown below represent counts and are related to G-forces only.

The first tests were used to establish base-line readings for the sensors. The BHA was run into the well and the drill string was rotated with the bit off bottom and moved up and down in the derrick. Figure 39 shows a typical output screen during these tests. The top graph is speed, the middle string weight and the bottom torque. About midway across the screen on string weight, a reversal from running into the well to pulling out can be seen as an increase in string weight due to drag. Apart from this, the data show only normal variation in speed and torque due to rig equipment and drag. The FFT trace on the lower right is of speed; it shows a spike corresponding to rotational frequency and a 2X harmonic. While fluctuations in speed and torque (the upper and lower traces) appear to be significant, the graph scales for these parameters have been adjusted (zoomed) to better display the variations.

![Figure 39. Running in and Pulling out the Drill String](image-url)
Similar results are seen in Figure 40, which shows sensor output immediately before a drop test was conducted. To simulate bit bounce, the string was raised to the highest point in the derrick, and then released and allowed to fall several feet before the brake is applied. Upon braking there was an initial increase in bit weight as the string stretched and then a significant decrease when the string snapped back.

Figure 40. Sensor Data Before Drop Test

Figure 41 shows raw data recording during the test and Figure 42 the same data after processing. A close look at the drop event in Figure 42 shows first a significant reduction in string weight as the string is released followed by oscillations as the string slides quickly into the well and approaches a steady-state condition. Then string weight rapidly increases as the brakes are applied and inertia of the string continues downward. The string then stretches and snaps back, after which the string weight returns to the static value. An interesting signal pattern (signature) is observed in string weight. This is the RMS vibration in the axial direction. The vibration envelope forms a cone or “Christmas tree” shape when this type of event occurs. This generic wave shape might be used by a computer algorithm to detect this event and flag it for the driller so he could modify conditions to prevent further occurrences.
Another important series of tests was to create bit stick/slip. (Stick/slip is described in Section 1.1.) This was simulated by setting the bit on bottom, stacking additional weight on the bit and then starting rotation. Figure 43 shows plots for bit weight and torque during a series of these tests. As bit weight is increased (which makes apparent string weight decrease), torque increases rapidly as rotation is started and then, after the bit breaks free, decreases and damps out to a steady value. Torque here exhibits classic behavior of a damped spring under excitation. This signal is similar to that reported in the literature by others using downhole (in-string) recording devices placed close to the bit.
In a later test, the team drilled new hole for several minutes with the same PDC bit with high bit weights. Stick/slip could be detected during the test once the character of that signal was known. Figure 44 shows curves for speed, string weight, and torque while drilling new hole. Each spike represents an instance of stick/slip; the event can be observed in the curves of all three parameters. This is of great benefit, because two or more signals can be compared as conformation of the event.
Figure 45 is another plot of torque during the stick/slip tests. A fast Fourier transform (FFT) was performed for each of these events; results are displayed in Figure 46. It is seen that, as initial weight on bit was increased, the higher frequency data decreased in amplitude. The change is relatively subtle and in deeper wells might be overshadowed by the attenuation of higher frequencies due to string length.
Similar tests were run the next day with a roller bit. While this type of bit is less prone to stick/slip than is a PDC bit, some stick/slip behavior was observed with the same characteristic signature (Figure 47).
Another test with the roller bit revealed unexpected and interesting behavior. Torque was recorded as rotary speed was alternated between 50 and 125 rpm (Figure 48). Torque changes as speed changes (as expected); however, torque is higher at lower speeds. This behavior is not intuitive to members of the project team. This may be the result of how deep the cutters are able to penetrate the formation. At low speeds, the cutters dig in and remove more rock so torque is high. At higher speeds, the inserts may skip across the top of the formation and be able to penetrate less, so torque is lower. More investigation would be is needed to confirm whether this behavior is repeatable or unique to this particular run, but these observations are nonetheless interesting.
4. Conclusions

Several important accomplishments were achieved during this project. Highlights include design, fabrication, calibration, analysis, testing, and redesign of a surface data-acquisition sub for use on a typical drilling rig; and full-scale testing of the sub system on a drilling rig. The following conclusions were derived from work completed under this project:

1. The original design of the instrumented sub (developed before this project began) was found to be inadequate (too fragile and not intrinsically safe) for use on a typical drilling rig. The design was successfully upgraded and made rugged enough for field use during the effort.

2. During the final field tests, the sub and associated systems worked reliably. The sealed electronics bay and pressure-activated on/off switch were very effective as designed.

3. The sub’s radio transmitter and battery power worked consistently during field tests; however, for permanent installations, an inductive slip ring with power in and signal out is preferred.

4. A means to determine lateral position of the sub in the derrick is needed so that rate of penetration can be added to the list of measurements recorded by the sub.

5. Field test results show that signatures from downhole events can be detected with this sub at the surface. Significant work remains to develop computer algorithms that will be able to discern different signal types associated with damaging vibration or other events.

6. Downhole event signatures can be observed on several different parameter measurements (e.g., bit stick/slip can be discerned in torque, speed, and string weight data).

7. Stick/slip behavior was observed during field tests with both PDC and roller bits.

8. The instrumented sub performed very reliably on the rig and is ready for application in any drilling environment for recording data in real time. Although another design iteration is needed for the sub to be ready for commercial application, in its present state, the sub is an excellent tool for efficiently collecting drilling data for any use.
5. References


EXLOG staff, 1990: “ADAMS Advanced Drillstring Analysis and Measurement System,” Corporate Brochure 800-008 2.5M 1/90-E.


6. Acronyms and Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>BHA</td>
<td>bottom-hole assembly</td>
</tr>
<tr>
<td>GTI</td>
<td>Gas Technology Institute</td>
</tr>
<tr>
<td>Catoosa</td>
<td>GTI-run drilling test facility near Catoosa, Oklahoma</td>
</tr>
<tr>
<td>LWD</td>
<td>logging while drilling</td>
</tr>
<tr>
<td>MTI</td>
<td>Maurer Technology Inc. (prime contractor)</td>
</tr>
<tr>
<td>MWD</td>
<td>measurement while drilling</td>
</tr>
<tr>
<td>NDT</td>
<td>Noble Downhole Technology (a sister subsidiary to the prime contractor)</td>
</tr>
<tr>
<td>NED</td>
<td>Noble Engineering and Development (a Noble subsidiary responsible for early development of the instrumented sub)</td>
</tr>
<tr>
<td>RMS</td>
<td>root mean square</td>
</tr>
<tr>
<td>ROP</td>
<td>rate of penetration (drilling rate)</td>
</tr>
<tr>
<td>TOB</td>
<td>torque on bit</td>
</tr>
<tr>
<td>WOB</td>
<td>weight on bit</td>
</tr>
</tbody>
</table>
Appendix A —
Field Tests at GTI Catoosa Site

16–17 November 2005

Test Plan
Instrumented Sub Test Plan
GTI Catoosa Test Facility

15–17 November 2005

Introduction

The instrumented sub was originally developed to be a single-point collection center for rig data that would be used in a number of Noble Engineering and Development's (NED's) products. The sub was designed to collect hook load, rotary torque, rotary speed, rotary position, drill pipe pressure, mud temperature, triaxial vibration, and triaxial magnetometer data. Power and communication for the sub would be via an induction slip ring. The sub was designed and built by Sandia National Labs under NED direction and was tested with and compared to Sandia's diagnostic-while-drilling downhole package.

A Department of Energy (DOE) proposal was written and subsequently funded to determine if information concerning performance and condition of the BHA was embedded in the data recorded by the instrumented sub. As this contract was being negotiated, Noble's NED group was disbanded and their work terminated. This required that all the planned work on the instrumented sub be completed by the DOE project alone.

During this effort the sub has been significantly modified. The slip ring was replaced with a radio link. This was changed so the sub would be easier to move to different rigs and to ease the set-up process. In addition, the sub’s previous design would prevent it being used on oil and gas rigs due to potential explosion hazard. The sub was redesigned so that during operations all electrical components on the sub are under a nitrogen blanket. A pressure switch is used so that, should a leak develop, the sub will shut down and prevent operation until the leak can be fixed.

Tests of the sub after its redesign also showed that some of the data channels did not operate properly due to incorrect circuit design. These problems have also been fixed and those channels that can be calibrated (hook load, torque, pressure, speed) have been calibrated. One last test sequence will be conducted before writing the final report to the DOE. Several parties have expressed interest in the sub and these are being pursued as potential commercializers of the technology.

Test Objectives

Objectives of this test sequence are to observe and establish signal patterns and signatures for the various measurements taken by the instrumented sub first under ideal conditions and then under simulated problem conditions. Once data have been recorded under each set of conditions, these signals can be compared and analyzed to determine if any tell-tale information is transmitted up the drill string and is available for observation at the surface. This test work will be performed in a shallow, straight well representing the best possible chance that some type of data is brought to the surface.
Test Procedure

Date: November 15–17, 2005

Location: Catoosa Test Site near Tulsa, Oklahoma

The Catoosa test site will provide a well of at least 1000 ft depth. The BHA (of simple design—only a bit and collars) will be run into the hole and the instrumented sub rigged up below the top drive. A log of activities with accurate times will be kept along with testing parameters. In addition, Catoosa will supply a disk of data from their system. A difference table showing discrepancies between Catoosa parameters and the sub parameters will be maintained during the test.

Tests to be run include the following:

1. Run the string up and down in the wellbore 30 to 60 feet.
   a. Record response using sub
   b. Vary speed of string movement
      i. Slow
      ii. Medium
      iii. Fast
   c. Repeat at least three times for each

2. Rotate bit off bottom
   a. Vary speed from 50 to 200 rpm in 25 rpm increments
   b. Record response
   c. Measure pulling out and running in
   d. Hold speed for a minimum of 10 sec or until equilibrium is reached
   e. Repeat twice

3. Flow test
   a. Start mud pumps
   b. Run flow from minimum flow rate to maximum flow rate for hole size and bit selected
   c. Record data while increasing flow and decreasing flow
   d. Repeat twice

4. Drilling test
   a. Start string rotation and flow at minimal (but acceptable) rates
   b. Start drilling at minimal (but acceptable) bit weights
   c. Drill for 5 minutes
   d. Stop and repeat two more times
   e. Increase parameters to mid range and drill for 5 minutes
f. Increase parameters to high end of range and drill for 5 minutes

g. Weight on bit test
   i. While drilling, increase weight on bit 2000 lb; hold for 10 seconds and
      repeat 5 times. Repeat test after increasing weight 5000 lb.
   ii. Increase bit weight 2000 lb and repeat step (i) using new weight.

h. RPM test
   i. Start drilling with minimal string rotation speed.
   ii. While drilling increase speed 10 rpm, hold for 10 sec and return to original
      speed. Repeat 10 times. Repeat test increasing speed 20 rpm.
   iii. Increase speed 25 rpm and repeat step (ii) at new speed. Continue to 200
      rpm or maximum recommended speed for bit.

i. Flow test
   i. Establish drilling with minimal flow rate.
   ii. While drilling, increase flow 20 gpm; hold for 10 seconds and return to
      original flow.
   iii. Increase flow 25 gpm and repeat step (ii) until maximum practical flow is
      reached.

j. If time permits, drill with different combinations of parameters.

5. Stick/slip test. This test will create an artificial stick-slip condition where the bit stops
   rotating and stores torsional string energy in the drill string. Once enough torque has
   built up, the string will begin to rotate and release the stored torsional energy.
   a. Start flow but no rotation
   b. Set bit on bottom with minimal bit weight
   c. Start rotation and drill for 1 minute
   d. Repeat steps (a)–(c) while increasing first bit weight and then rotary speed

6. Bit bounce Test. This test will bounce the bit or a bull nose off the bottom of the hole to
   determine the signature of this behavior that is picked up at the surface.

7. Repeat above tests using roller cone bit.

Each test will be carefully monitored and documented as to procedure and time of day so that
the data can be examined with accurate knowledge of corresponding conditions.
Appendix B —
Field Tests at GTI Catoosa Site

16–17 November 2005

Test Log
<table>
<thead>
<tr>
<th>Time</th>
<th>Test No.</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>17:20</td>
<td></td>
<td>turn sub on; software malfunction</td>
</tr>
<tr>
<td>17:30</td>
<td></td>
<td>pause testing to revert to previous version of LabVIEW</td>
</tr>
<tr>
<td>17:51</td>
<td>2C</td>
<td>POOH 75 ft/hr @ 38 rpm; 245 gpm; 300 psi</td>
</tr>
<tr>
<td>18:09</td>
<td>2C</td>
<td>RIH 80 ft/hr 38 rpm</td>
</tr>
<tr>
<td>18:42</td>
<td>2C</td>
<td>end</td>
</tr>
<tr>
<td>18:43</td>
<td>2B</td>
<td>POOH 150 ft/hr 39 rpm</td>
</tr>
<tr>
<td>18:56</td>
<td>2B</td>
<td>RIH 150 ft/hr; 2500 ft-lb; 247 GPM; 227 psi</td>
</tr>
<tr>
<td>19:09</td>
<td>2B</td>
<td>end</td>
</tr>
<tr>
<td>19:10</td>
<td>2A</td>
<td>POOH 300 ft/hr</td>
</tr>
<tr>
<td>19:16</td>
<td>2A</td>
<td>RIH 300 ft/hr</td>
</tr>
<tr>
<td>19:24</td>
<td>2A</td>
<td>end (corresponds to file 28)</td>
</tr>
<tr>
<td>19:28</td>
<td>3</td>
<td>lower and stop 3 times</td>
</tr>
<tr>
<td>19:30</td>
<td>3</td>
<td>end</td>
</tr>
<tr>
<td>19:39</td>
<td>3</td>
<td>repeat test with more pause between cycles</td>
</tr>
<tr>
<td>19:44</td>
<td>3</td>
<td>end</td>
</tr>
<tr>
<td>19:49</td>
<td>4</td>
<td>ramp up rpm; 0 to 50, 75, 100, 125</td>
</tr>
<tr>
<td>19:55</td>
<td>4</td>
<td>end</td>
</tr>
<tr>
<td>19:56</td>
<td>5</td>
<td>change rotary speed; 75 to 80; 75 to 90; 75 to 100 rpm</td>
</tr>
<tr>
<td>20:09</td>
<td>5</td>
<td>end</td>
</tr>
<tr>
<td>20:10</td>
<td></td>
<td>getting ready to begin drilling shale; adding stand of DP</td>
</tr>
<tr>
<td>20:53</td>
<td>6</td>
<td>start drilling limestone; collar bit; 31 ft/hr, later 59 ft/hr</td>
</tr>
<tr>
<td>21:08</td>
<td>6</td>
<td>end</td>
</tr>
<tr>
<td>21:09</td>
<td>7</td>
<td>set bit on bottom, add WOB then begin rotation for WOB=5k, 15k, 20k and 25k</td>
</tr>
<tr>
<td>21:25</td>
<td>7</td>
<td>repeat sequence</td>
</tr>
<tr>
<td>21:26</td>
<td>8</td>
<td>WOB cycle 10k to 15k; 75 rpm; 4 cycles (?)</td>
</tr>
<tr>
<td>21:36</td>
<td>8</td>
<td>WOB cycle 15k to 25k; looks like stick/slip in first cycle</td>
</tr>
<tr>
<td>21:49</td>
<td>8</td>
<td>end</td>
</tr>
<tr>
<td>21:49</td>
<td>9A</td>
<td>cycle rpm 75 to 100 rpm; 15k WOB</td>
</tr>
<tr>
<td>22:01</td>
<td>9B</td>
<td>cycle 50 to 125 rpm; 15k WOB</td>
</tr>
<tr>
<td>22:18</td>
<td>9C</td>
<td>cycle 50 to 125 rpm; 25k WOB</td>
</tr>
<tr>
<td>22:20</td>
<td>10</td>
<td>continuous drilling; 25k WOB; 100 rpm</td>
</tr>
<tr>
<td>22:28</td>
<td>10</td>
<td>end of DP stand; some stick/slip observed ?</td>
</tr>
<tr>
<td>Time</td>
<td>Test No.</td>
<td>Comments</td>
</tr>
<tr>
<td>--------</td>
<td>----------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>22:32</td>
<td>12</td>
<td>picking up from bottom and dropping bit</td>
</tr>
<tr>
<td>22:45</td>
<td>12</td>
<td>end</td>
</tr>
<tr>
<td>23:00</td>
<td></td>
<td>END OF DAY</td>
</tr>
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</table>

TOTAL footage for day – drilled 24 ft from 1284 to 1308 MD

### Table B-2. Tests with Roller Bit (11/17/05)

<table>
<thead>
<tr>
<th>Time</th>
<th>Test No.</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:15</td>
<td></td>
<td>begin reaming yesterday's hole to gauge; 80 rpm</td>
</tr>
<tr>
<td>11:48</td>
<td></td>
<td>stop reaming, add stand of DP</td>
</tr>
<tr>
<td>12:11</td>
<td>6</td>
<td>start drilling new hole; collar the bit</td>
</tr>
<tr>
<td>12:15</td>
<td>7</td>
<td>set bit on bottom, then begin rotation for WOB=5k, 15k, 20k and 25k</td>
</tr>
<tr>
<td>12:23</td>
<td>8</td>
<td>WOB cycling 10k to 15k</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>WOB cycling 15k to 25k</td>
</tr>
<tr>
<td>12:40</td>
<td>9A</td>
<td>cycle 75 to 100 rpm; 15k WOB</td>
</tr>
<tr>
<td></td>
<td>9B</td>
<td>cycle 50 to 125 rpm; 15k WOB</td>
</tr>
<tr>
<td></td>
<td>9C</td>
<td>cycle 50 to 125 rpm; 25k WOB</td>
</tr>
<tr>
<td>12:56</td>
<td>9D</td>
<td>cycle 75 (? probably 50) to 125 rpm; 30k WOB</td>
</tr>
<tr>
<td>13:06</td>
<td>9</td>
<td>end</td>
</tr>
<tr>
<td>13:08</td>
<td>10</td>
<td>continuous drilling; 25k WOB; 100 rpm; rough drilling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>stop after 15-20 minutes</td>
</tr>
</tbody>
</table>

TOTAL footage for day – drilled 23 ft

END OF TESTS