Integrated Underbalanced Directional Drilling System

Interim Report, for Period of Performance 10/1/95 - 2/14/96

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Introduction

Underbalanced drilling techniques and horizontal drilling have known for some time and have been utilized in reducing drilling costs and increasing production. Underbalanced drilling (UBD) motivations and techniques have been examined in the literature [1]. UBD is often performed with the primary motivation of reducing formation damage and thereby increasing production, and aerated fluid is commonly employed in the drilling process. In hard rock applications, UBD is often performed with the primary motivation of increasing ROP (rate of penetration), and here air/mist drilling fluids are commonly employed. Directional and horizontal drilling techniques are important for accessing the reservoirs of interest and maximizing reservoir exposure. There are many important applications though where horizontal drilling can not performed underbalanced in an economical manner, because of limitations of the available technology.

The US Department of Energy (DOE), Federal Energy Technology Center (FETC) has focused upon the need for extending the industry's current drilling capability to the point where directional and horizontal drilling through USA gas (and oil) reservoirs, with underbalanced drilling fluids ranging from aerated mud mixtures to dry air, is both technologically and economically feasible. With mud pulse measurement-while-drilling (MWD) inapplicable, survey and steering technology applied in these USA applications is often limited to wire-line steering tools, with their inherent limitations in operational flexibility and reliability, and rig-time costs. Current motor technology and drilling engineering competency in these applications is highly variable, and a comprehensive knowledge base on how best to drill the range of underbalanced applications is not known to exist. Operating and repair costs associated with the drilling tools and processes are often high in comparison to traditional continuous liquid drilling operations. In 1994, FETC solicited the industry for proposals towards development of an "Integrated Underbalanced Directional Drilling System" (IUDDS), to address these needs. This contractor submitted a proposal, and was awarded a cost share contract for development of such a system, its capabilities to include wireless Electromagnetic (EM) MWD telemetry link, and steerable motors, both operable in all underbalanced drilling fluid environments including air.

This paper is an interim report on progress, from contract initiation in October 1995 through February 1996. Specific areas of focus include the development goal, critical background technology being built upon, the resulting development methodology, project results to date, and continuing activities.

Industry Needs

There are many locations around the world, and in the USA, where drilling cost reduction and/or production improvement is likely to result through application of underbalanced directional drilling. Such UB directional drilling has been applied with success and has become routine in several specific areas. The common thread in these specific areas is that today's directional drilling technology can be employed while underbalanced, either due to that underbalanced condition being naturally achievable within the existing technology's range of operability, or the economics being sufficiently lucrative that work-around techniques making up for the inadequacies of the existing technology can be afforded. In the Austin Chalk trend of Texas, underbalanced drilling can often be achieved with unweighted continuous liquid drilling fluids, as pressured zones result in flowing hydrocarbons while drilling. Conventional mud pulse MWD and motors can therefore be employed. Primarily in Canada, but also in some other locations, parasite string and other annulus gas injection techniques are commonly used to reduce the hydrostatic pressure and minimize formation damage. While the costs of underbalancing this way are higher than with simply mixing nitrogen in with liquid phase being pumped down the drill string, these external gas lift techniques enable the use of the mud pulse MWD.

In many of the USA areas of interest for underbalanced directional drilling, the technology requirements are greater, and the economics require a more cost effective solution. There are many USA areas where directional and horizontal drilling in underpressured reservoirs is common, and like Canada, production improvements through reduced formation damage would result from employment of underbalancing fluids, typically aerated fluids or foams. The economics however typically preclude the external gas lift techniques that would enable use of the mud pulse MWD. Conversely, there are many hard rock areas of the USA, such as the Arcoma, San Juan, and Appalachian Basins that have been employing underbalanced drilling for years, typically with air or mist, to achieve adequate ROP. In these areas though directional and horizontal drilling has not been taken advantage of widely, because of the inapplicability of mud pulse MWD, the economic and technical limitations of single shot and wire-line steering tools, and also because of the performance, reliability, and operating cost issues associated with use of conventional steerable mud motors in air/mist.

Technologies have been introduced and applied successfully to address many of these issues. Electromagnetic (EM) MWD systems [2] have demonstrated telemetry in many underbalanced fluid situations. Conventional and modified mud motors have been used for directional drilling in many of these underbalanced fluids. These technologies have been applied with relative success in those areas of greatest technical ease, and where most lucrative. The general lack of proliferation of these technologies in the USA areas that could benefit substantially, speaks to greater technical challenge and more marginal economics of these areas.

There is therefore a need for technology to be applied in a cost effective manner, to enable the performance of underbalanced directional and horizontal drilling in these areas of the USA. Specifically, there is need for a directional drilling system and service including steerable motors, and providing EM telemetry of survey and steering information, for use on all underbalancing drilling fluids including aerated fluids, foam, and air/mist.

Project Objectives, Ultimate Goal for Commercial Service

The ultimate goal of this project is to enable the launch and operation of a commercially viable underbalanced directional drilling service, in the broad spectrum of USA markets and applications identified above. The development and launch effort must be focused on three competencies critical for commercial viability:

Hardware – A competent and economical EM MWD system and selection of UB Motors are required to be developed and/or evolved, capable of operation over a range of UB fluid conditions (Air/mist, foam, aerated fluids, water).

Understanding – Thorough knowledge is required on motor performance (i.e. performance characterization) over the range of UB fluids, as related to the controllable and uncontrollable motor configuration and drilling environment variables. Similar knowledge is required on the EM MWD's performance (lithology and well plan) envelope.

Service – The hardware elements and knowledgebase developed are required to be pulled together with models, software tools, procedures, manuals, and training such that a seamless service can be provided to the gas and oil companies by the contractor's field engineers and directional drillers, leveraging off of existing field service delivery channels and infrastructures.

Project Approach

The approach taken towards serving the above objectives has four major themes:

- Leverage off of existing and available hardware and competencies, some widely commercial such as the contractor's mud motor product line and certain MWD core modules, some developmental such as the contractor's recently acquired Geoscience Electronics Corporation (GEC) EM MWD technology.

- Focus new development and testing efforts primarily on the two areas most critical to technical success over the range of UB fluids and operating environments identified, namely the evolution of the EM MWD system, and the development of a thorough understanding of motor performance over the range of UB fluids.

- Focus effort additionally on developing those integration elements such as models, software tools, and manuals required to pull together a service.

- As the core developmental elements come together, focus efforts on testing -- significant laboratory testing and field testing on individual core elements, testing towards definition of the operating environment, and then integrated system field tests on a variety of underbalanced fluids and directional and horizontal drilling scenarios.

Project Description

Technology Overview: A schematic representation of the Integrated Underbalanced Directional Drilling System can be seen in Figure 1, as envisioned and being developed towards in this project. The major elements of the system are the UB motor, the EM MWD downhole system including the pressure-while-drilling (PWD) sensors and optionally with mid string repeater, and the surface computing system. The elements of the EM MWD downhole system are shown in Figure 2.

The EM MWD system employs Drill-String/Earth Communication (D-S/EC) telemetry method as described by Harrison et al in Reference 2. The mid string repeater is utilized to extend the depth range. The EM MWD system provides uplink of gravity and magnetic survey and steering data from the BHA, in the same form as is available from conventional mud pulse systems. Additionally, bore and annulus pressure data are acquired and transmitted to surface and stored in downhole memory. An EM telemetry downlink is also utilized, for survey data prompting and for mode switching. The downhole system is battery powered.

A range of mud motor power sections are to be employed, for full coverage of the range of underbalanced drilling fluids. A range of bent housings are also to be available for the range of directional drilling requirements, often entailing medium radius builds and significant horizontal sections. Sealed bearing sections are necessarily employed when drilling with predominantly air/nitrogen or other gasses, although mud lubricated bearing packs have been demonstrated as adequate and economical for use with drilling fluids with significant liquid proportion.

Key system specification points are defined to enable use in the wide range of USA underbalanced drilling fluid and operational scenarios. Tool size availability in at least nominal 3 ½”, 4 ¾”, 6 ½”, and likely 8”.

Pulled together as a system, and operated as a seamless service, a number of operational processes are to be provided towards the efficient drilling of the well, including the following:

- Appropriate and reliable speed, torque-available, and power to the bit in any chosen fluid.
- Survey data (inclination and azimuth) on demand to calculate well path being drilled.
- Continuous toolface orientation data during sliding, for steering the well path.
- Real time annulus pressure data, for determining degree of underbalance, often for enabling optimizing of nitrogen usage.
- Real time drill string pressure and BHA pressure drop, for determining actual CFM entering motor, inferring motor performance, and optimizing ROP and motor life.

Work Plan: At initiation of the project, a project work plan was developed following the above approach, towards serving the overall project objectives. This work plan leveraged off of the available hardware and competencies. This background technology and the major areas of activity are described below, and then expanded upon in the “Project Results” section.

EM MWD: Prior to the start of this project, the contractor and GEC had collaborated towards production of a small number of GEC M28 EM MWD systems. These systems, which were incrementally evolved from the DOE co-funded GEC M27 EM MWD system, were suitable for limited commerciality in a subset of the UB drilling market, primarily in Canada. They also provided an excellent experimental platform for gaining of operational knowledge on what greater capabilities would be required in a next generation development to take place under this project, for broad commercial viability in the range of USA underbalanced directional drilling scenarios. A collaborative development was planned from this point between GEC and the contractor, to port the EM MWD telemetry capability from the GEC platform onto the contractor’s MWD downhole and surface platforms. Specifically, the contractors’ field proven circuit modules, communications protocols, packaging methods, transducers, and certain software modules were planned to be utilized as building blocks along with the GEC technology, to result in what had been termed the “Series III”, and now is termed the “EMT” system.

Porting the GEC technology onto the contractor’s platform was deemed critical to the long term commercial viability in the broad range of markets and UB drilling applications. This porting would enable integration with the contractor’s existing asset base including the DEP directional probe, and eventual interface to the contractor’s other MWD sensors, as leveraging off existing assets is a key to viable economics. This porting would enable the integration of certain critical new capabilities, including PWD and enhanced safety features. It would enable user interface and procedures consistent with the contractor’s existing MWD services so that existing MWD engineers could provide a quality service in EM MWD, without extensive retraining or dedication to the product. And this porting would enable application of the contractor’s knowledgebase to this new MWD product, enabling the contractor to take responsibility over the long term for its operational and support processes, reliability, cost, and engineering support and continued evolution. The results of this porting are discussed in the “Project Results” section.

UB Motors: Coming into the project, the contractor was a leading provider of directional drilling services, with a large fleet of unsealed and Kalsi^{R} sealed bearing motors, in the complete range of diameters and stages, and in single and several multi-lobe configurations. These motors had already been used extensively in mixed flow UB drilling scenarios in Canada, as well as a limited amount of air drilling in the USA. It was clear from the existing field experience that there was room for optimizing the motor design for performance, reliability, and cost. But it was also clear that the greatest gains in overall drilling process efficiency were to be realized in (i) developing a thorough understanding of the motor performance in each of the UB drilling fluid scenarios and the sensitivity of motor performance and life to the controllable and uncontrollable motor configuration and drilling environment variables, and then (ii) utilizing that knowledge in choosing the right motor configuration for each particular UB drilling scenario, and in managing the controllable variables to the extent possible during the course of each UB job.

A plan was therefore developed and evolved with extensive focus on motor performance testing, with a range of motor configurations to be tested over a range of fluids and variation of other key parameters. The setting up of the testing facility, development of the specific test plan, and execution of the testing is further detailed in the “Project Results” section. The plan additionally called for some mechanical improvements to the motors for external and internal wear life extension.

Integration Elements: In pulling the major hardware elements and knowledge being developed into a service, it was recognized in the planning stage that certain “integration elements” would be required to be developed. An EM MWD telemetry model and field software implementation was required to support the well planning process, to screen the specific customers’ UB drilling job candidates for EM telemetry feasibility, and for on-the-job support. An assessment of the safety aspects of EM MWD was required to drive certain hardware and procedural enhancements. An EM MWD system users manual was required. An assimilation of the knowledge gained from the motor testing was required, and the creation of motor performance curves for the range of UB fluids, analogous to those currently existing for water. A UB motor configuration and usage guideline, and an overall IUDDS system guideline was required, with specific pre-job planning and on-the-job execution recommendations for every UB fluid scenario. For each of these items, specific activities were planned, and results are discussed in the “Project Results” section.

Laboratory Testing: In addition to the laboratory motor characterization activities discussed above, the workplan spelled out a series of laboratory tests at the component level (i.e. EM MWD modules, software, and motor samples), as part of the design process. Qualification testing was also planned on the EM MWD new downhole modules, including vibration and other environmental tests, to the contractor’s standard MWD specifications. At the outset, a testing activity was deemed necessary for wear life qualification of the UB motor, from the standpoint of power section longevity. It was noted that this might be performed in the laboratory, or might be more practically examined in the field.

Laboratory integration testing was planned, in which all the existing and new hardware and software elements comprising the EM MWD system are assembled, and the field engineers responsible for service delivery take the system through its paces, in all potential operational scenarios.

***Field Testing*:** The ultimate proving ground for this system is the field, and an extensive field testing program was planned. A set of five relatively low exposure field tests were planned to be executed as part of the development process, to examine capabilities of individual components of the IUDDS in field conditions. Some of these tests were earmarked for examining the underbalanced drilling environment itself, especially with air/mist as the drilling fluid where there is less existing knowledge. The major thrust of the field testing was planned however for the entire integrated system. Ten tests were contemplated in various underbalanced fluids, and directional and horizontal drilling scenarios.

Project Results

Overview: As of February 1997, the IUDDS project had been underway for 18 months. Substantial effort has been focused upon the EM MWD system engineering, the UB motor performance characterization testing, and certain critical integration elements. Five low exposure field tests have been performed to examine the performance of specific components and to examine the drilling environment. The EMT EM MWD system has demonstrated operational competency in the field. While there is still continuing engineering required on the system and its major elements, the directional and horizontal field testing in the target UB drilling scenarios is going to be started soon.

EM MWD – Phase 0 Development and Testing: The porting activity discussed in the "Project Description" section was undertaken, in a two step process. The development first focused on producing a "Phase 0" surface and downhole hardware set, as an experimental platform upon which to first port the EM Telemetry capability. This system was developed relatively quickly, and with the relatively minimal software and user interface required for examining the telemetry process, but not adequate to perform a service.

The Phase 0 hardware set built upon many of the contractor's existing hardware elements, both at a high level and a lower level. At a high level, the existing DEP2 directional probe, used with mud pulse MWD, was employed with minimal software modification. The Phase 0 also built upon the "EM Antenna Sub", evolved from the Geoscience design, for which several units had already been produced with the limited commerciality M28 kits in the field.

There was substantial new module design, incorporating existing MWD-proven design details. An "EM Probe" was defined as the downhole system master, with functional requirements for the downhole data acquisition, uplink and downlink encoding/decoding, creating the analog uplink signal and driving it through the downhole antenna section, and likewise the receiving function for the downlinks. This EM Probe utilized the contractor's standard downhole microprocessor, inter-module communication protocol, other circuit details, and packaging techniques. The Geoscience circuits associated with the EM telemetry transmitting and receiving functions were ported onto the EM Probe, as well as significant blocks of Geoscience's software. The EM Probe also incorporated the PWD sensors, although the software was not yet in place in the Phase 0 kit to take advantage of it. Existing MWD design elements were applied to result in a new electrical/mechanical interface of the antenna sub to the sondes (i.e. the pressure tubes containing electronics), for incorporation of the pressure measurement ports, reduced erosion, and enabling interchangability between different tool sizes. Existing battery staves were incorporated into a new downhole battery module. At surface, a special set of software was designed for the contractor's PC based surface computer, with significant blocks of the Geoscience software incorporated. This Phase 0 software set was however limited to use by the R&D engineers, without the full functionality or user interface.

One minimal set of Phase 0 prototype hardware was built, with the express mission of proving out this first porting of EM technology to the contractor's platforms, and identifying potential problem areas. The Phase 0 prototype hardware underwent significant functional testing as individual units concurrent with the software development process, and then underwent complete system integration testing in the lab. The Phase 0 system field test then followed in June 1996, successfully demonstrating EM MWD single hop (no repeater) telemetry on the contractor's hardware platform. This testing is described further in the "*Field Testing*" section.

Software development continued, towards incorporating the repeater use capability into the Phase 0 hardware, both surface and downhole. This was a significant effort, but was completed and integration tested by September 1996. A "Phase 0a" field test was performed, demonstrating EM MWD telemetry with repeater use. This too is further described in the "*Field Testing*" section.

EM MWD – Phase 1 "EMT" Development and Testing: The Phase 0 laboratory testing and the two field tests demonstrated the feasibility performing the EM Telemetry processes on the contractor's platforms. These tests also identified design issues and provided invaluable insight to drive the full featured tool development. The Phase 1 "EMT" development proceeded, towards incorporation of the full set of requirements for commercial viability in the broad UB drilling market. Many of the key operational specifications for this system are listed below (note the system is developmental, and this should not be taken as a publication of specifications):

- EM Telemetry, data rates comparable to mud pulse
  - Survey transmission 2.6 - 4.5 minutes
  - Toolface update rate 15 seconds
- EM Uplink and Downlink
- Single hop, or with mid-string repeater
- Depth range depends on lithology, 10,000' common
- Existing "DEP" Directional probe used with mud pulse:
  - Azimuth +/- 1.5 deg
  - Inclination +/- 0.2 deg
  - Toolface +/- 2.8 deg
- Pressure-While-Drilling, bore and annulus, 15 psi resolution
- O.D. Available -- 3.5" , 4.75", and 6.5"

In addition to these specifications, the design process was driven by the environmental qualification requirements, reliability requirements, packaging requirements, safety requirements, maintainability requirements, integration/connectivity requirements, and cost requirements required for commercial viability in the industry, and specific to the contractor.

The PWD bore and annulus sensors were linked in to the real time survey transmission process. Certain hardware and software design features were incorporated in the EM MWD probe downhole and the surface system to provide for enhancing the safety of the system. A PC based surface system and user interface was implemented that provides for pre-run downhole tool programming, easy control of the downhole tool survey, telemetry, and housekeeping functions, and continuous displaying and logging of toolface and pressure data. Many of the contractor's existing software modules for tool communication, survey data validation, peripherals communication, and plotting were directly employed to minimize development effort, and to minimize new processes for the users (field engineers) to learn.

Hardware and software Interface was made (some still in progress) to existing peripherals used with mud pulse MWD, such as the rig floor driller's display unit (DDU), printers and plotters, and depth system.

A set of hardware was prototyped, and assembled for integration testing. This testing was first performed by the R&D engineers in their lab, and then the equipment was shipped to the field district office, where the field engineers took the system through its paces. A first field test on the core elements of this EMT Phase 1 system was successfully performed, with repeater, demonstrating a commercial quality EM MWD capability. The field test is examined in further detail in the "*Field Testing*" section.

UB Motors – Performance Characterization Testing: A substantial effort went into setting up a test facility, establishing a rational methodology, and then performing an extensive set of motor performance characterization tests with a range of fluids and motor parameter variation. Performance data already exists and has been published for operation of the various motors on water, so the primary focus here was to examine performance on compressible fluids, namely air/mist and mixed flow. The data resulting from this testing process requires significant analysis as of yet, and ultimately a UB motor selection, configuration, and usage guideline is anticipated along with specific UB fluid performance curves for these motors in the range of fluids. To ensure the validity of the data and of the curves and guidelines that will result, significant effort went into establishing a rigorous and theoretically sound process for this testing and the data acquisition. This effort and process, which represented a collaborative effort between the contractor and subcontractor Kalsi Engineering (KEI), is examined below along with some preliminary testing results.

Test Facility (refer to schematic, Figure 3): The contractor's test facility at Brittmoore Road, Houston, was already outfitted with a flexible configuration motor test stand, a dynamometer, water tanks, a pair of electric motor driven triplex mud pumps, associated measurement transducers and controls, and a control room. For this performance characterization exercise, compressed air service was contracted and brought on site. This included a pair of trailer mounted packaged Ingersol-Rand (I-R), 5-inch, 3-stage HHE compressors with Waukesha natural gas engines, an I-R booster unit comprised of a 5-inch 2-stage HHE compressor with Waukesha natural gas engine, and a triplex mist pump. Rated capacity of the primary units was 1200 SCFM each and 310 psig each, and with the booster, maximum capacity was rated at 2400 SCFM and 1500 psig. Natural gas lines were run to the engines, and piping for the air units was installed to come together with the mud (water) system, with appropriate valving to ensure safe operation, protect the air equipment, and enable metering and mixing of flows. The combined flow was routed to the motor test stand, to the top end of which ever motor was on the stand.

The motor test stand and dynamometer were set up to accept any size and configuration motor (complete motors - power section, coupling section, and sealed bearing section) within our range of testing. The motor's bit box was interfaced through a special cross-over into the dynamometer, which is basically a large brake. Flow entered the top of the power section of the specimen mud motor being tested, and exited through the dynamometer cross-over, through a configurable orifice plate (to simulate pressure drop below the motor).

Transducers were installed at all strategic locations to capture the critical air and water flow rates, pressures, temperatures, and the motor RPM and brake torque. Transducers were wired into the control room, along with the control lines for the brake and certain valves. A commercial software package was custom programmed to enable real time data acquisition, plotting, analysis, and archiving.

Testing Methodology and Plan: A methodology for testing was developed in conjunction with the installation and debugging of the test facility. This methodology was built around two major elements: (1) The matrix of motors, configurations, fluids, and parameter variations to be tested, and (2) the test plan itself to be applied to each configuration, to ensure meaningful and repeatable data. The matrix was at first cut market driven, focusing upon the

4 ¾” and 6 ½” motor sizes most strongly and then also examining some larger and smaller. A systems study was performed on the contractor’s entire fleet of available motor configurations, to determine which ones were even potential candidates for use on compressible fluids, as many motor configurations used today with incompressible fluids will necessarily over speed and fail on air. Utilizing exiting water performance data and knowledge of the motor geometries, data from some early air tests, and employing first principles governing motor performance and governing incompressible and compressible fluid mechanics, performance expectation envelopes were generated for the range of air flows expected in the field. Several motors in the sizes of interest were deemed appropriate for testing, and this drove the motor configuration matrix. The matrix was filled out with tests aimed at examining effect of subtle variation of key parameters, including the rotor/stator interference and friction. The test plan was centered around testing each of these configuration, fluid, and parameter variations, with a test process geared towards capture of the performance characterization as well as the configuration and dimensional variables before and after the test. The test process is schematically represented in Figure 4.

Testing: Over 150 test segments were performed per the test methodology and plan, on water (to confirm the baseline performance), air/mist, and mixed flow. Preliminary analysis suggests that sufficient quantity and quality of data was obtained to enable the main goals of this exercise to be realized, namely the creation of motor selection, configuration, and usage guidelines on these UB fluids, and performance curves. One typical set of performance curves is shown in Figure 5, of a particular motor running with a relatively constant SCFM input, but multiple motor pressures. In addition to the motor curves that will be developed, some important findings and relationships are identified below that the data has already or is anticipated to shed significant light on:

- Realities of air compressor outputs, and importance of accurate and continuous measurement of air volumetric and pressure data.
- Actual performance on compressible fluids at a given SCFM and pressure, as compared to that expected based upon inferred CFM and GPM through motor.
- Contribution of the controllable and measurable parameters such as rotor/stator interference, materials, bending moment, and lubricants, to the mechanical efficiency and volumetric efficiency factors, and to motor performance.
- Configurations and practices for use with air, conducive to avoiding inability to start on bottom, tendency towards stall, and off-bottom runaway.
- Degree and methods of lubrication acceptable or required in “dry” air situations.
- Performance of “Air Motors” versus standard multi-lobe motors on air.
- Performance on mixed flow, in the different regimes.
- Presence of mixed flow slugging regime, where performance is unpredictable.

Integration Elements: In pulling together the hardware elements and the understanding being gained from the activities above into a seamless service, several integrating tasks have been in progress:

- An EM telemetry model has been in programming, building upon the fundamental telemetry theory provided by GEC. This model will be used in the well planning process to determine feasibility of EM telemetry, and then to trade off repeater placement, power use and battery longevity, data rate, and other influencing variables. It is also intended to be used on site, to re-assess based upon unanticipated circumstances.
- The first phase EM MWD manual has been completed, using the GEC M29 system currently in the field as a model. A second release based upon the EMT system is currently in progress.
- Other integration elements yet to be started on, including the UB Motor Performance curves and Integrated System Guidelines, are reviewed in the "Future Activities" section.

Field Testing: Three low exposure component field tests on the EM MWD have been completed, as well as two tests to examine the air drilling vibration environment. These tests are examined further below:

Field Test #1 – June '96, Saskatchewan -- Phase 0 EM MWD System: The purpose of this test was to validate the technology porting process from GEC to contractor, and prove the basic EM telemetry capability on the contractor's downhole and surface platforms. The Canada location was chosen for this and subsequent early tests for several reasons all stemming back to the goals of maximizing the learning, while minimizing the costs and risks. The contractor's (as well as the industry's) underbalanced directional drilling and EM MWD use have been predominantly in Canada. Testing in an area with known EM telemetry characteristics would allow a benchmark comparison to the GEC hardware.

This first test entailed running the EM MWD Phase 0 system behind ("piggy-back") to a mud pulse system, in a continuous liquid fluids system, in a multilateral drilling program. The EM MWD was not being counted on for critical data, and as such this was deemed a low exposure situation. Single hop EM MWD was performed as two curve sections (KOP around 1300 m) were being drilled, with successful uplinks and downlinks. Semi-quantitative benchmark comparisons to the known GEC performance were favorable. Downlink detection capability was improved as compared to the benchmark, with downlinks detected irrespective of rig operations. Directional data from the DEP2 probe was of the usual high quality. No downhole tool survival issues came to light, although this was a mild drilling environment.

Several difficulties or design issues were encountered, as expected on this first job, with minimal job impact. The surface downlink amplifier failed, some galling occurred on a downhole locking ring, some software functionality issues were identified, and the mechanical implementation of the PWD sensor (not yet activated) was determined to be too complex. These issues all drove design improvements in the Phase 1 tool.

Field Test #2 – September '96, Alberta – Phase 0a EM MWD System: The purpose of this test was to prove the basic EM telemetry capability with the addition of the repeater hardware and software. From a systems and programming standpoint, this is a significant complicating element. The Canada location was again chosen as optimal on the same rationale. The tool was run piggy-back to the mud pulse tool again. A single 4 ¾" EM MWD assembly and repeater were used on two successive bit runs in a horizontal section at 966 m TVD, drilling from 1157 m to 1473 m MD. EM telemetry uplink and downlink were successfully demonstrated with the repeater and in single-hop mode, both for surveys-on-demand and in continuous toolface (steering) mode. There was opportunity for extensive exercising of the software, and a list of feature additions/changes was generated for implementation in the Phase 1. There was a problem with electrical noise, but it was found during the test to be self generated by the surface system, and remedied by the R&D engineers on site.

Field Test #5 – January '97, Saskatchewan – "EMT" Phase 1 EM MWD System: The purpose of this test was a first functionality demonstration of the EM MWD system intended for commerciality, with the PWD and other enhanced features, and the core of the commercial-ready software set. A Canada location was again chosen on the same rationale. A 4 ¾" tool was run with repeater, coming out of casing near horizontal at around 600 m TVD, with fresh water drilling fluid. Again the EM system was run piggy-back to the mud-pulse system. The functional tests were for the most part successful, and in addition to the functions examined on previous field tests, downhole pressure measurements were taken and successfully transmitted to surface. Some minor mechanical issues were found at disassembly, including one resulting in the redesign of a sonde bulkhead. Also, some software issues were noted and are being addressed.

Field Test #3 – October '96, Colorado – Drill-String Dynamics Sensor behind Motor, on Air: The purpose of this test was to examine the downhole vibration environment when drilling with a motor, with air as the drilling fluid. Anecdotal evidence has been that the vibration environment in air drilling with a motor is substantially worse than with conventional mud, and wireline steering tools often do not fare well in this environment. The EM MWD system ultimately will have to endure this vibration environment, and reliability and repair costs of the EM MWD have substantial impact on the overall economics of the IUDDS. This knowledge is therefore important in driving the EM MWD design and qualification testing processes. The contractor's Drill-String Dynamics Sensor, or "DDS", is a triaxial accelerometer sensor package which measures lateral, torsional, and longitudinal vibrations. The DDS maintains a record downhole of peak and average vibration over time, which can be depth correlated at surface.

This particular Colorado job entailed drilling through hard rock (Cretaceous sand and shale), and air was being used for increased ROP and to mitigate lost circulation problems. This was a directional hole, building to around 25 degrees inclination. The DDS was utilized on four bit runs, from around 2000 - 6500 feet, behind a 6 ¾" multi-lobe motor and tri-cone bit, running on air/nitrogen with mist. The DDS logs for the four runs showed high vibration levels in the context of typical results (there is a wide range of "typical") seen in the DDS experience base with conventional liquid muds. Peak vibration was seen to exceed 200 g. But the more telling contrast was seen near the end of Run #4, as the drilling fluid was switched over to water. At that point, the peak and average vibrations dropped dramatically, as can be seen in Figure 6. This job provided good evidence of the severity of the air drilling environment.

Field Test #4 – November ’96, Arkansas – Drill-String Dynamics Sensor behind Motor, on Air: The purpose of this test was again to examine the downhole vibration environment with a motor on air. Based upon the results of the Colorado job, further data was desired from other air drilling candidate IUDDS areas to determine what kind of range existed. Arkansas’ Arkoma basin is an area of great interest for application of the IUDDS. A further goal of this test was to rigorously monitor the air and surface parameters associated with drilling, actions being taken at surface, and drilling performance, and then post-job to correlate these data to the downhole vibration.

On this particular Arkansas job, dry air (with some detergent) was being run for purposes of ROP, and to mitigate a shale hydration problem. The well plan involved coming out of casing at 20 degrees, building and drilling 7 7/8” hole to the target at 27 degrees. A steerable multi-lobe motor specially chosen for air was employed. The section was drilled with relative success, but the DDS tool failed due to high vibration, and no data was recovered. This in itself has been taken as an indication of the vibration environment. Significant insight was additionally gained into some of the issues that will be encountered down the line in operation of the IUDDS in air drilling circumstances where higher technology directional drilling techniques (i.e. motors and MWD) are not often employed. Employing of this new technology will also require working with the customer, rig contractor, and air service company to ensure that there is accurate and continuous means of air flow and other measurement at surface, and an appreciation of the sensitivity of the motor and MWD to all the potential actions taken at surface.

Commercial Application

There are many potential USA markets and applications for this IUDDS system and service. Some of them have been touched upon in the “Introduction” section. There is a vast number of USA wells directionally drilled with conventional overbalanced techniques, where formation damage could be hindering production, and there is a vast number of air/mist wells drilled today without the benefits of higher technology directional drilling tools and techniques.

Progress is being made already towards commercial application of elements of the IUDDS, with capital build taking place on the EMT EM MWD system. With completion of this project, especially the reduction of the motor testing data into a useful form and creation of UB directional drilling guidelines, the technology will become applicable to many of the USA areas that could benefit. What will dictate the availability of this technology are several fundamental drivers:

- First, commercialization is customer and market driven. As the gas and oil companies are exposed to this technology, those that see the greatest benefit and/or are technology leaders will create demand for its use on multi-well programs, which to a great extent will determine where the technology will be focused.

- Commercialization is also technology driven. There will be a natural tendency to first serve those applications of lower difficulty and technical risk (e.g. mixed flow drilling). Then as confidence and experience with the technology grows, and the technology is perhaps evolved further, those higher difficulty applications will be also be served to a greater extent.
- Finally, commercialization is economics driven. The first two points can be boiled down to economics terms of customer value, price, revenue, and service company operating cost. Additional factors such as tool utilization will play a role, as will the macroeconomic factors affecting the gas and oil companies' drilling programs.

Future Activities

Continuing Activities on Current Project: Continuing activities under the current DOE project, towards completion of the IUDDS, include the following:

- Continuing engineering on the EMT, with considerable work still required in software.
- Vibration and other environmental qualification on the EMT major modules.
- Reduction of motor characterization data into useful performance curves.
- Perform motor endurance test (possibly in field).
- Implement motor design improvements for ruggedness in air environment.
- Create IUDDS user guidelines and related documentation.
- Assemble the contractor's well planning software and industry-available UB fluids software into a suite for UB job capability.
- Complete field testing program.

Potential Future Work: Beyond the current program, there are several areas of continued work that would add considerable capability to the IUDDS system, and value to the resulting service:

- Create a comprehensive mud motor performance model, on a theoretical basis but with benefit of the considerable data obtained on the test stand, to drive further design improvements and the application of specific configurations to specific drilling situations.
- Integrate the contractor's existing software applications used in well planning with the software modules available to the industry relating to UB fluids. Further integrate these software modules with the real time data acquisition processes associated with the downhole PWD sensors, and the surface fluids monitoring equipment.
- Interface the IUDDS EMT system with additional existing sensors.

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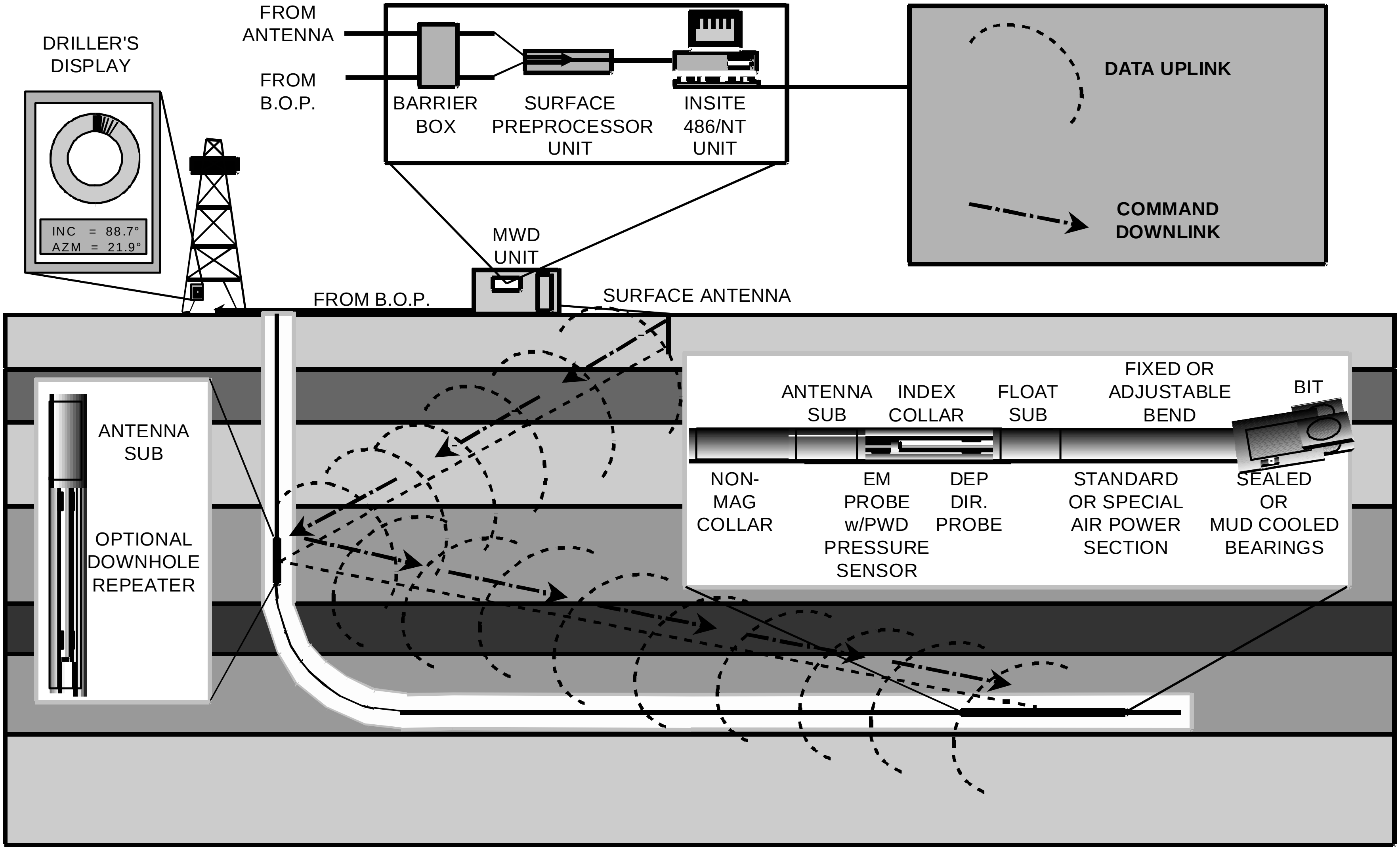


Figure 1. Schematic of Underbalanced Directional Drilling System

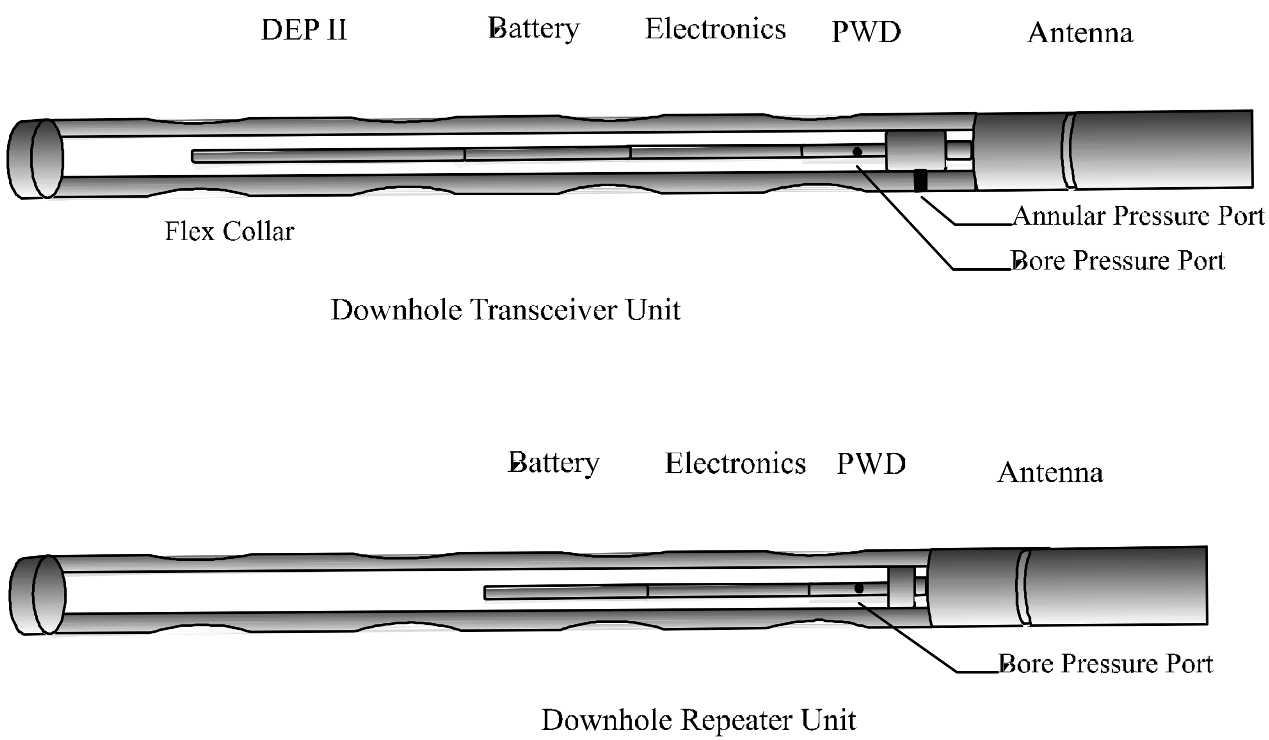


Figure 2. EM MWD Downhole Tools

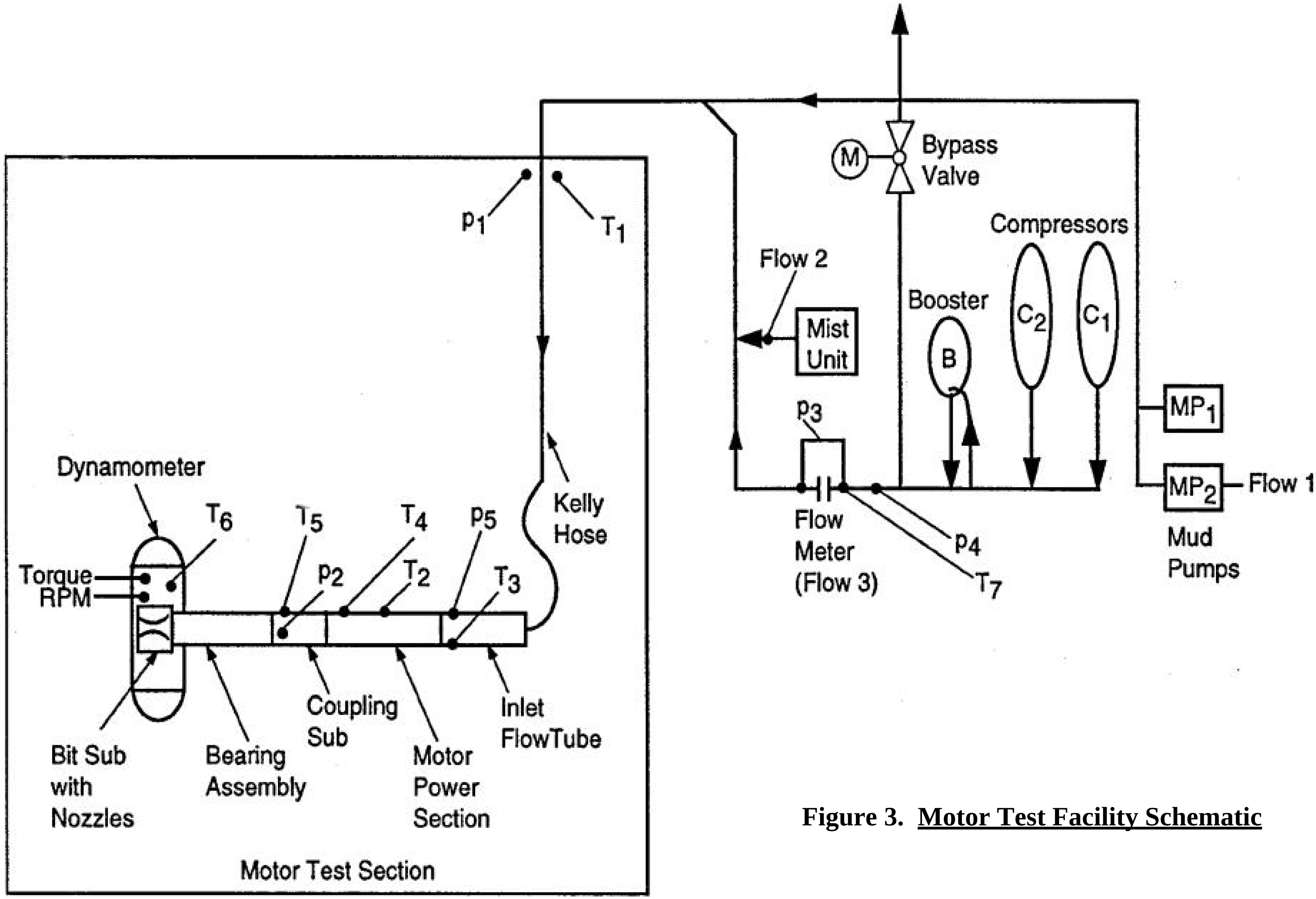


Figure 3. __Motor Test Facility Schematic__

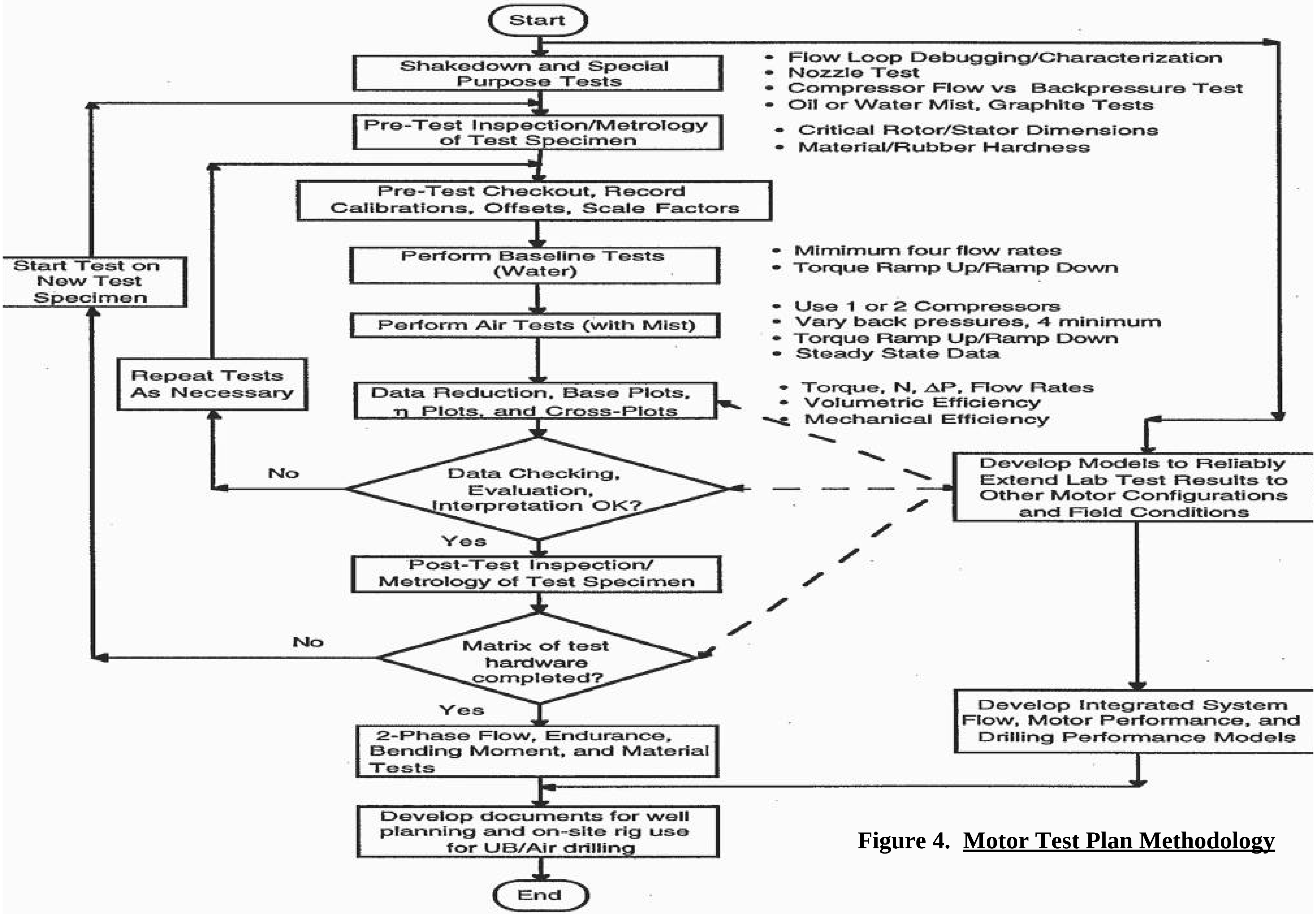


Figure 4. <u>**Motor Test Plan Methodology**</u>

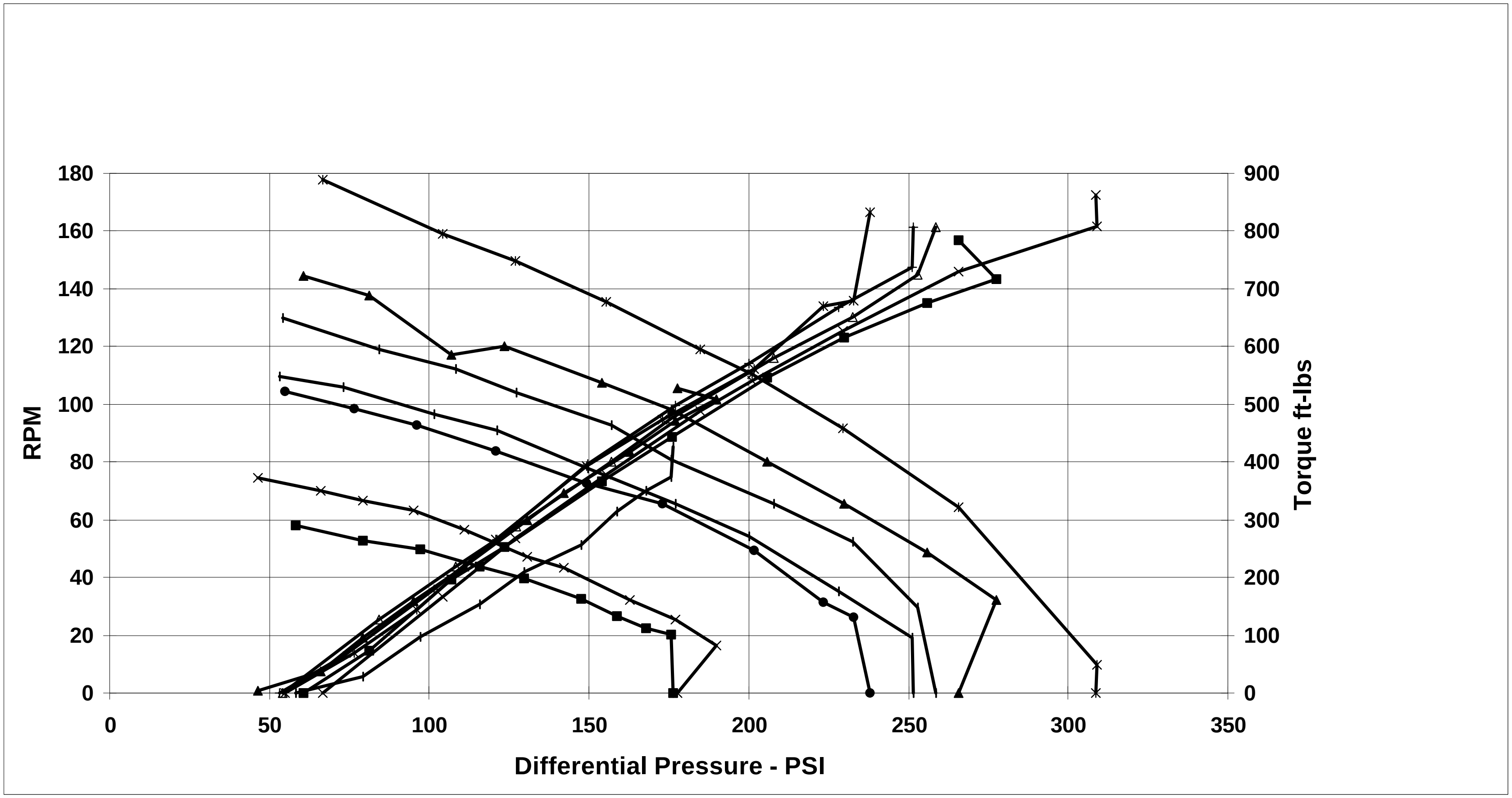
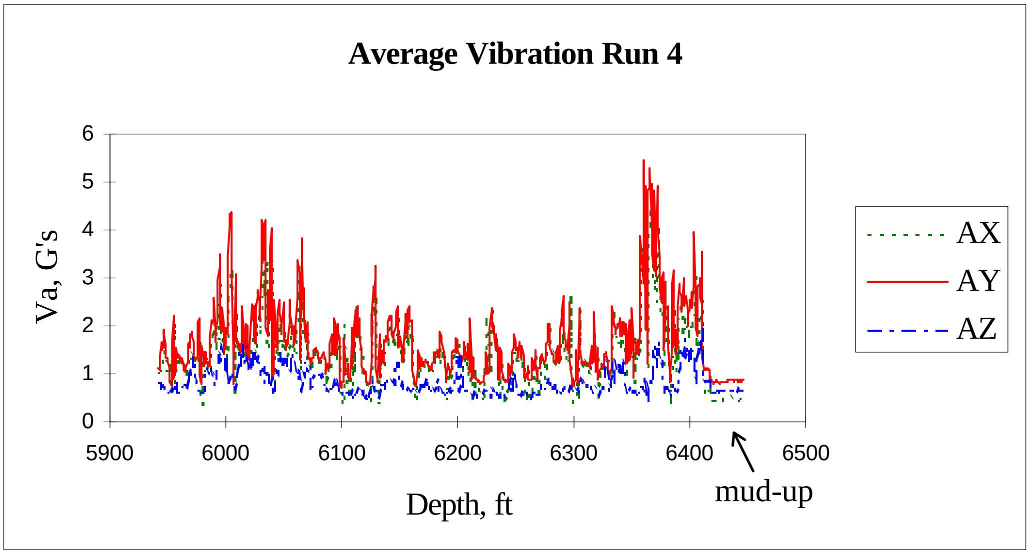


Figure 5. A Typical Motor on Dry Air, 2x1200SCFM Compressors: Family of Curves (raw data) for Range of Air Pressures



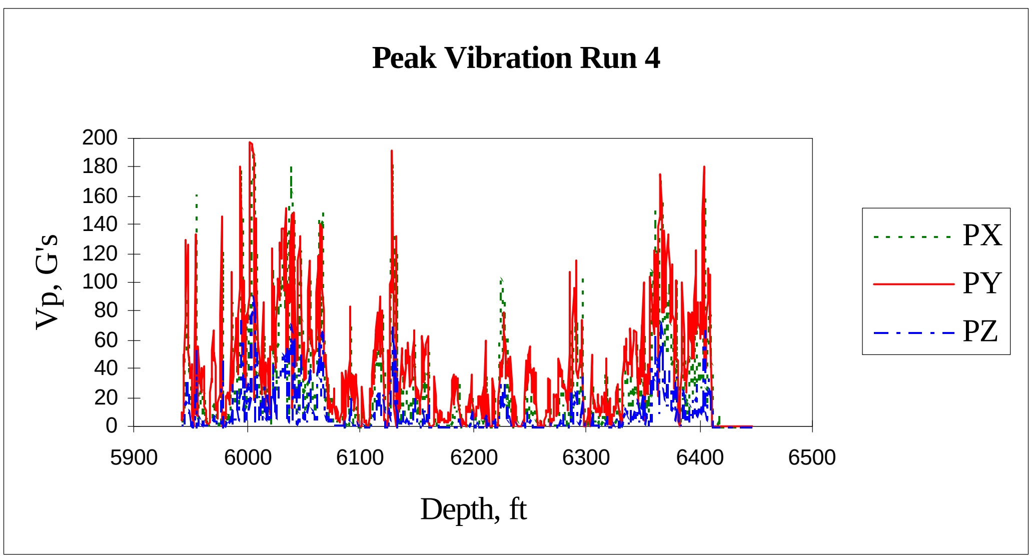


Figure 6. Air Drilling Job Downhole Vibration